Dark sector searches at CAST XRT with a novel opto-mechanical force sensor

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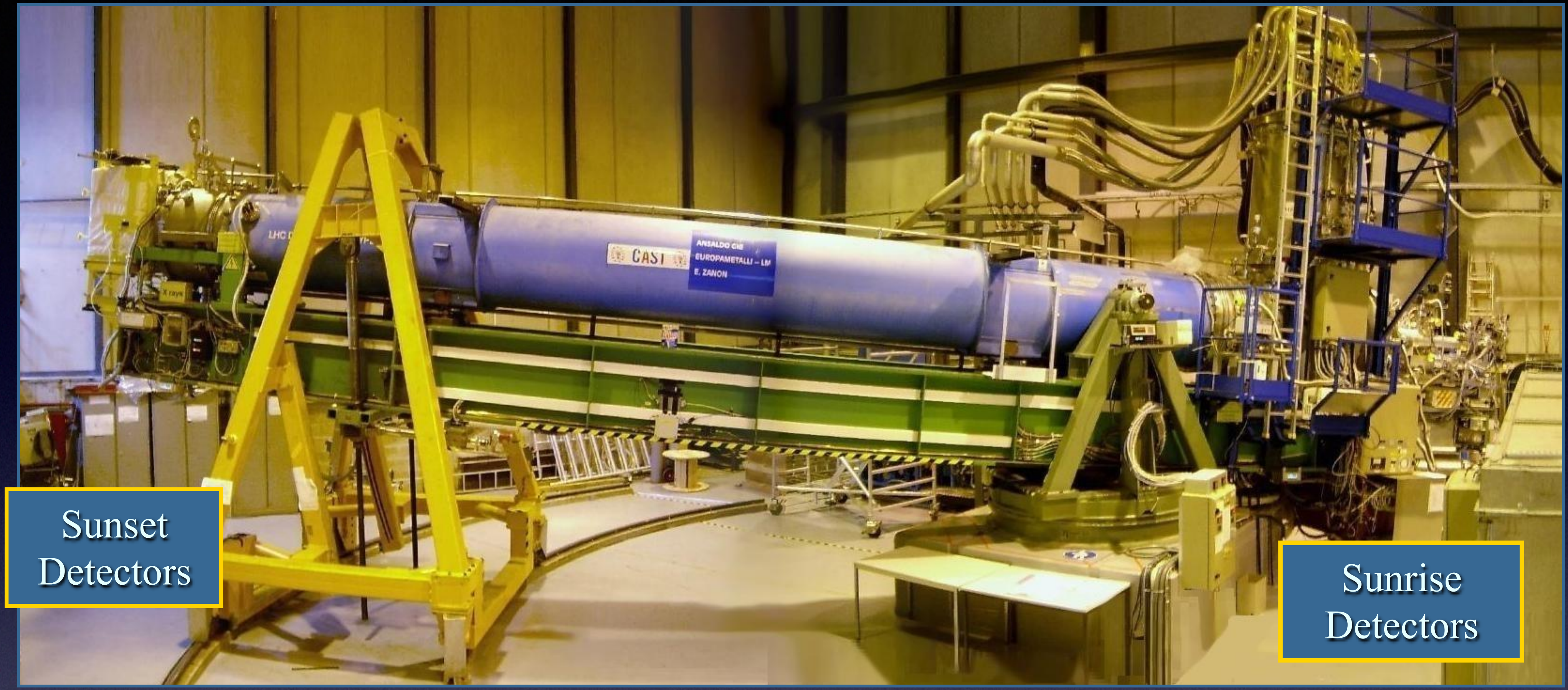
Summary

- VSI to opto-mechanical sensors
- KWISP: motivation and concept
- Current status
- Goals and achievements
- Conclusions (if any…)

CAST in pictures

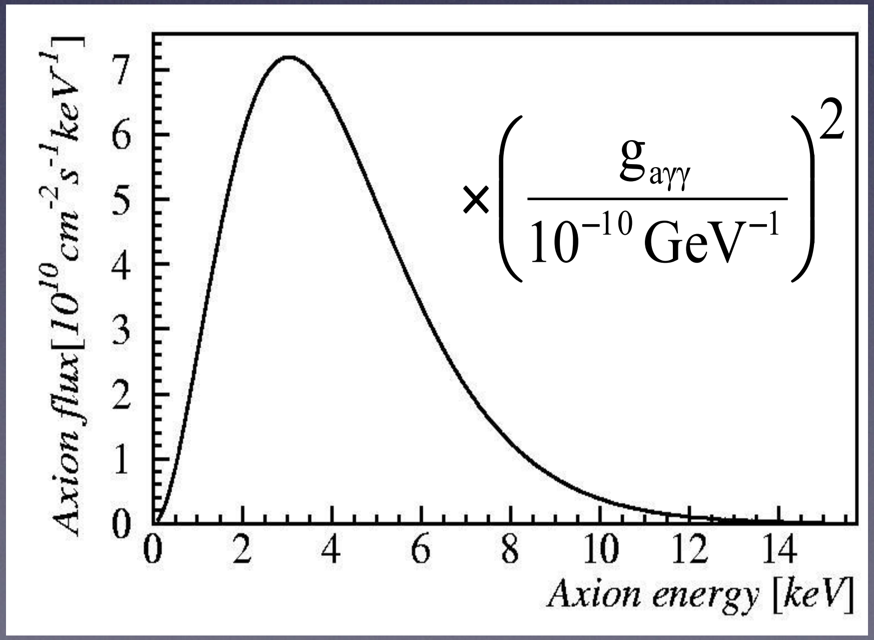
- CAST location at CERN

CAST in pictures



CAST in words

- LHC dipole magnet (9 m length, 9 T constant field intensity, two 43 mm dia. cold bores)
- Magnet is mounted on a moving carriage and can track (point its bores at) the Sun for ~1.5 hrs. at sunrise and ~1.5 hrs. at sunset - background data are taken in the remaining time
- The four available bore ports are instrumented with soft X-ray detectors (peak sensitivity at 4 keV) and two out of four always "see" the sun during a single tracking. One of the ports is also equipped with a dichroic mirror directing eventual low energy photons towards and off-axis visible photon counter
  - Two "sunset ports" both equipped with a MicroMegas X-ray counter
  - One "sunrise port" equipped with an X-ray focusing telescope and an InGrid sensor
  - One "sunrise port" equipped with a MicroMegas detector and an off-axis visible photon counter
- The magnet bore is at 1.8 K and can be kept in vacuum or filled with He gas isotopes to explore wider mass ranges



$$P_{a\to\gamma} = 1.7\times 10^{-17}\left(\frac{BL}{(9.0\ \mathrm{T})\ (9.3\ \mathrm{m})}\right)^2\left(\frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^2$$

$$N_\gamma = \Phi_a S P_{a\to\gamma} \approx 0.3\ \mathrm{events/hour}\ \left(g_{a\gamma\gamma} = 10^{-10}\ \mathrm{GeV}^{-1}\ \mathrm{and}\ S \simeq 14\ \mathrm{cm}^2\right)$$

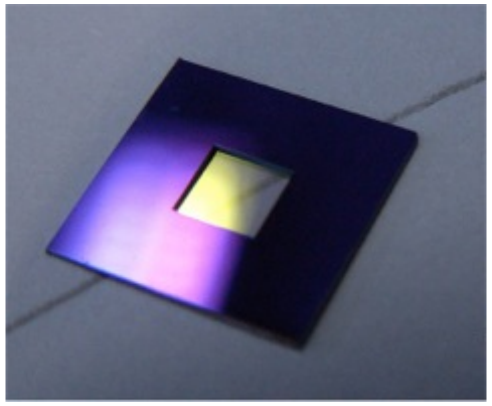
A novel opto-mechanical sensor for Chameleon searches

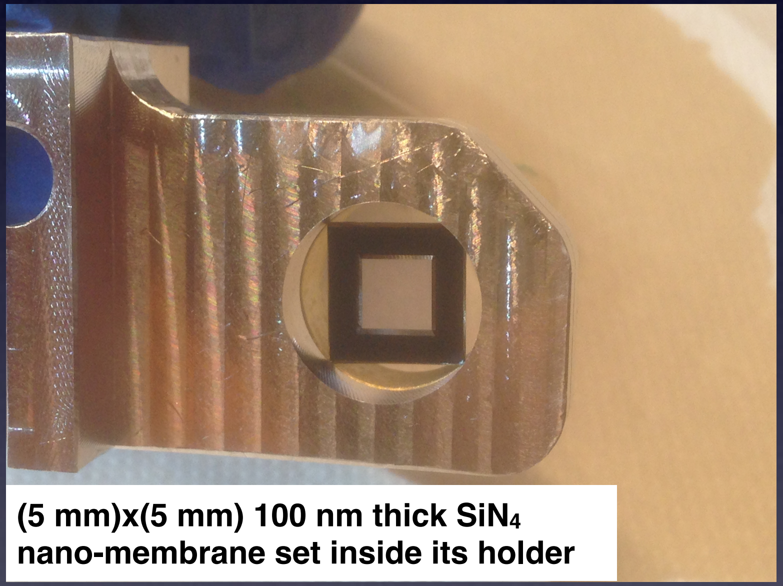
- **Chameleons** are a type of **scalar WISPs** having a mass dependent on the local energy density. They are a possible candidate constituent the Dark Energy (see for instance arXiv: 0706.1024v2 and P. Brax et al., Chameleon Dark Energy, AIP Conf.Proc. 736 (2005) 105-110)
- Chameleons couple to photons *à-la-Primakoff*, and also directly to matter with a coupling strength also depending on the local energy density
- Chameleons can be produced inside the magnetic field of the Sun from photon-photon collisions and then stream to the Earth
- **Two detection possibilities**
  - Primakoff conversion inside a magnetic field (coupling to photons)
  - equivalent radiation pressure on a suitable surface at grazing incidence (direct coupling to matter)
- **Detecting the solar chameleon flux @CAST:**
  - search for photon-chameleon coupling with sub-eV photon detectors (see talk by T. Vafeiadis)
  - **detect directly the chameleon pressure on a surface with a force sensor coupled to the a CAST XRT**
- **Key challenge: develop a a sensitive force sensor and install it on CAST ⇒ KWISP - Kinetic WISP detection**

Opto-mechanical force sensors

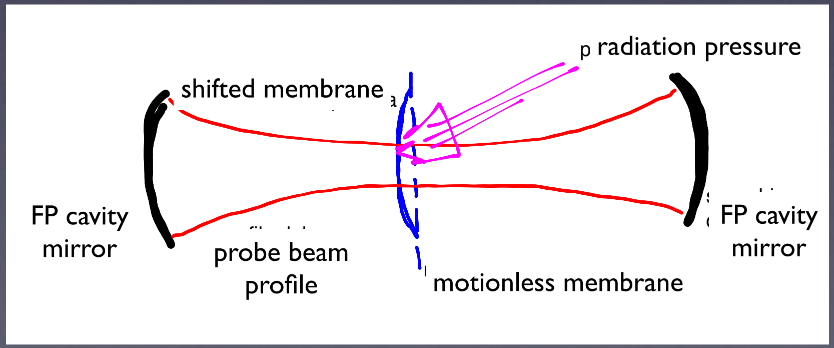
- A nano-membrane (a few 10s of nm thick) placed inside an optical Fabry-Perot resonant cavity does not perturb cavity modes if perfectly centered and aligned
- Membrane movements in response to an applied force shift the cavity mode frequencies
- If a laser beam is frequency-locked to the cavity using a feedback loop, the error signal senses frequency shifts and can be used to measure membrane movements

(1 mm)x(1 mm), 50 nm thick Si_3N_4 micromembrane mounted on a 200 μm thick Si substrate





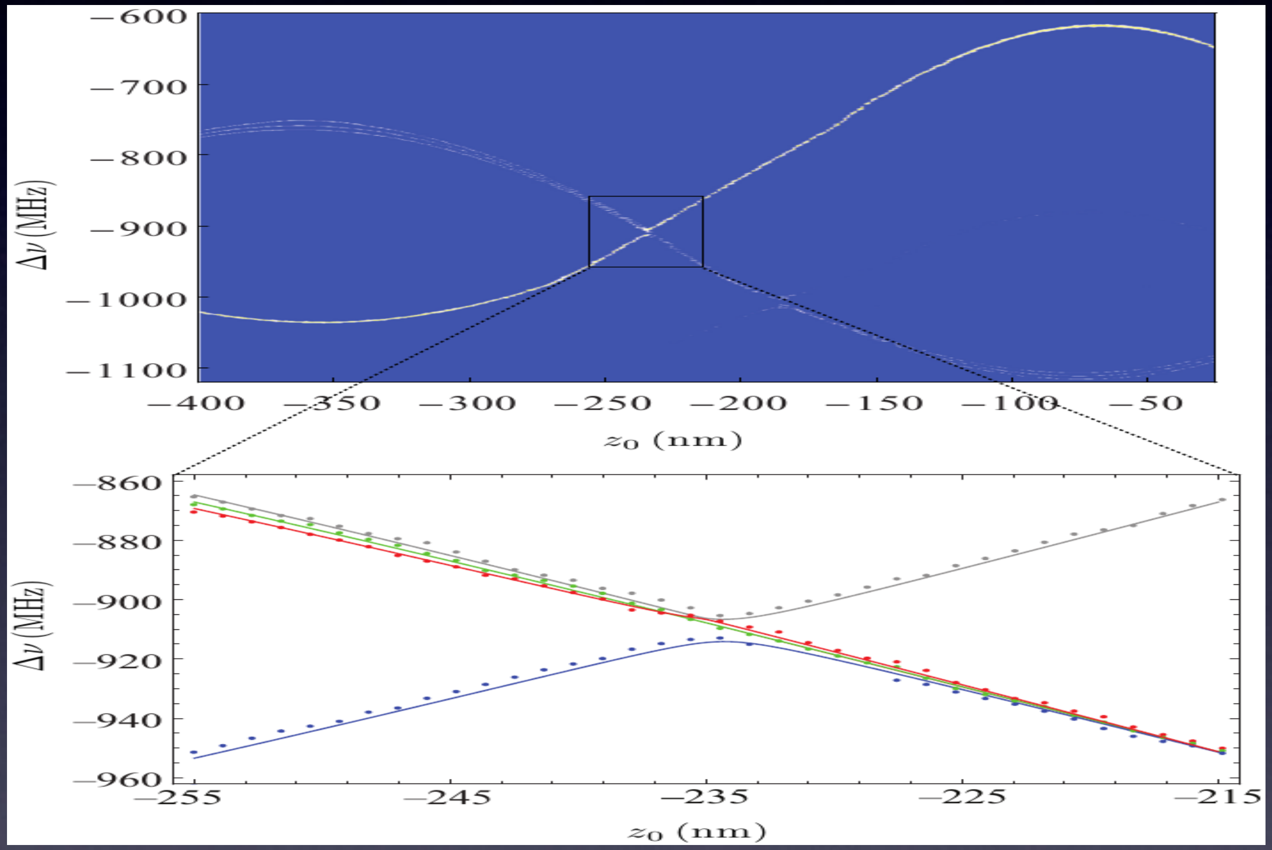
(5 mm)x(5 mm) 100 nm thick SiN_4 nano-membrane set inside its holder



Measurement principle

- Resonance modes of a confocal FP cavity are not perturbed if a transparent nano-membrane is aligned and positioned una node of the standing intra-cavity electric field.
- A membrane displacement couples the membrane mechanical modes to the TEM modes of the cavity. Mode proper frequencies are displaced with a detuning dependent on membrane position along the cavity axis.

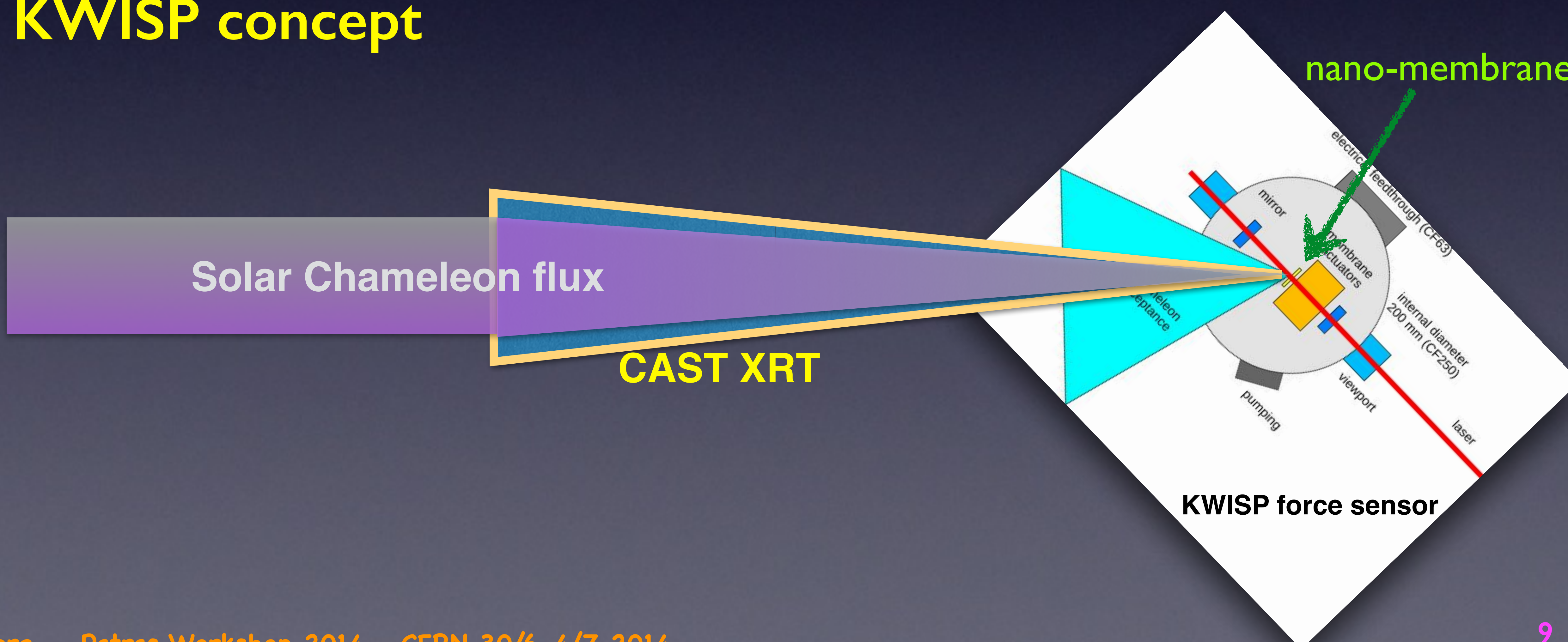
  - Mode frequency detuning (Δν) as a function of membrane displacement along the cavity axis (z) has a typical oscillatory dependence
  - Other effects
    - degenerate modes resolved and missed frequency crossings
    - linear combinations of nearby TEM modes become new cavity modes



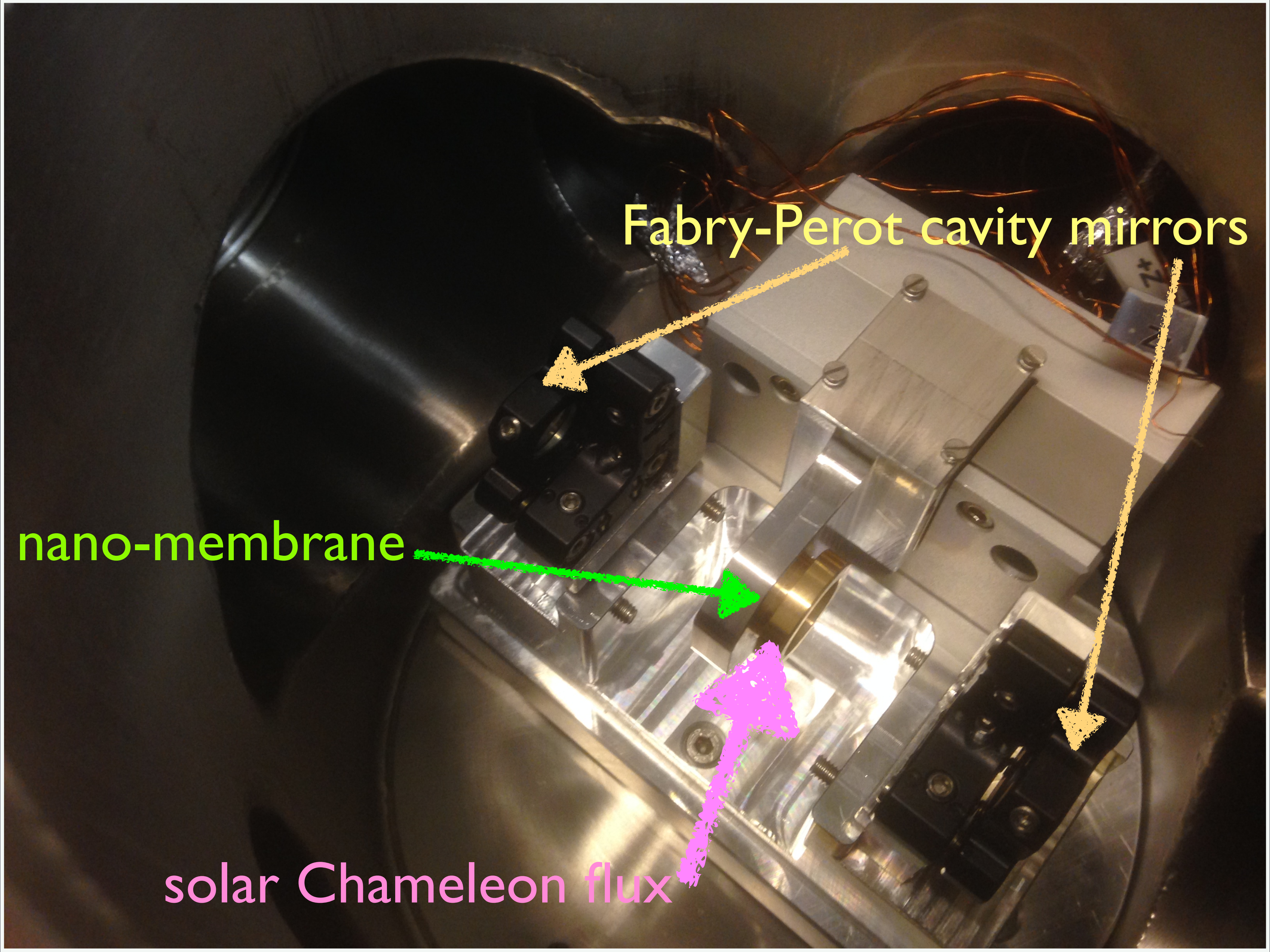
- The above graph was obtained by moving the nano-membrane alone the cavity axis (z) and by measuring the corresponding mode detuning with respect to the initial "zero" membrane position (see M. Karuza et al., New J. of Phys **14** (2012) 095015)
- The best sensitivity to membrane displacement is in the zones of the plot where the slope is largest

KWISP Motivation & Concept

- Why this complicated technique to measure such a trivial thing as a force? Why the Fabry-Perot cavity?
  - Because extremely tiny forces can be measured, and the FP finesse acts a gain multiplier increasing the force sensitivity by a large factor
- Novel application
  - sense directly the coupling to matter of solar chameleons exploiting the pressure exerted by the chameleon flux on a nano-membrane
- **KWISP concept**



Trieste force sensor prototype



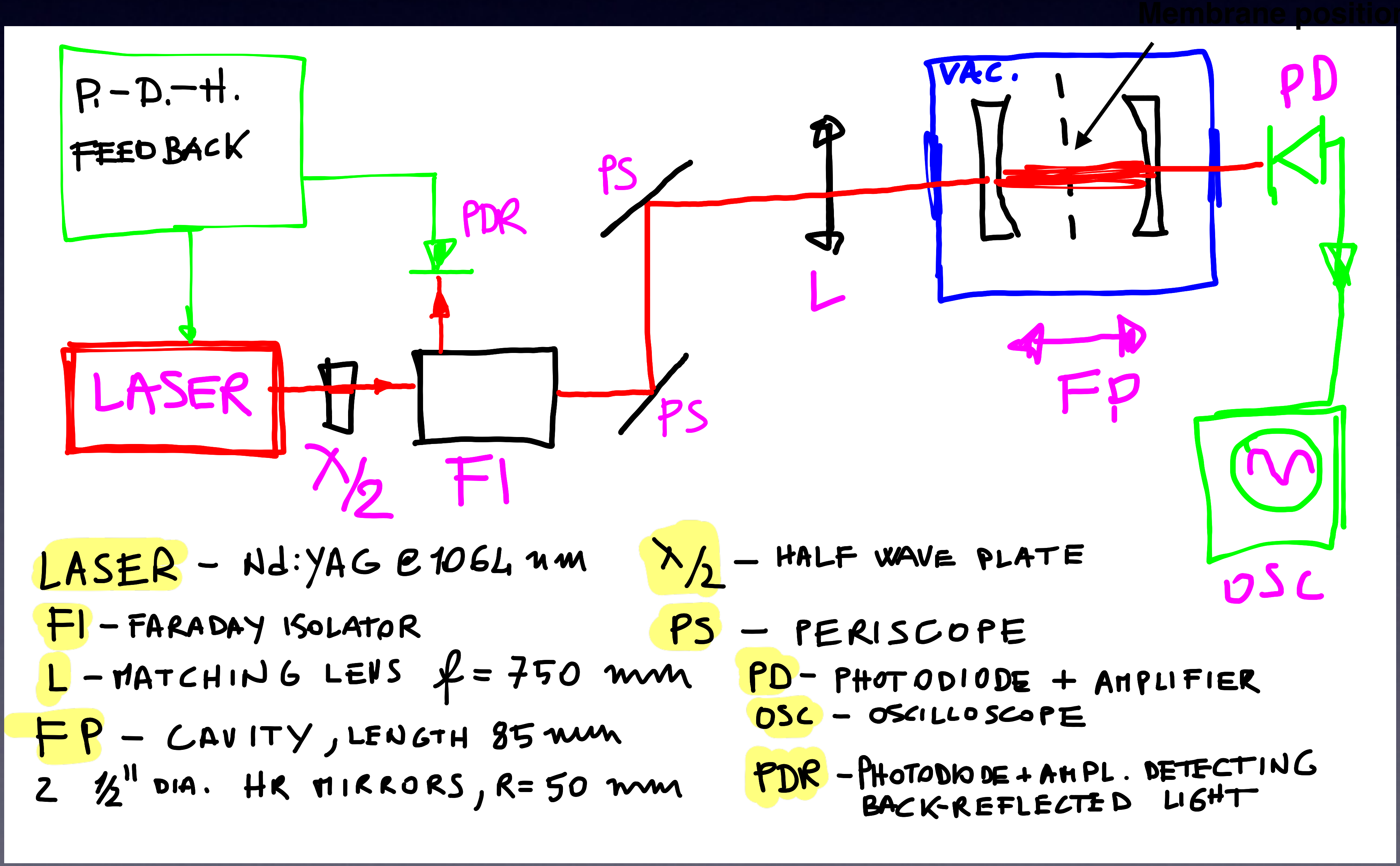
- Force sensitivity estimate for the Trieste prototype
  - measured base force sensitivity ("single pass" FP): 3×10^{-9} N/$\sqrt{\text{Hz}}$
  - projected sensitivity with 60000 finesse FP: 5×10^{-14} N/$\sqrt{\text{Hz}}$

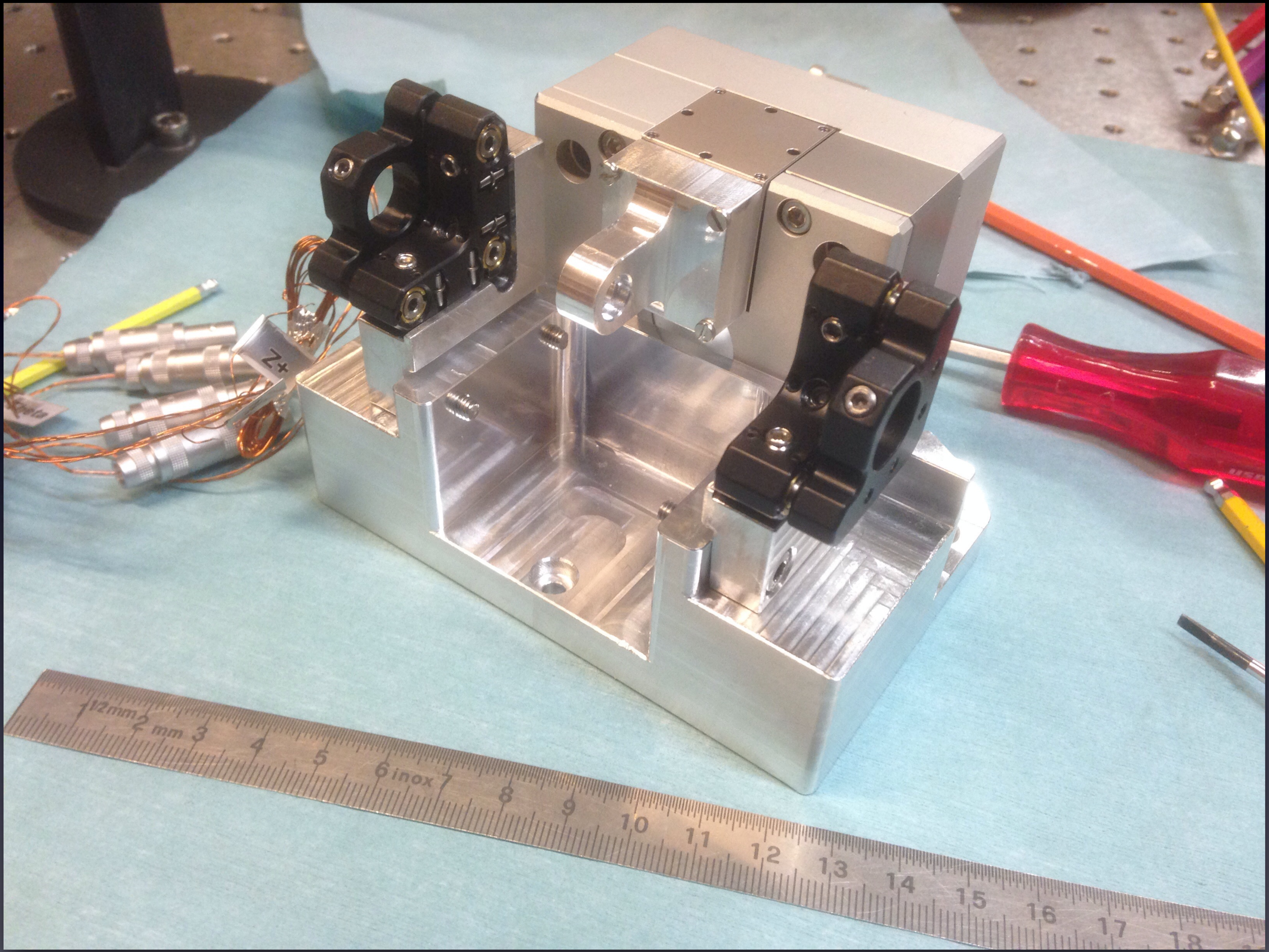
Trieste sensor prototype current results

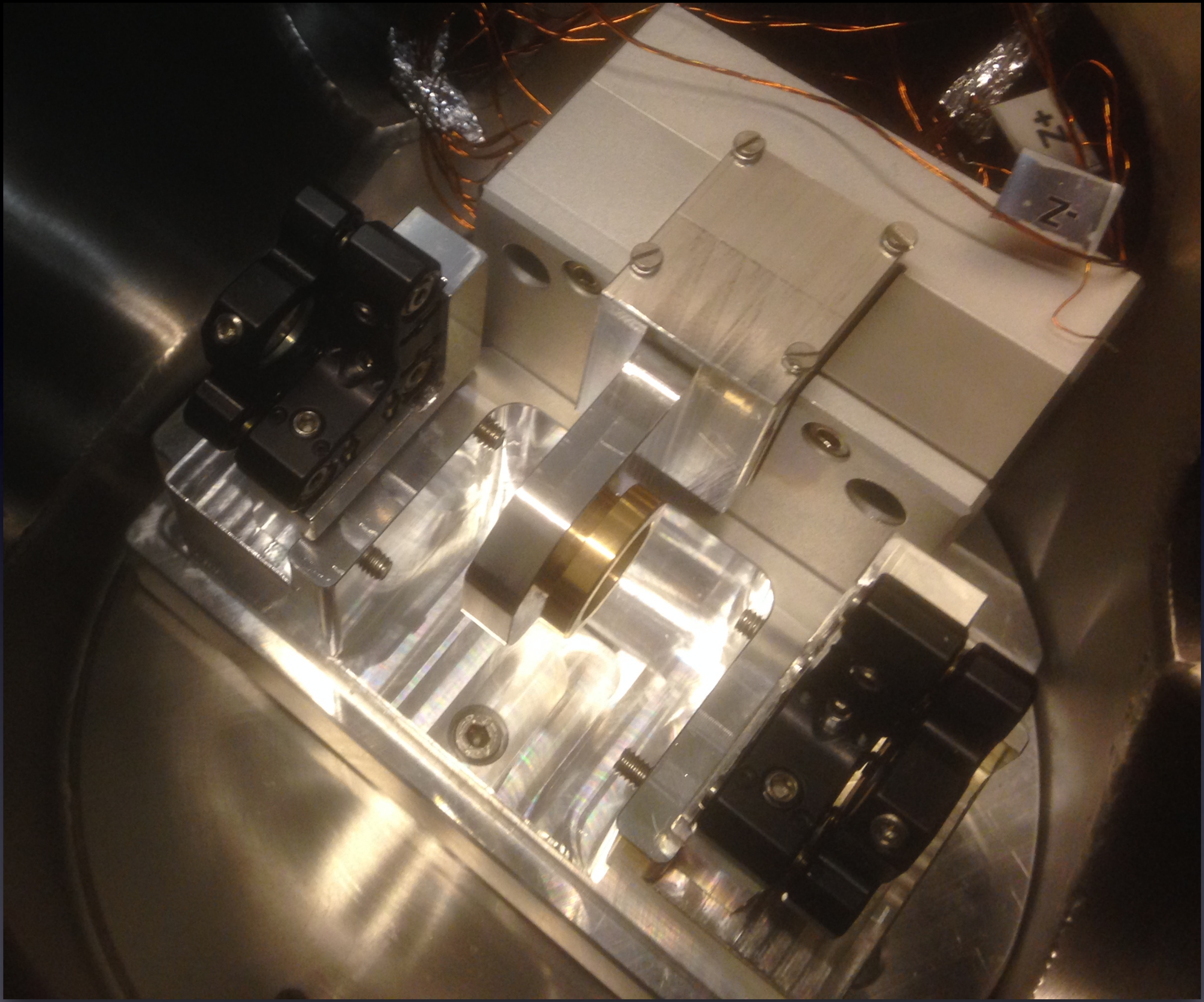
- Base sensitivity measurements
  - base sensitivity measured with Michelson-type interferometer (equivalent to single-pass Fabry-Perot): 3×10^{-9} N/$\sqrt{\text{Hz}}$
- Sensor assembly version 0
  - assembled cavity in vacuum
  - aligned and measured Finesse ~ 60000
- Sensor assembly version 1
  - redesigned mechanics
  - vacuum tests
  - alignment and matching
  - checked finesse
- Ongoing: insertion and alignment of (0.5 mm)x(0.5 mm) nano-membrane at center cavity

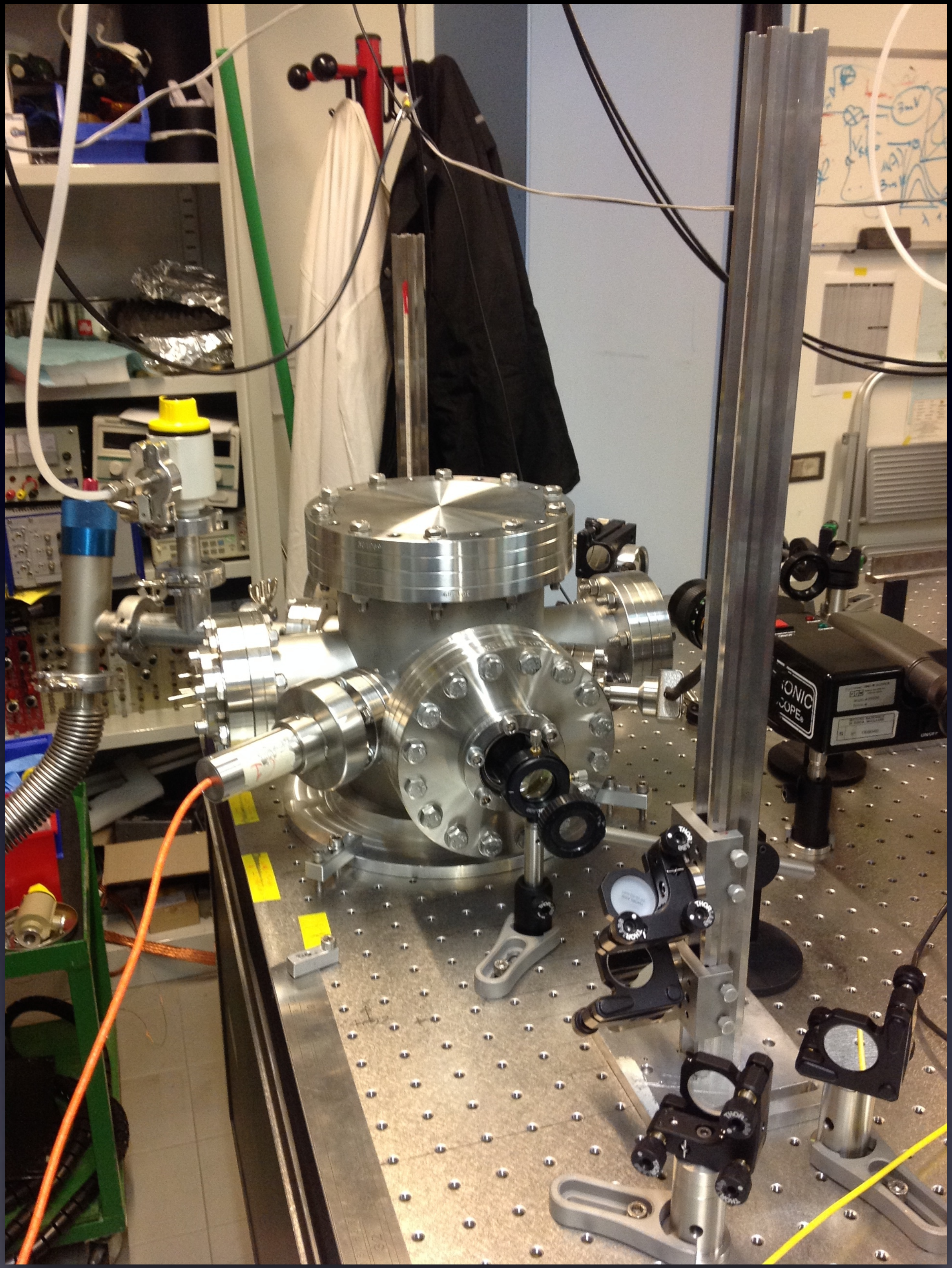
Sensor optics scheme

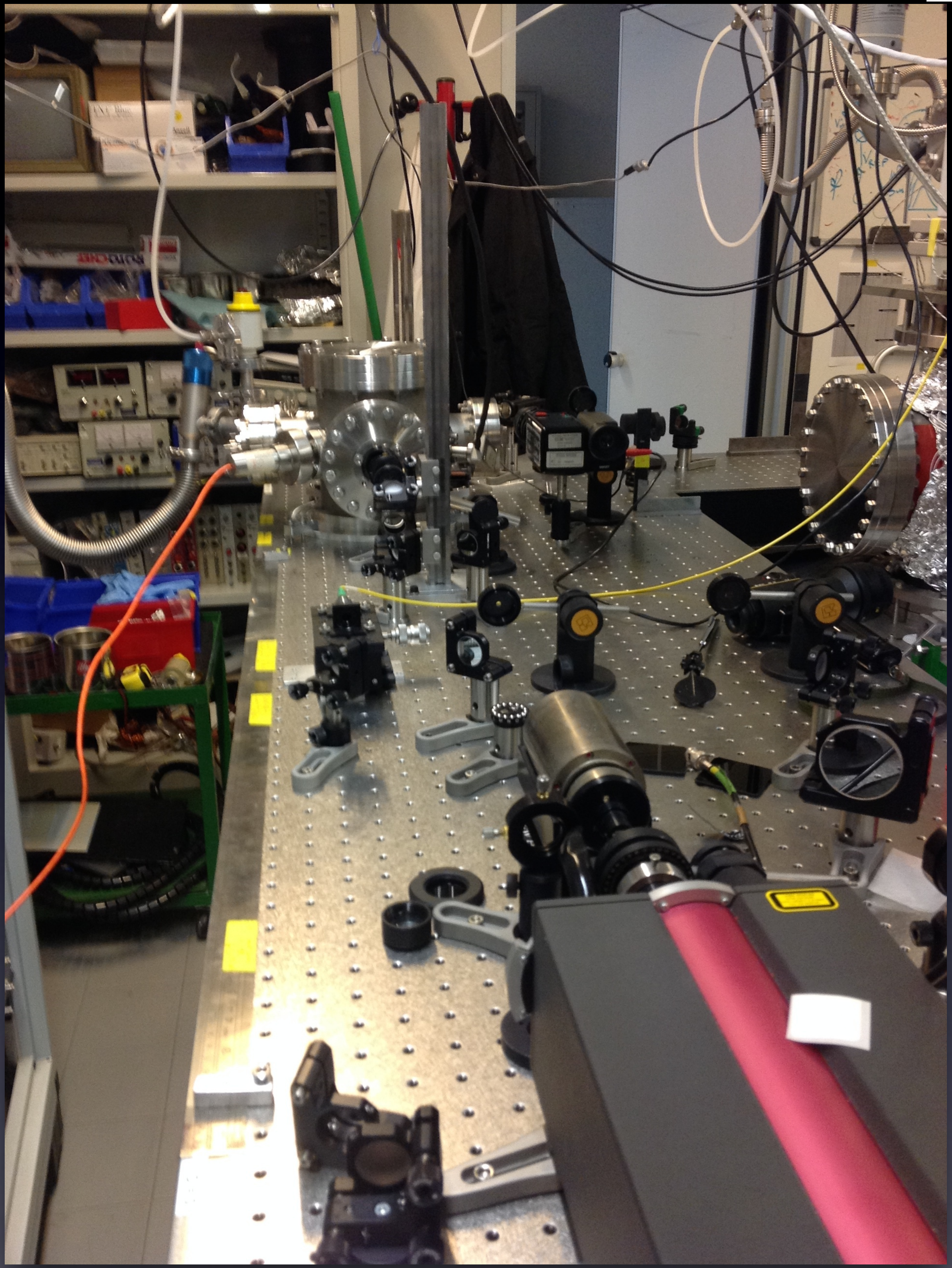
- Sensor cavity mounted on monolithic Al support with mirror mounts and PZT-driven 5-axis movement stage for the nano-membrane
- Nd:YAG CW laser at 1064 nm (also 532 nm for alignment)
- Laser-Cavity frequency-locking with modified Pound-Drever-Hall technique

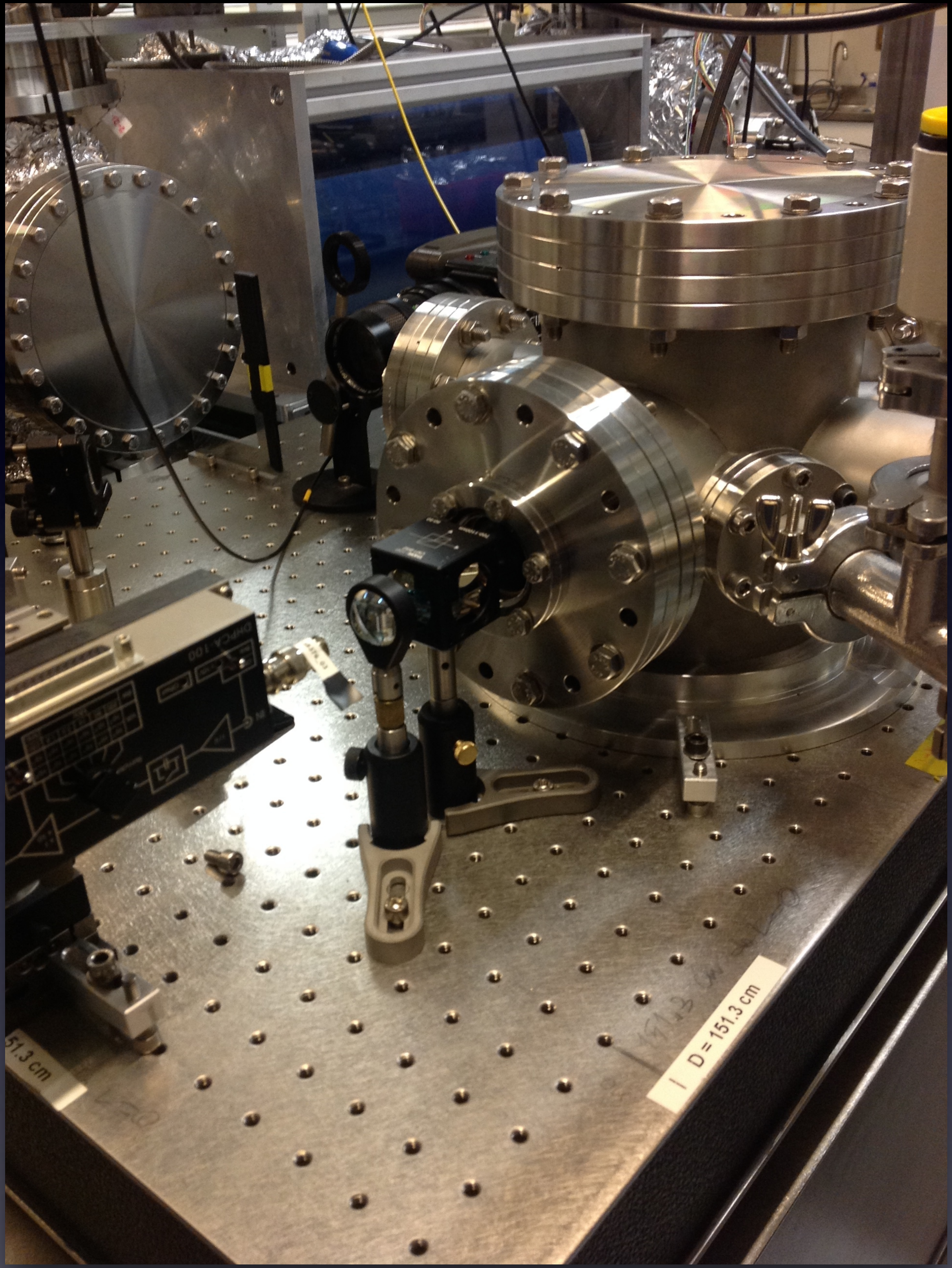


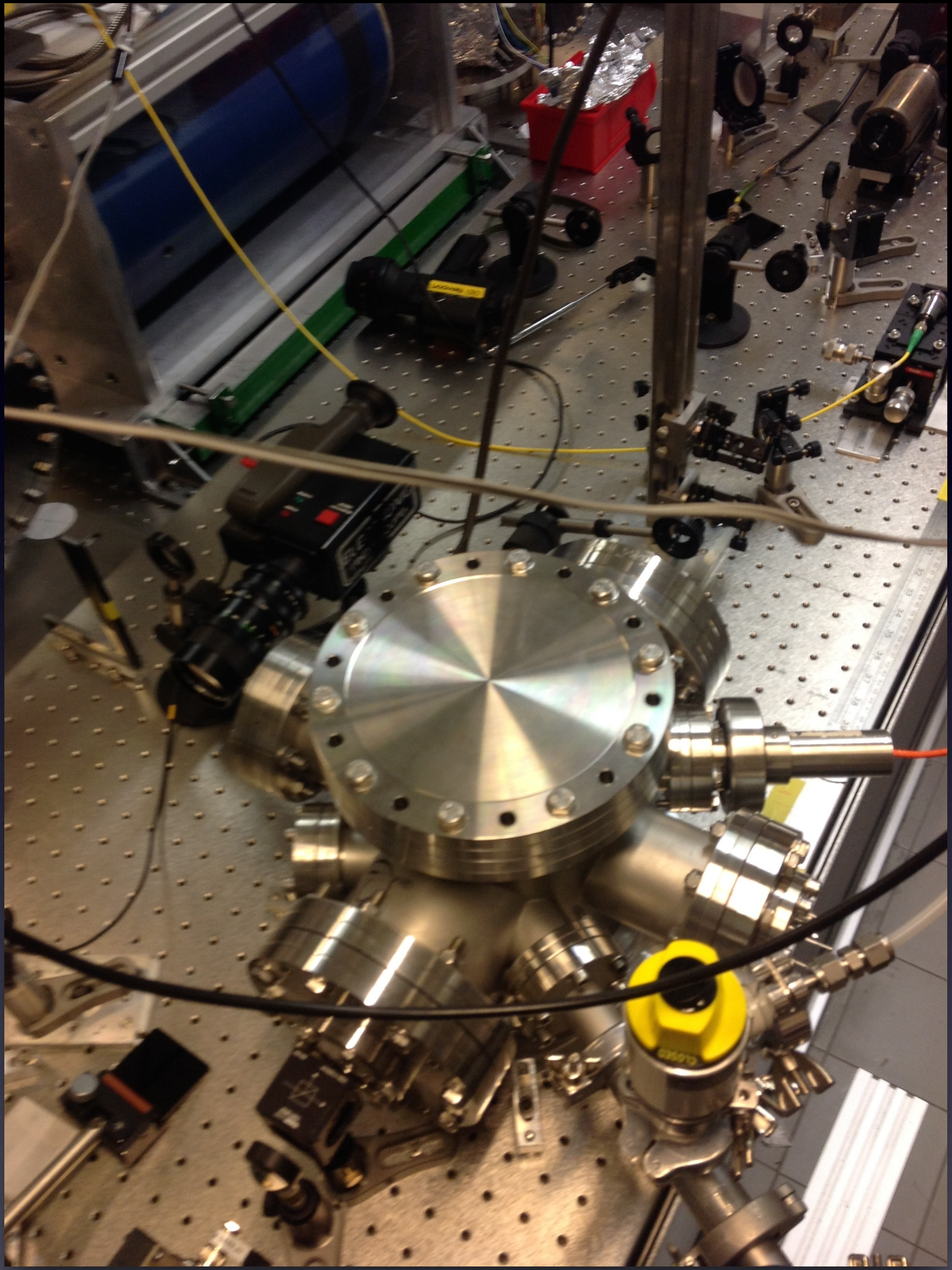

Z+
inox


Z+
Z-



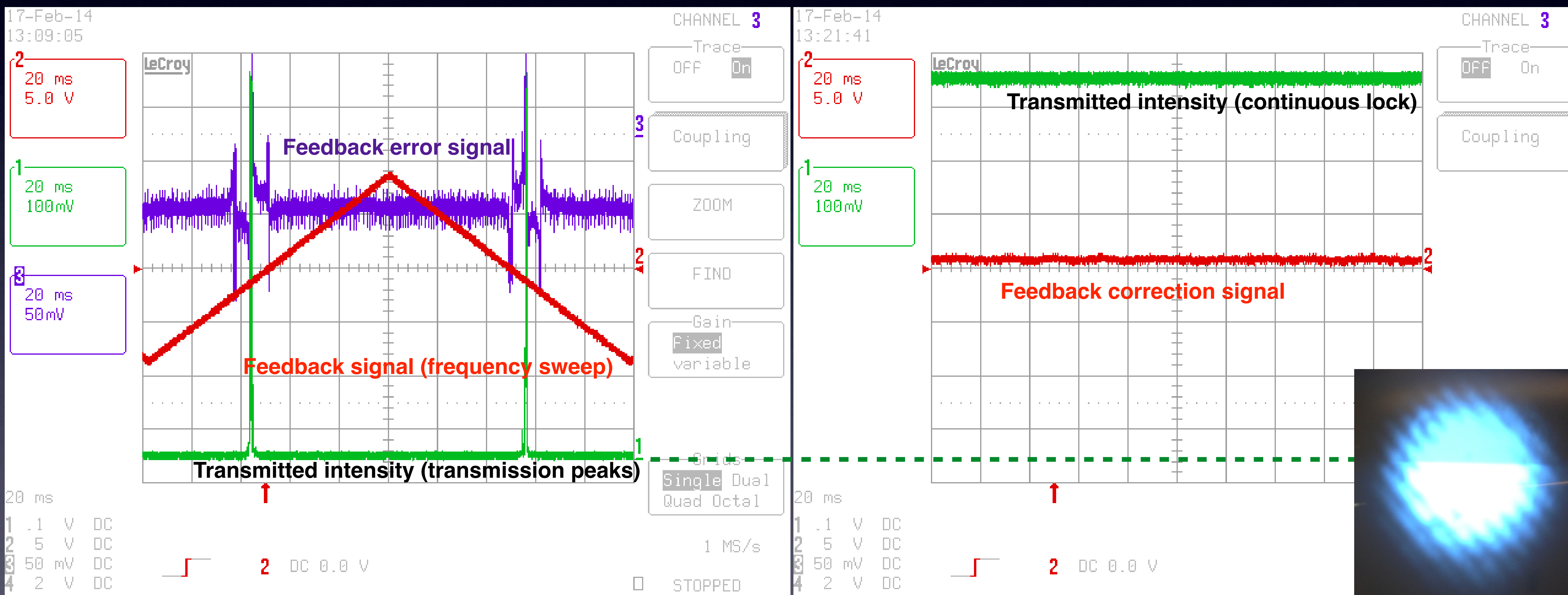



D = 151.3 cm
51.3 cm



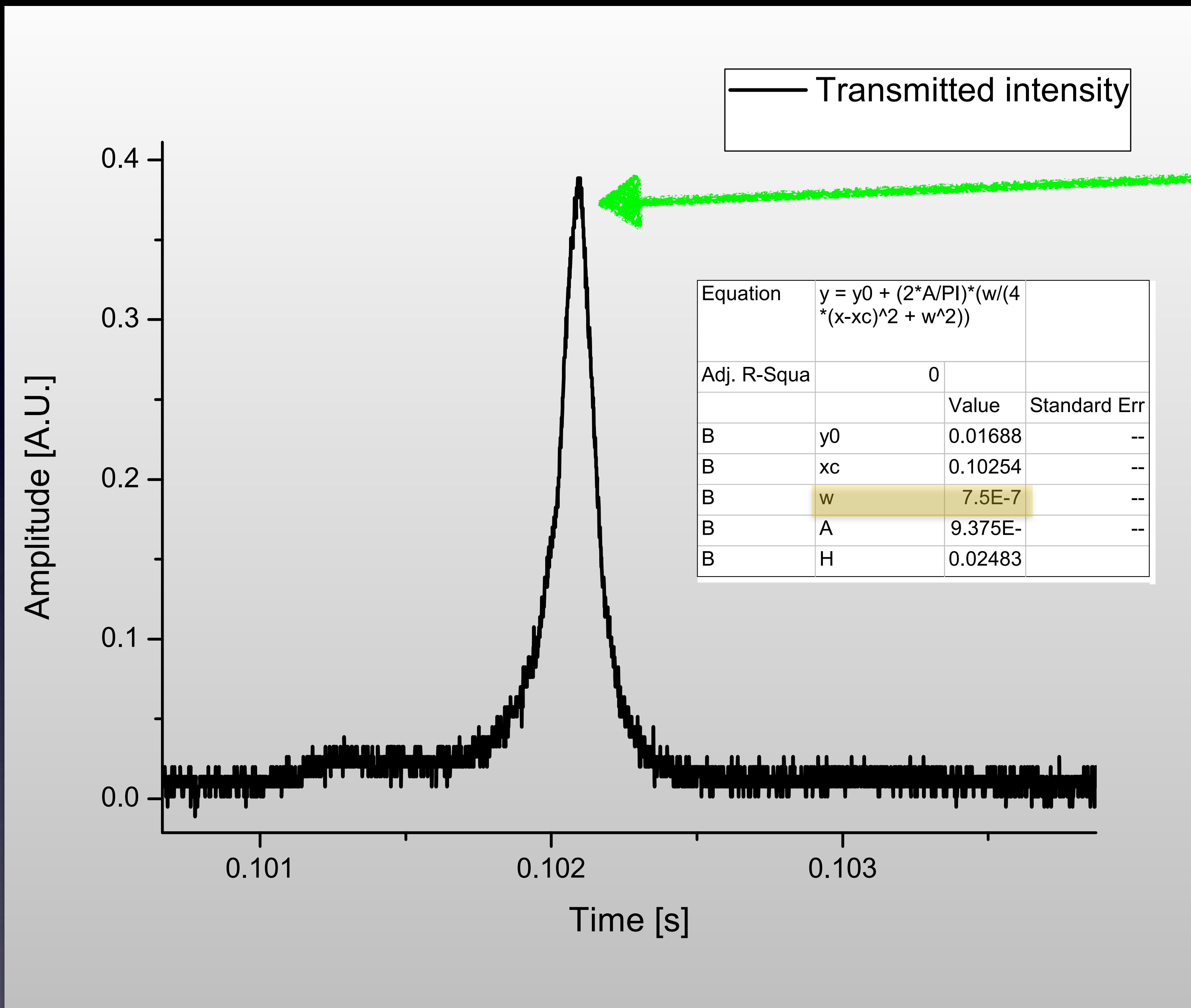
KWISP laser-cavity lock

- Laser-cavity frequency lock using a modified Pound-Drever-Hall scheme
  (see G. Cantatore et al., Rev. Sci. Inst. **66**, 2785 (1995))



Cavity TEM00 mode

Fabry-Perot finesse measurement



Resonant mode trasmission peak

Fitted with a Lorentzian to find the FWHM = 150 μs

Triangular waveform slope C = 200 V/s
Laser PZT characteristic K = 1.0 MHz/V

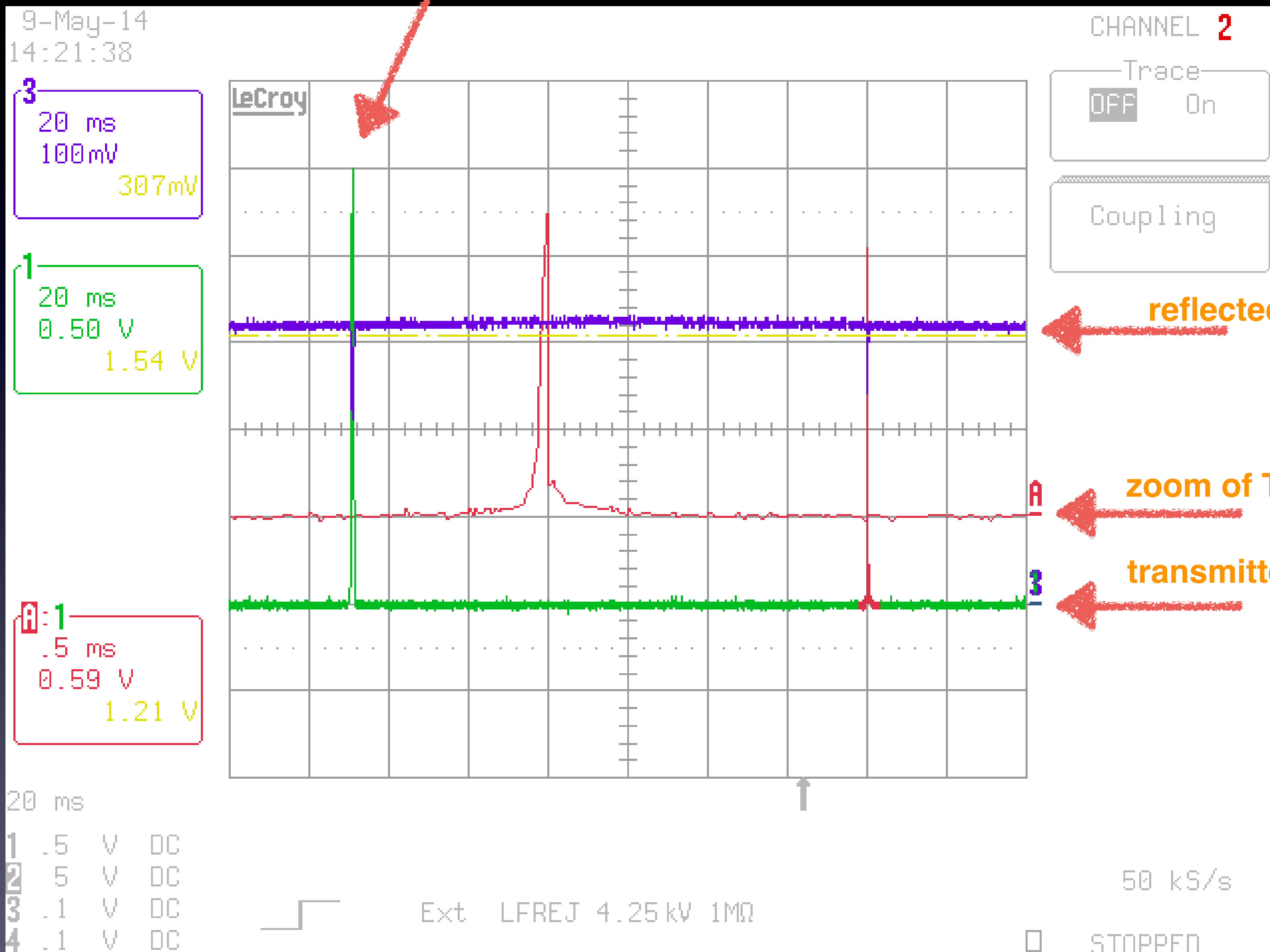
$$\Delta\nu = K \cdot C \cdot (FWHM) = 3.0\times10^{3}\,\mathrm{Hz}$$

$$FSR = \frac{c}{2L} = 1.76\times10^{9}\,\mathrm{Hz}$$

$$Finesse = \frac{FSR}{\Delta\nu} = 58000$$

Cavity check

TEM00 mode transmission peak



Cavity reflectivity at resonance (100 mV)/(320 mV) = 31.2 %

reflected intensity

zoom of TEM00 peak

transmitted intensity

Cavity transmissivity at resonance = 68.8 %

(consistent with F ~ 59000)

Ongoing and upcoming steps in Trieste

- Insertion of (0.5 mm)x(0.5 mm) nano-membrane
  - align membrane at center cavity with 5-axis PZT actuator
  - check cavity resonance and calibrate mode frequencies against membrane position along cavity axis
  - measure noise and force sensitivity at room temperature
- Sensor calibration with external "source"
  - setup frequency shifted non-resonant beam (using AOM's on a portion of the main beam)
  - excite membrane with radiation pressure form non-resonant beam
  - pressure sensitivity calibration

Goals and achievements for KWISP

- Short term
  - build a bench-top prototype force sensor and measure force sensitivity
- Medium term
  - Prepare setup for initial tests at CAST
  - Place setup in the focal plane of the XRT to increase the solar chameleon flux by ~100 (or more)
  - Live data taking at CAST
- Long term
  - Study increase force sensitivity by cooling the nano-membrane down to ~K temperatures or less (further factor 100 possible)

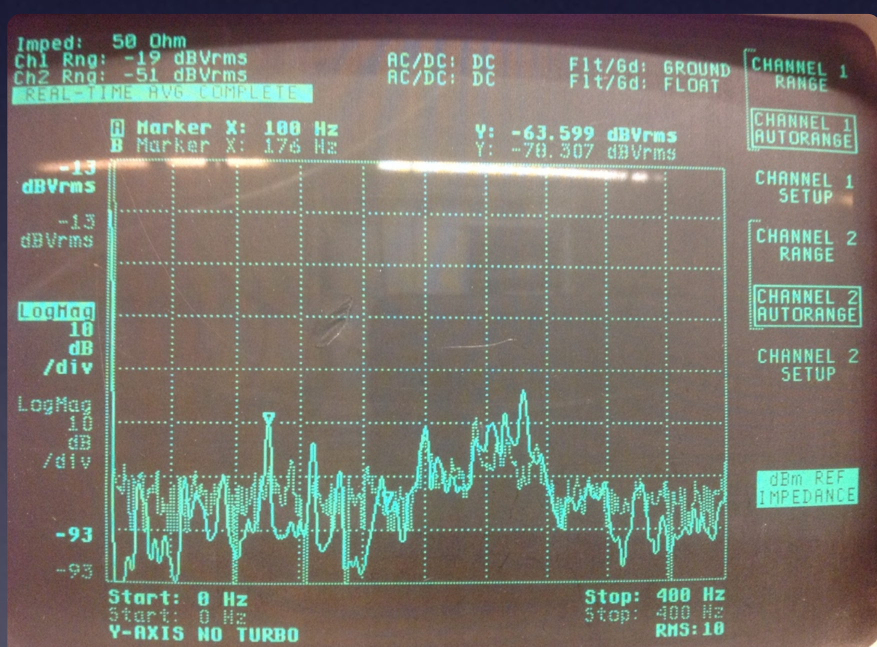
Measurement program and projected time schedule

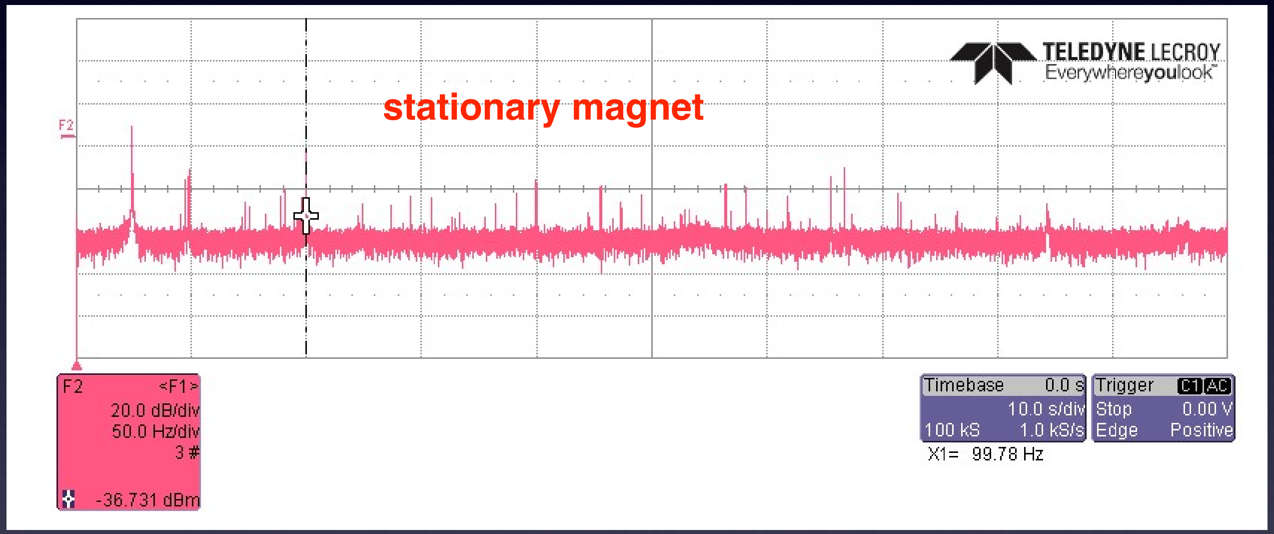
- Overall measurement program
  - sensor complete characterization (Trieste)
  - preliminary commissioning: off-beam prototype test in the CAST area (CERN)
  - design of sensor coupling to the CAST beamline (CERN)
  - assembly and commissioning (CERN)
  - live data taking (CERN)
- Projected time schedule (2014)
  - July-September (Trieste)
    - bench-top force sensitivity measurements
  - October-December (CERN)
    - off-beam preliminary commissioning at CAST
    - design of coupling to CAST beam-line
    - prepare for on-beam assembly and commissioning

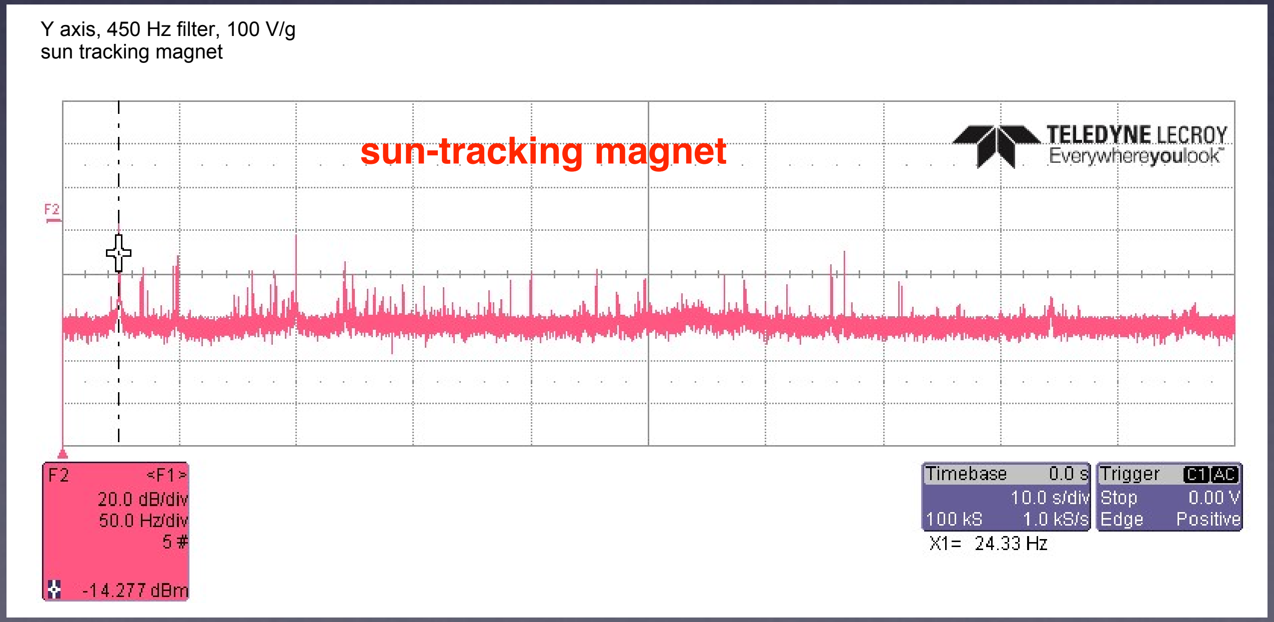
Preliminary accelerometer tests

- Accelerometer measurements were done both at CAST, on the sunrise end of the magnet, and in the Trieste laboratory
- At CAST
  - peak accelerations at around 25 Hz (and higher harmonics) of about 1.7×10^{-2} g, with the magnet stationary, and 5×10^{-2} g with the magnet moving.
- In Trieste
  - peak accelerations of ~ 7×10^{-6} g at around 100 Hz.
- Off-beam preliminary commissioning of the sensor at CAST will be very important

Sample accelerometer spectrum in Trieste



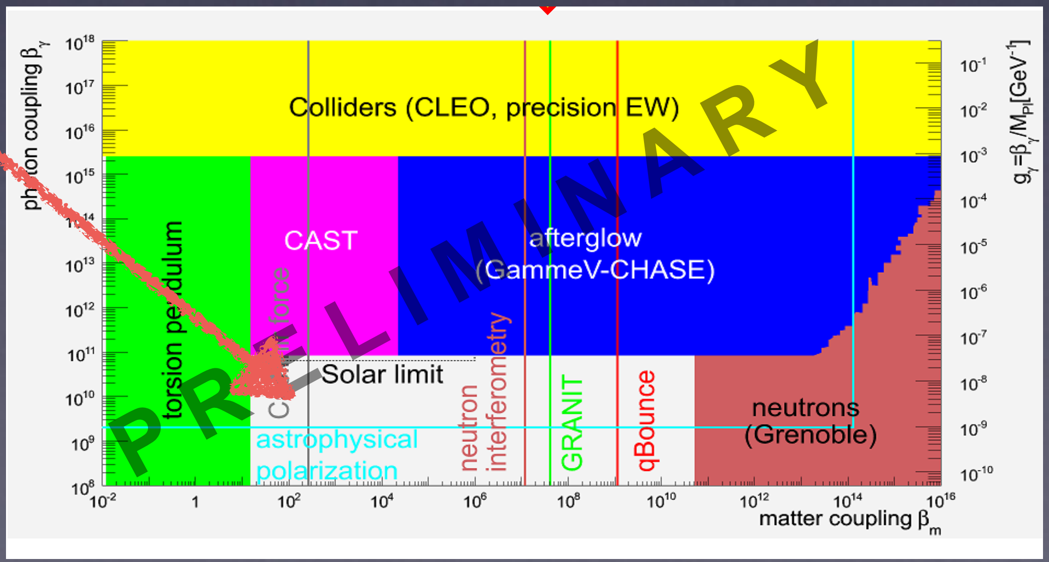




Sample accelerometer spectra at CAST

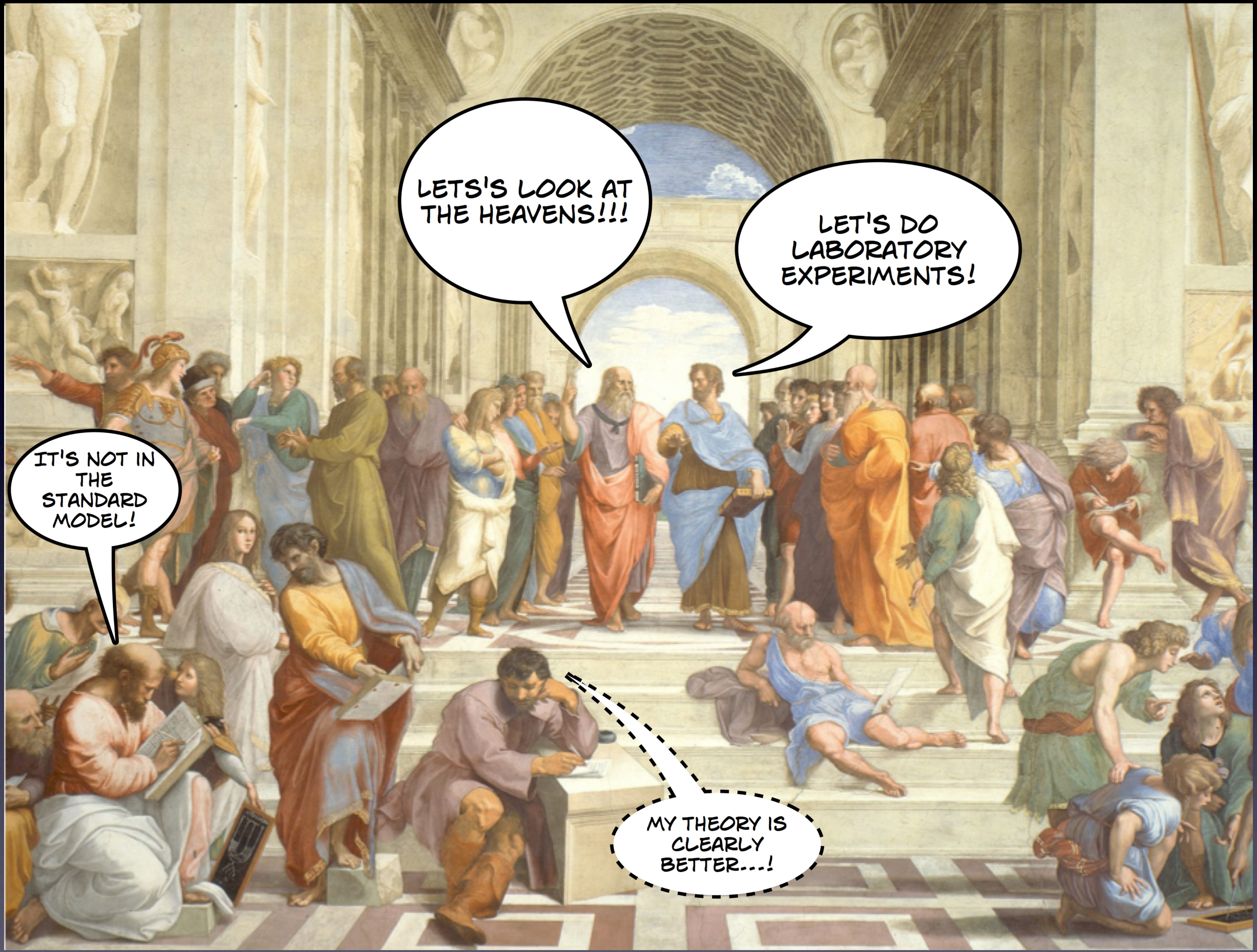
Final remarks on KWISP

- The projected sensitivity for the prototype force sensor is $5 \cdot 10^{-14}$ N/√Hz
- A 10^{-7} Pa pressure corresponds to a solar chameleon flux of $10^{-2} \cdot L_{solar}$, assuming chameleons consitute the totality of “exotics” emitted by the Sun (see P. Brax and K. Zioutas, Phys.Rev. D82 (2010) 043007)
- The KWISP prototype with a sensitivity of $5.0 \cdot 10^{-14}$ N/√Hz on a (0.5 mm)x(0.5 mm) nano-membrane is then sensitive to a solar chameleon flux of $4 \cdot 10^{-6} \cdot L_{solar}$ in 10^4 s
- Access to the uncharted region?



Conclusions

- The KWISP force sensor prototype is now in the critical phase of nano-membrane insertion prior to sensitivity tests (Trieste lab)
- Preliminary accelerometer measurements have been done both at CAST and in Trieste to evaluate the environment.
- Planning the move to CAST
  - bring complete sensor to CERN and run off-beam commissioning tests
  - design on-beam sensor setup
  - procure material and prepare for installation and commissioning
- Future sensor upgrades
  - cool nano-membrane below 1 K

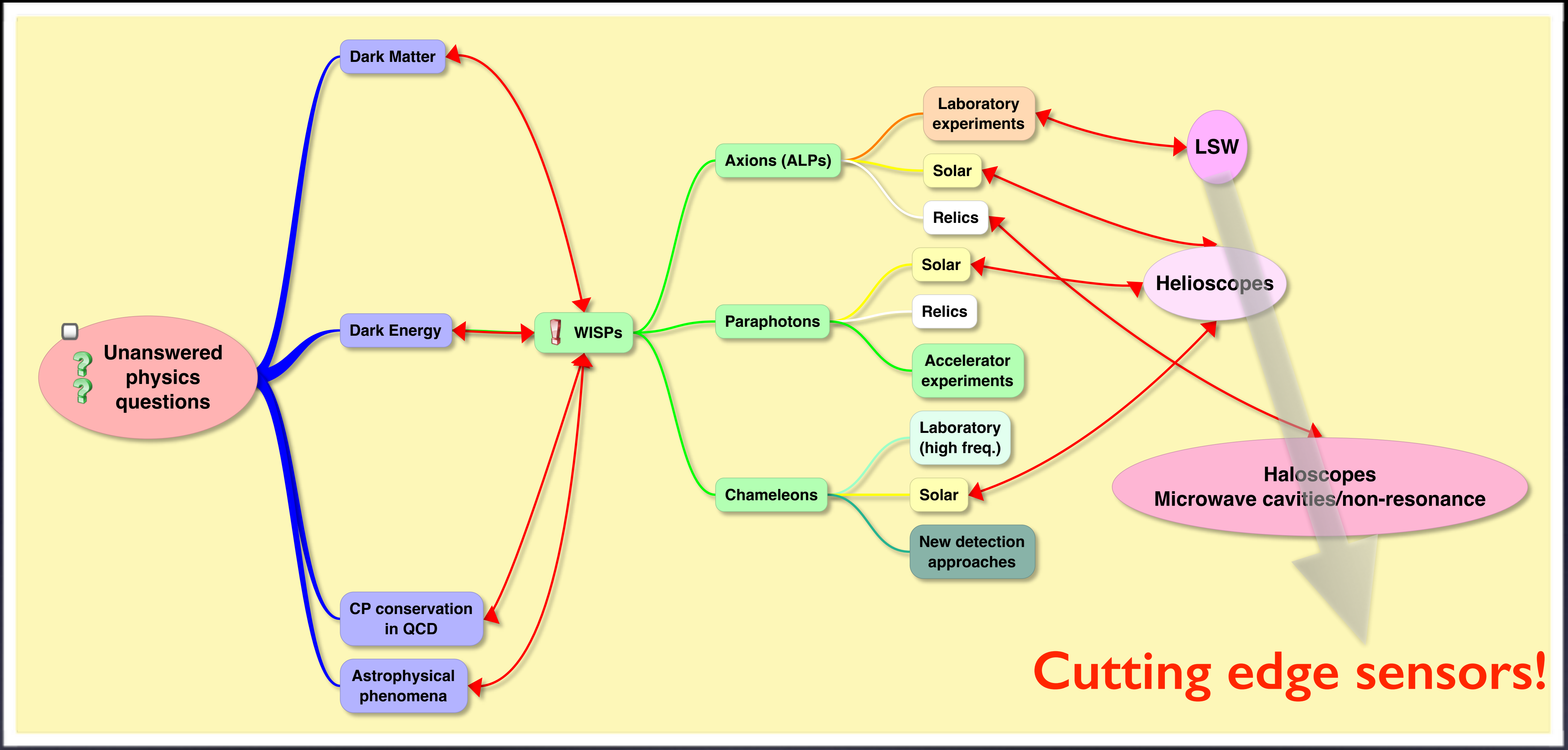


Raffaello Sanzio - "La Scuola di Patrasso" (The Patras Workshop)
Musei Vaticani - Roma

Chameleonistas…

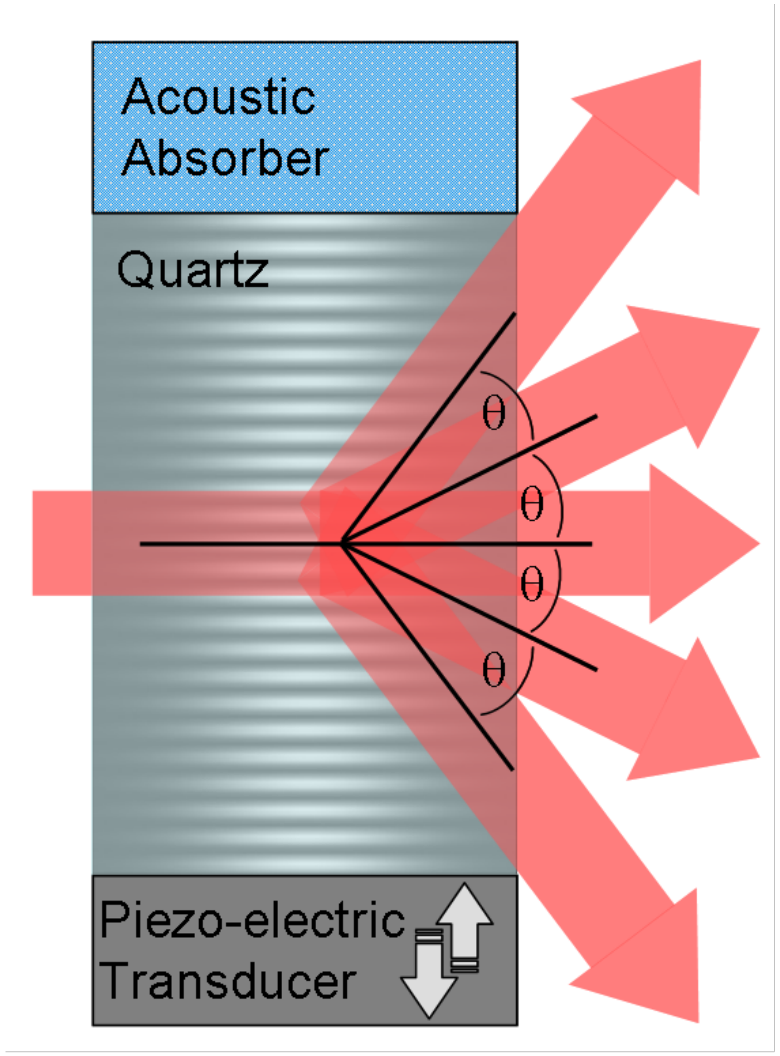
Backup slides

Concluding remarks



- **Many unanswered questions in physics lead to consider Weakly Interacting Slim Particles (theorist Gym)**
- **Many experimental ideas and techniques must be brought to bear (experimentalist Gym)**
- **The bottom line: success rests on developing a range of cutting-edge sensor to adequately equip experiments**

Acousto-Optic Modulator



Optical bench setup for membrane sensing

Two light beams are used to excite and sense membrane movements

probe beam (ω_p) - frequency-locked to the FP cavity (PDH feedback) - senses membrane movements

control beam - (ω_L) - frequency shifted by two cascaded AOMs - exerts a controlled radiation pressure on the membrane