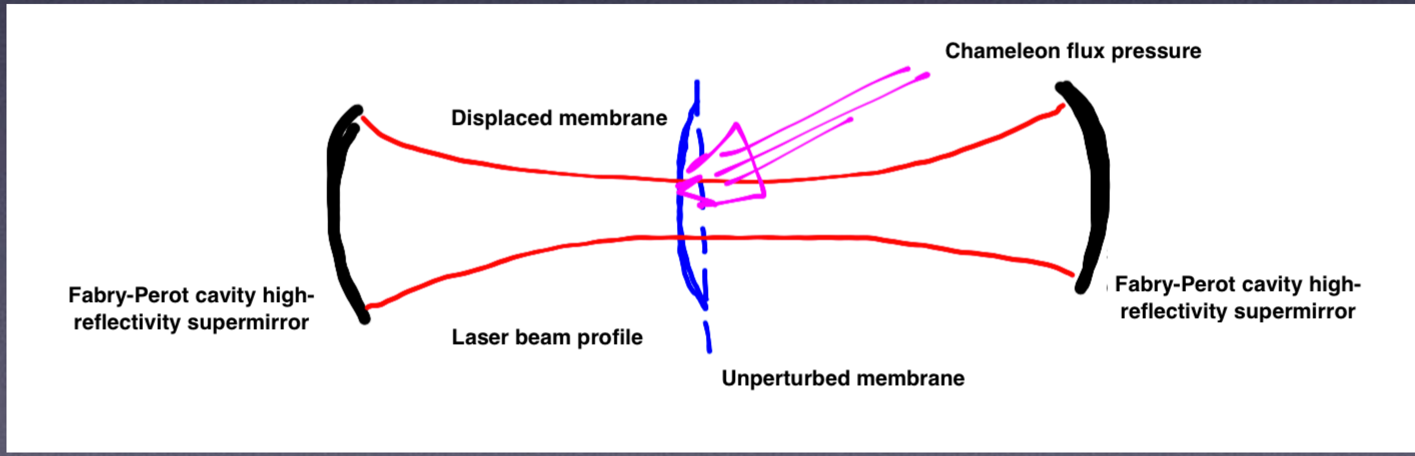
Recent progress with the KWISP force sensor

G. Cantatore - University and INFN Trieste
on behalf of the working group: G. Cantatore, A. Gardikiotis, D. Hoffmann, M. Karuza, Y. Semertzidis, K. Zioutas

Summary

- KWISP and solar Chameleons
- Recent results in Trieste
- Conclusions, plans and perspectives



KWISP: a novel opto-mechanical sensor for Chameleon searches

- **Chameleons** are a type of **scalar WISPs** having an effective mass dependent on the local energy density. Solar Chameleons are Primakoff-produced inside the magnetic field of the Sun and then stream to Earth

- **Two couplings, two detection possibilities:**
  - inverse Primakoff conversion inside a magnetic field ⟹ photon coupling β_γ
  - force exerted at **grazing incidence** on a surface ⟹ direct coupling to matter β_m

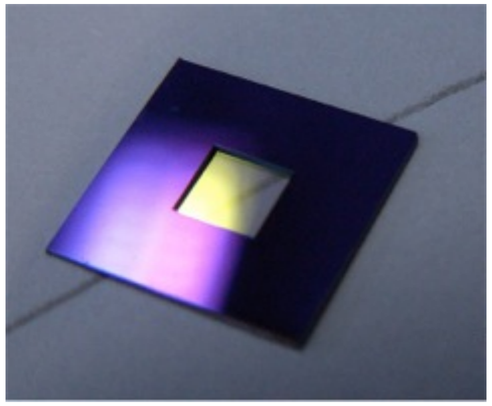
- **Key idea: build a sensitive force sensor and use it to detect solar Chameleons from their direct interaction with matter**

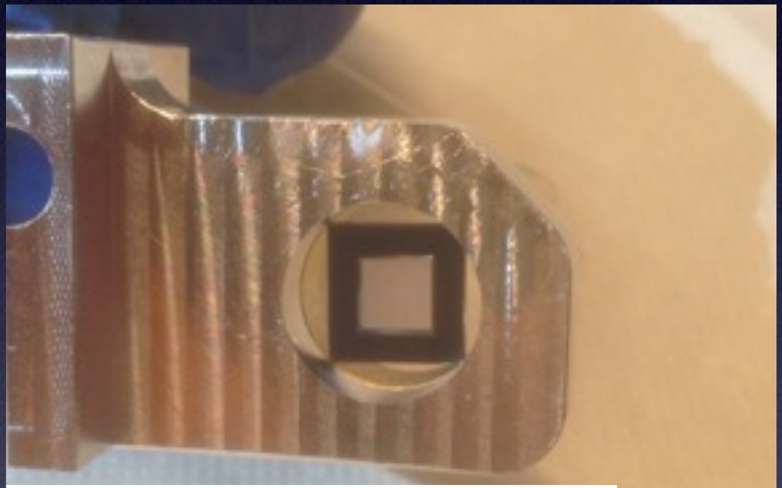
⇒ KWISP - Kinetic WISP detection

Opto-mechanical force sensors

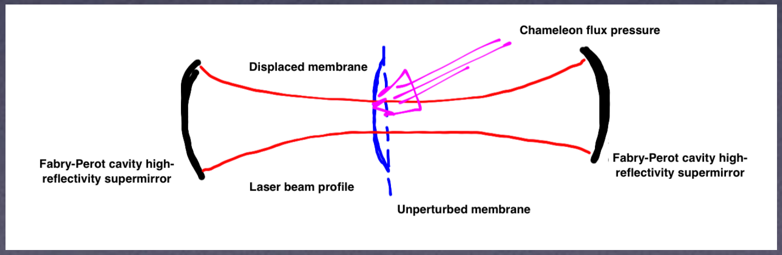
- A nano-membrane (a few 10's of nm thick Si_3N_4) is centered and aligned inside an optical Fabry-Perot resonant cavity
- Membrane displacements in response to an externally applied force shift the cavity mode frequencies
- When a laser beam is frequency-locked to the cavity using a feedback loop, the feedback error signal senses frequency shifts and contains the information on membrane movements

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





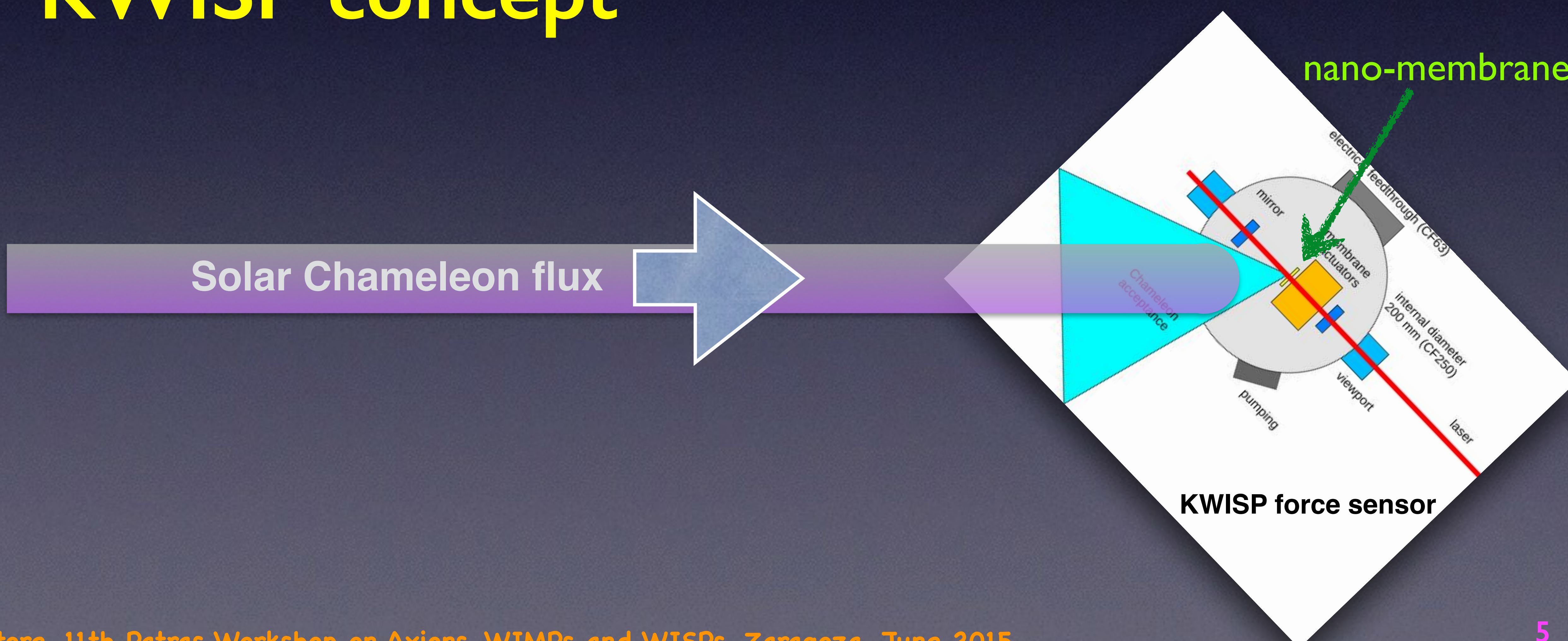
(5 mm)x(5 mm) 100 nm thick SiN_4 nano-membrane set inside its holder



KWISP Motivation &Concept

- Why this complicated technique to measure such a trivial thing as a force?
  - Because extremely tiny forces can be measured: the FP finesse acts a gain multiplier and a further increase in sensitivity comes from the membrane mechanical Q-factor

- **KWISP concept**



Chameleonistas…

Chameleonistas…

… and how they subsist …

Chameleonistas…

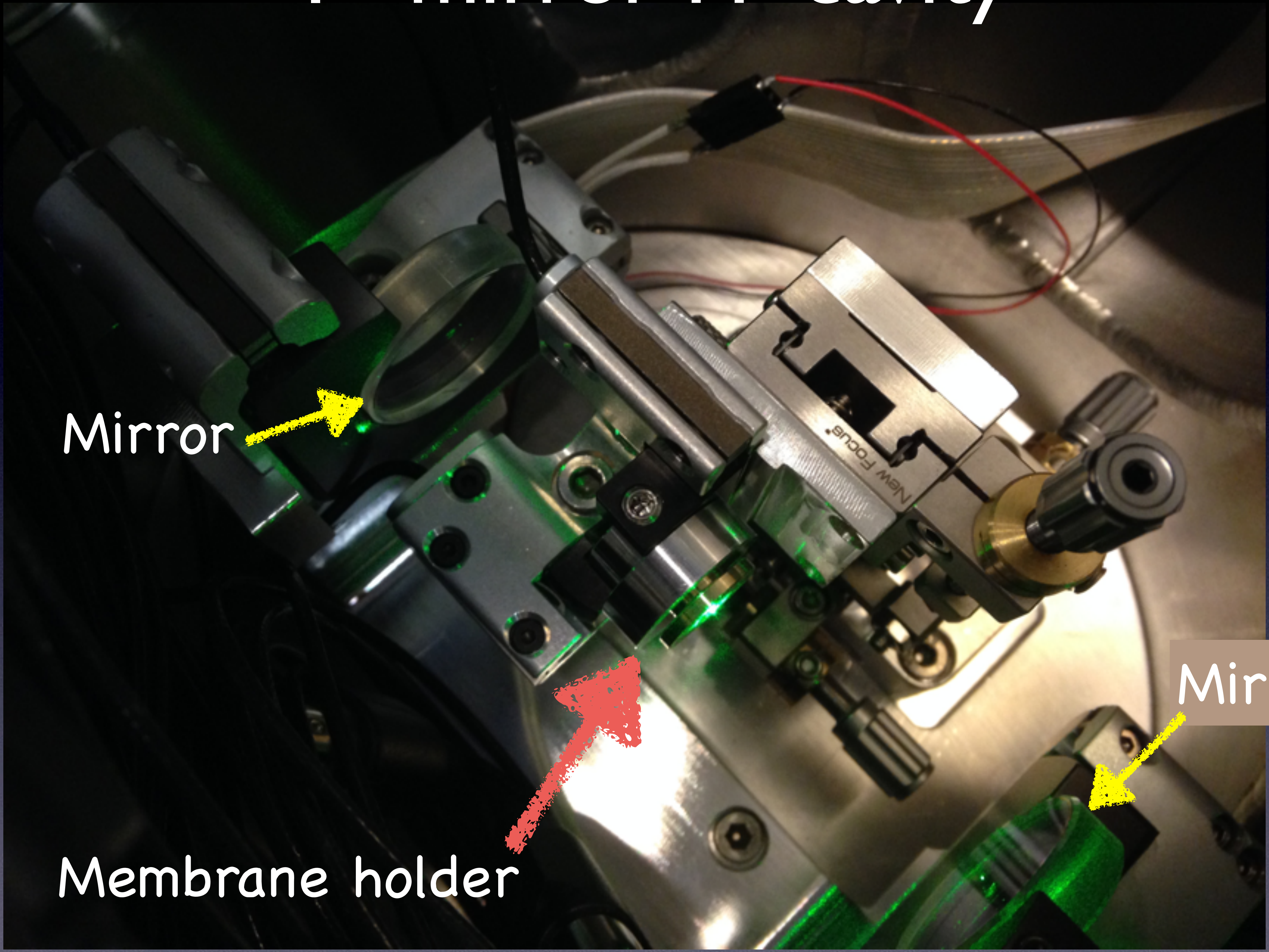
Recent results in the INFN Trieste laboratory

KWISP@TS - June 2015

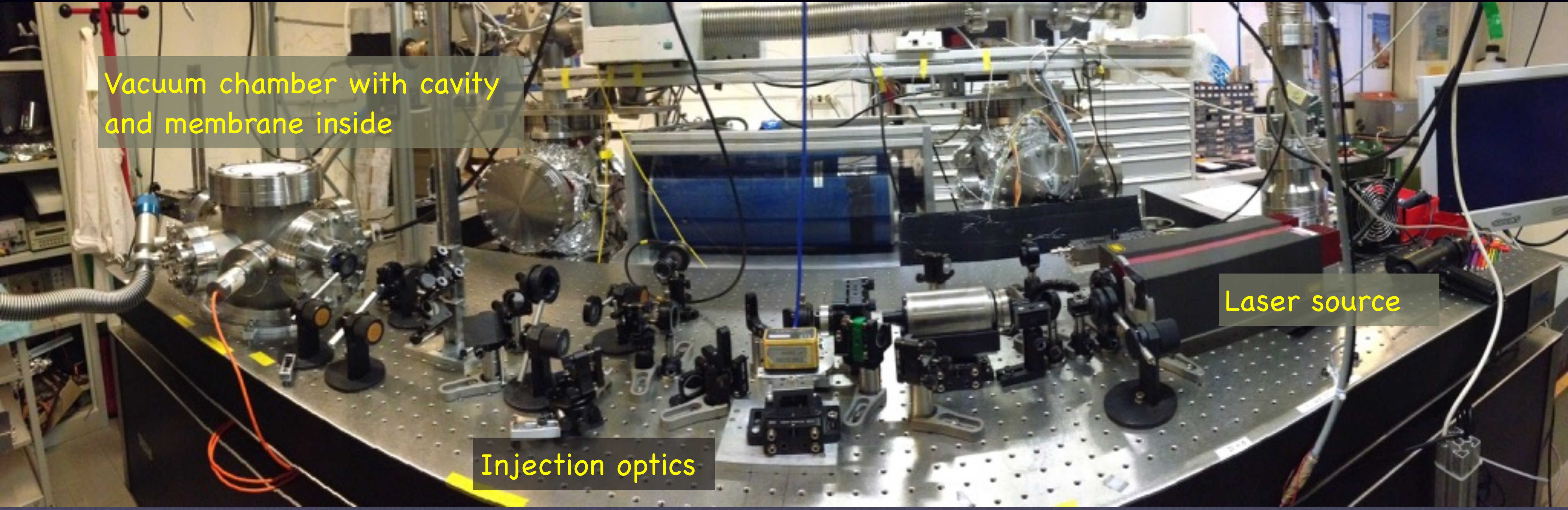
- INFN laboratory in Trieste - pilot KWISP setup
  - Fabry-Perot cavity in vacuum excited by IR laser with electro-optic Pound-Drever-Hall frequency-locking feedback
  - sensor running with 5x5 mm^2, 100 nm thick membrane inserted in the cavity and aligned in-vacuum
  - complete double-beam setup with 1064 nm "sensing" beam and 532 nm "pump" beam
  - solar Chameleon chopper

5x5 mm^2 membrane

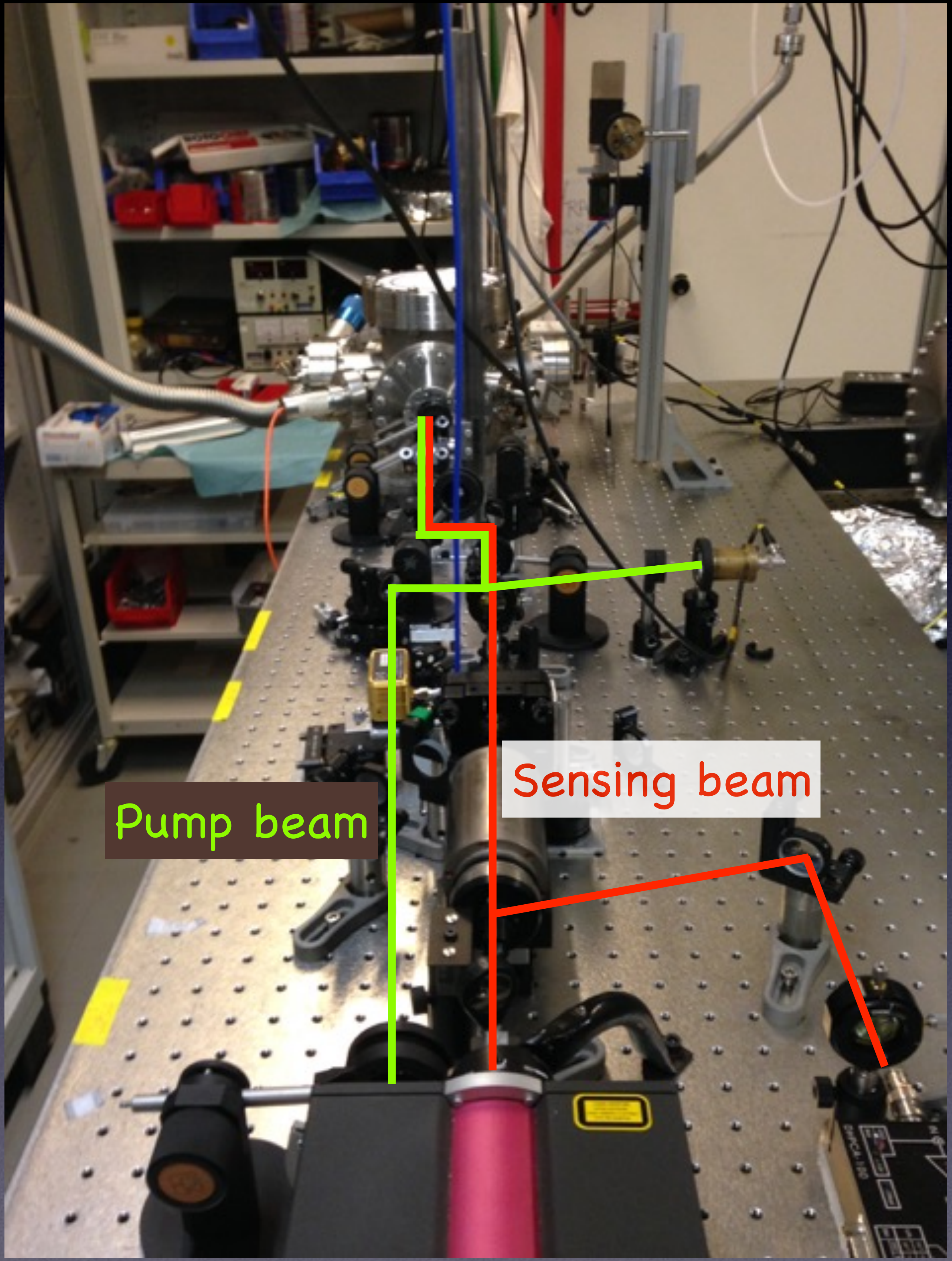
1"-mirror FP cavity

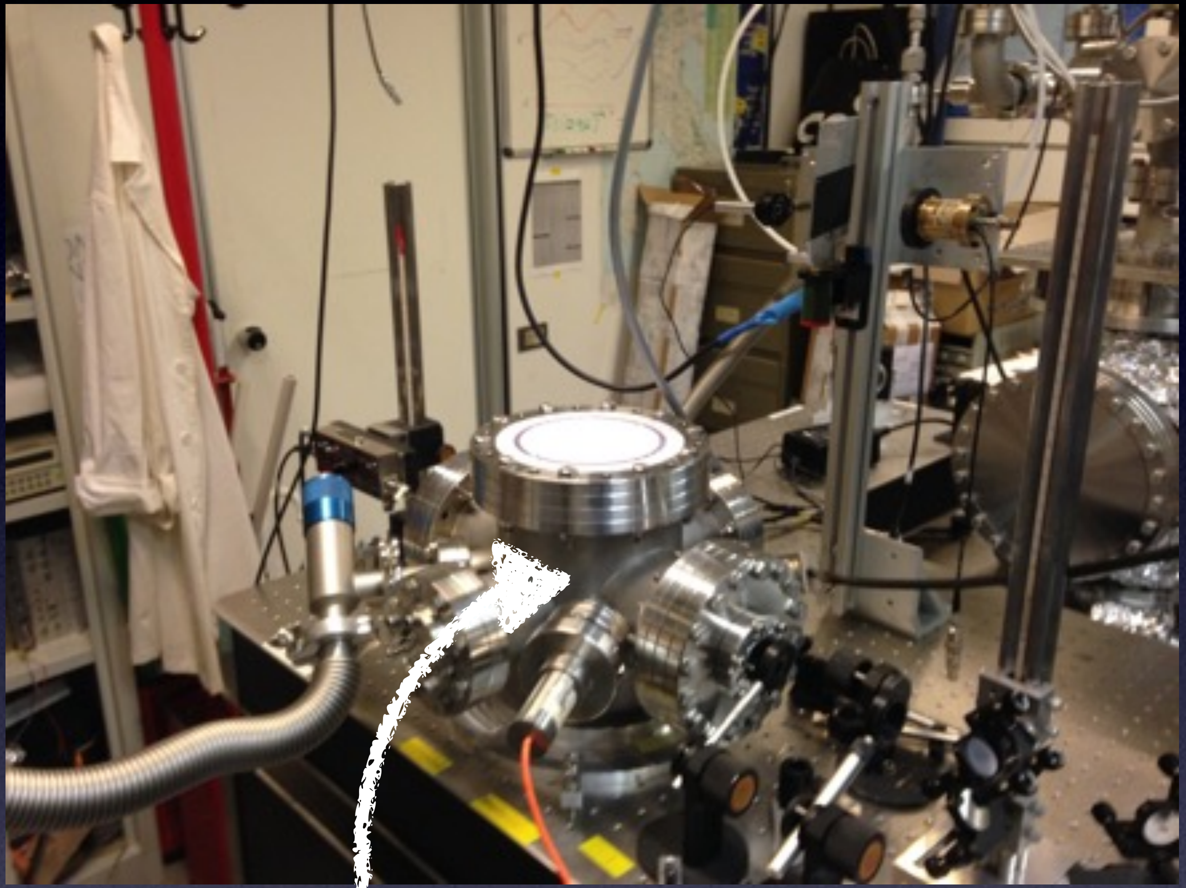


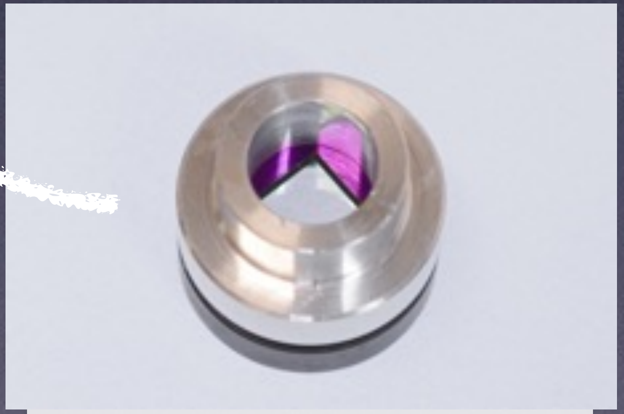
Optical bench panorama



Two-beam setup

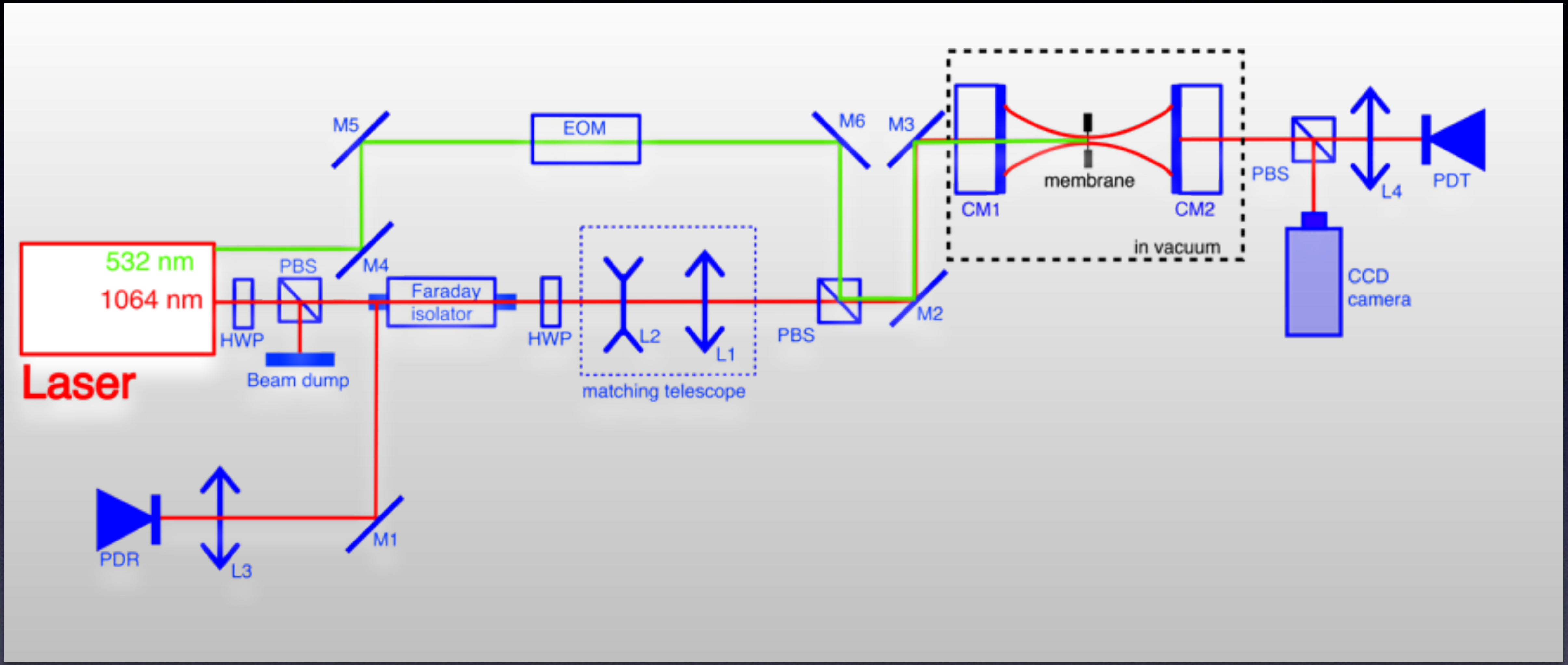




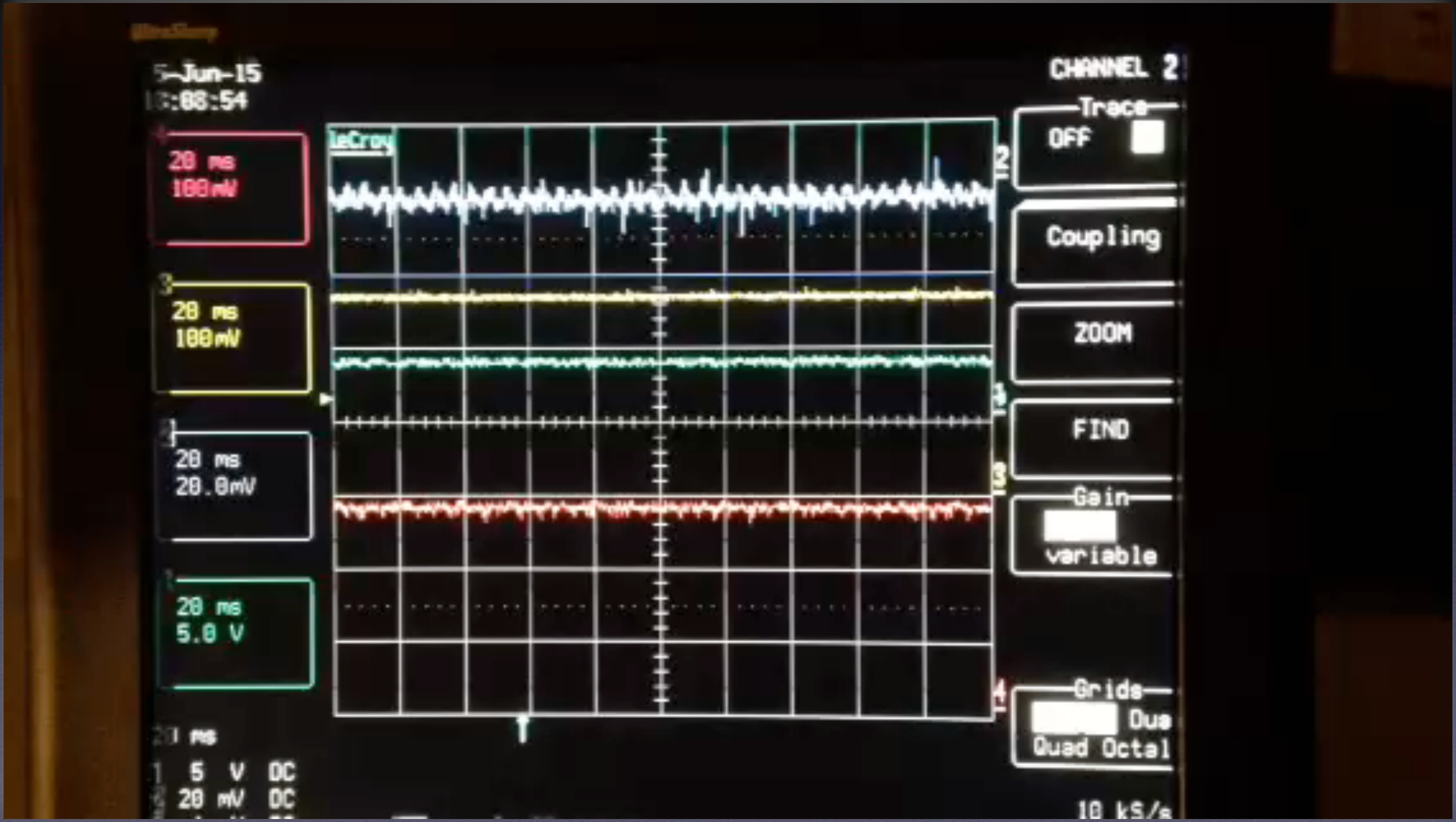


Membrane&holder

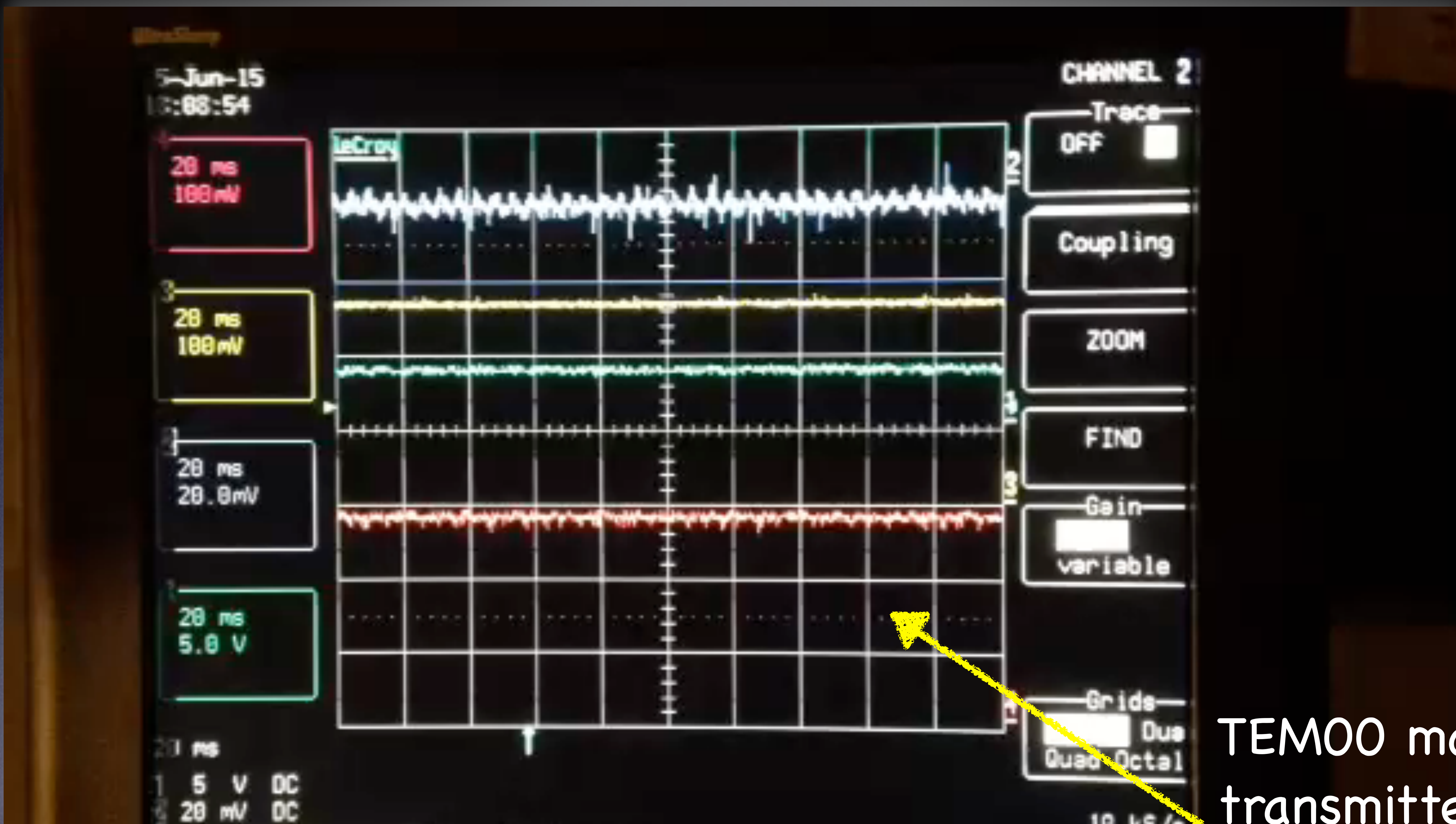
KWISP optics layout



Frequency-lock with membrane

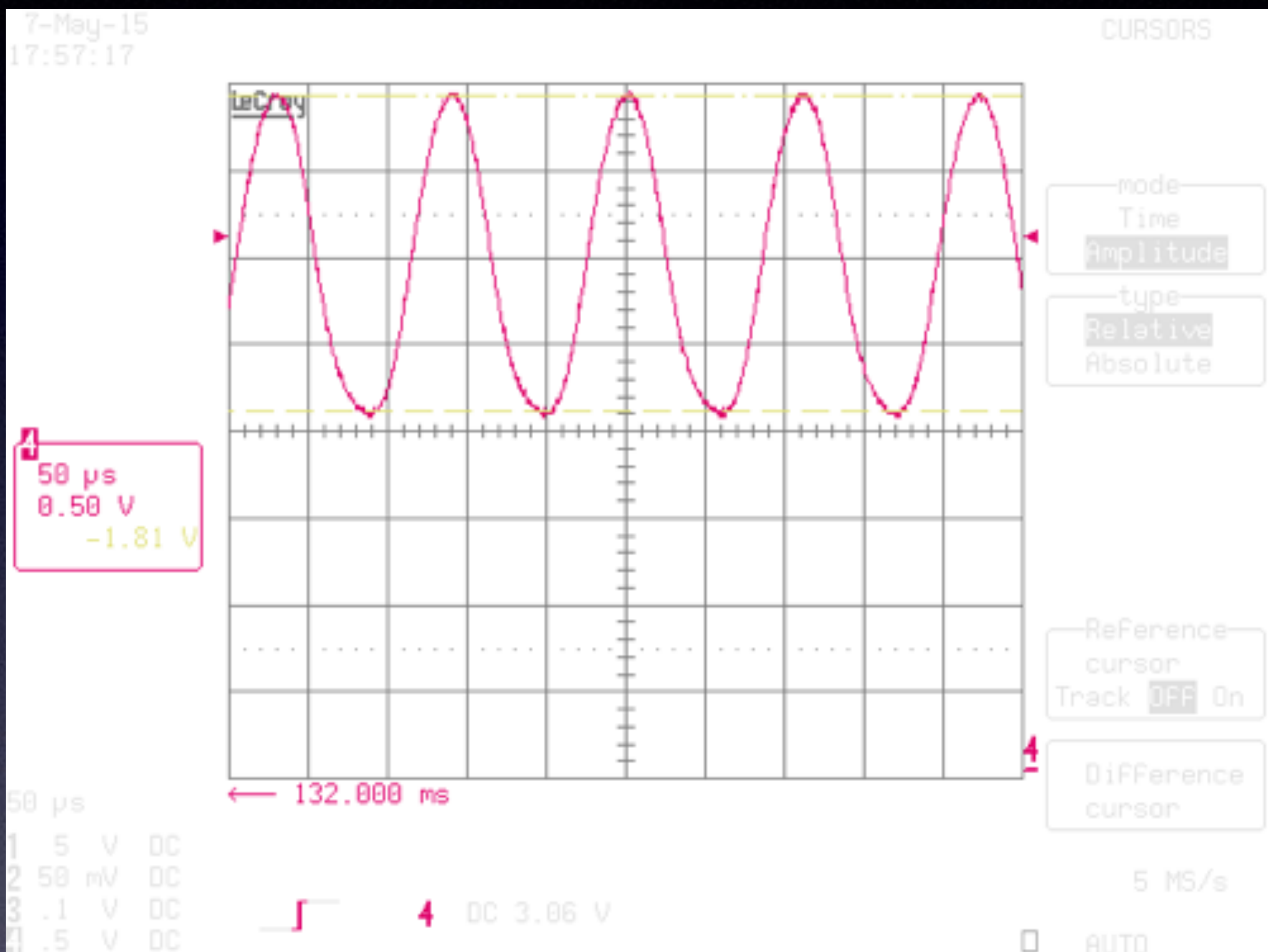


Frequency-lock with membrane



TEM00 mode transmitted by cavity at resonance

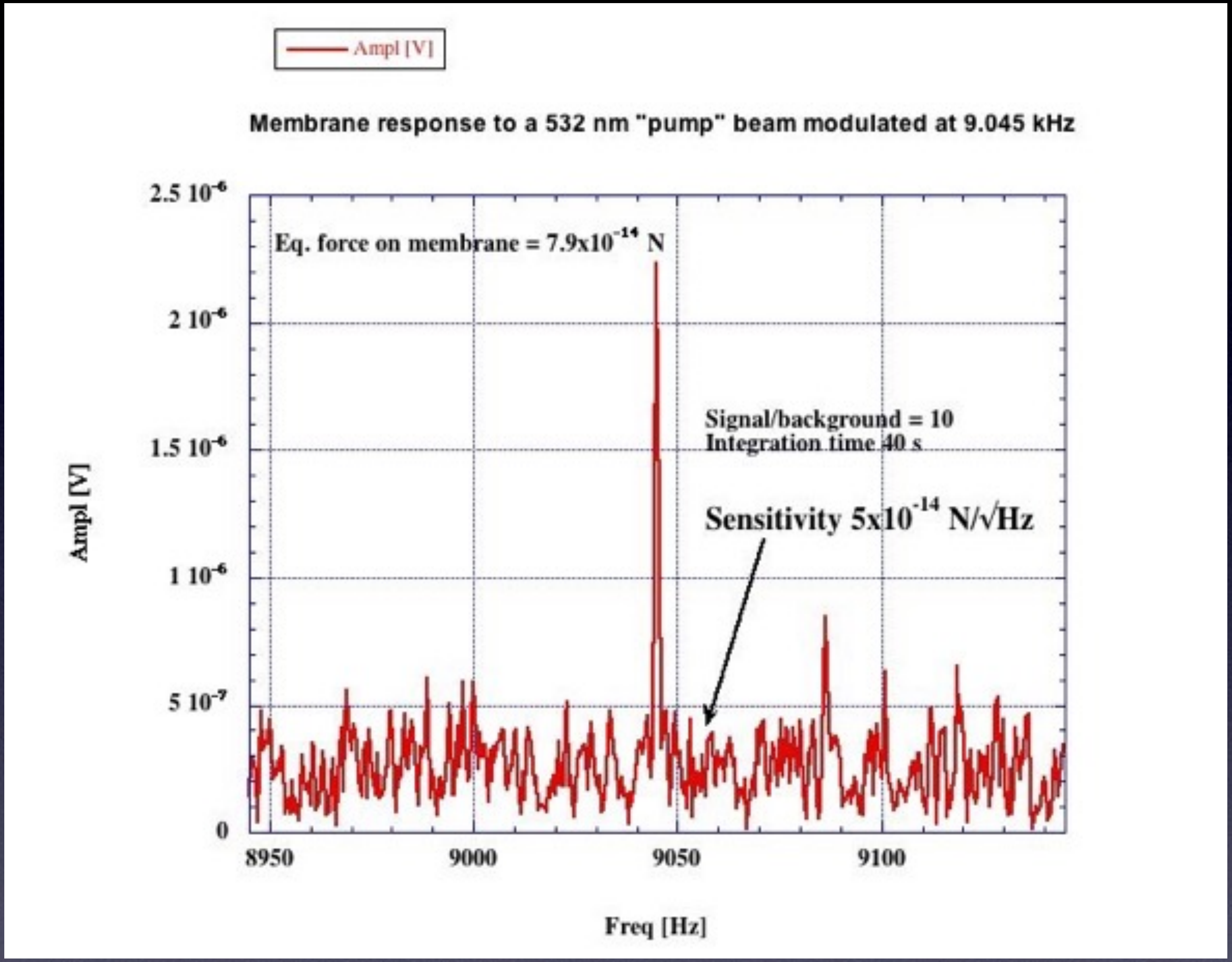
Pump beam at 532 nm



Pump beam monitor signal

- Total CW light power at 532 nm incident on membrane : 166 μW
- Amplitude modulated at 9.045 kHz with EOM, modulation depth: 28%
- Measured membrane reflectivity @ 532 nm: 25%
- Equivalent force on membrane: $2.8 \cdot 10^{-13}$ N

Direct force calibration of KWISP sensor with 532 nm pump beam

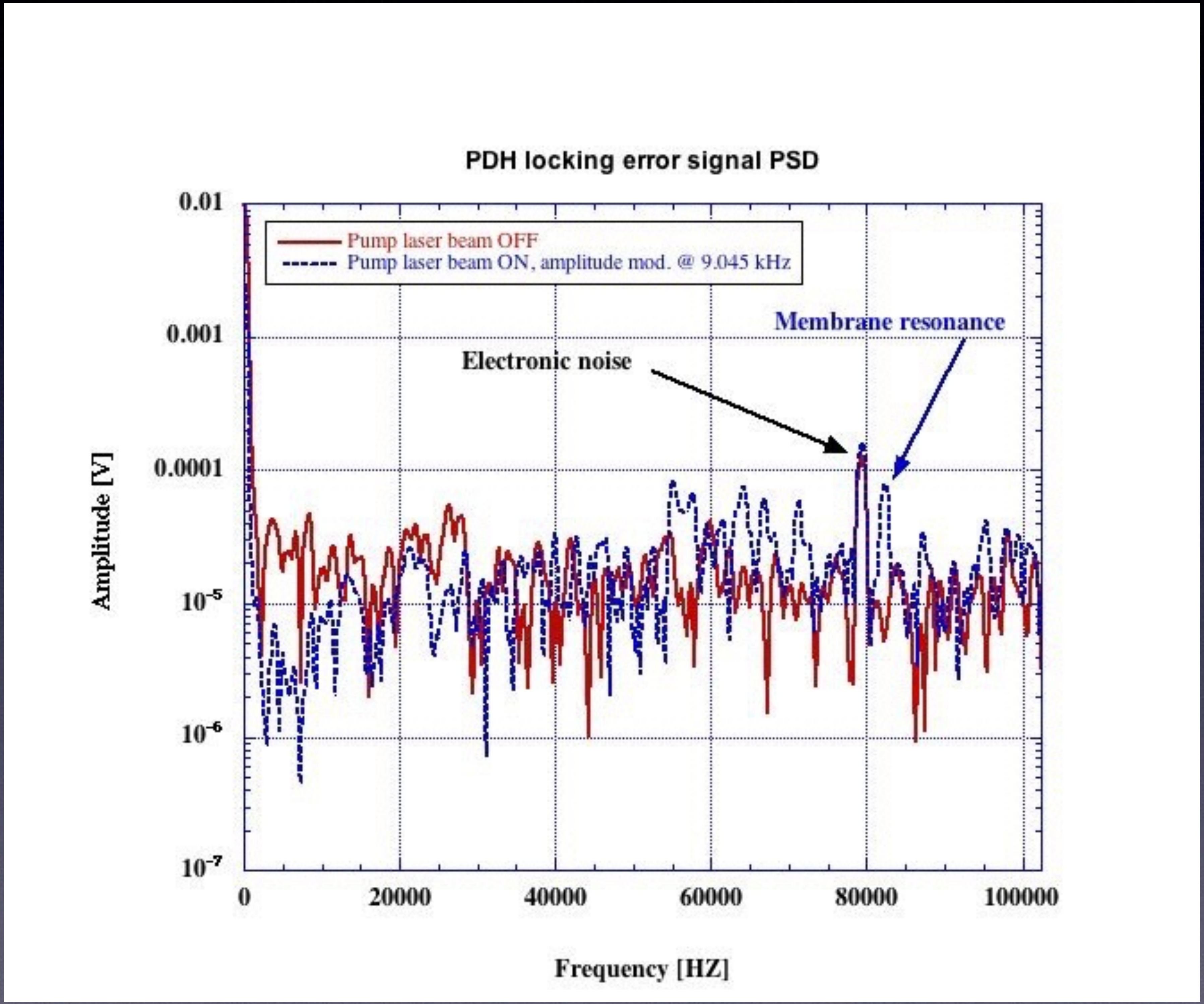


- Total CW light power at 532 nm incident on membrane :166 μW
- Amplitude-modulated at 9.045 kHz, modulation depth: 28%
- Measured membrane reflectivity @ 532 nm: 25%
- Equivalent force on membrane: $7.9 \cdot 10^{-14}$ N
- **Sensitivity: $5 \cdot 10^{-14}$ N/√Hz**

This measurement is equivalent to calibrating a detector with a radioactive source

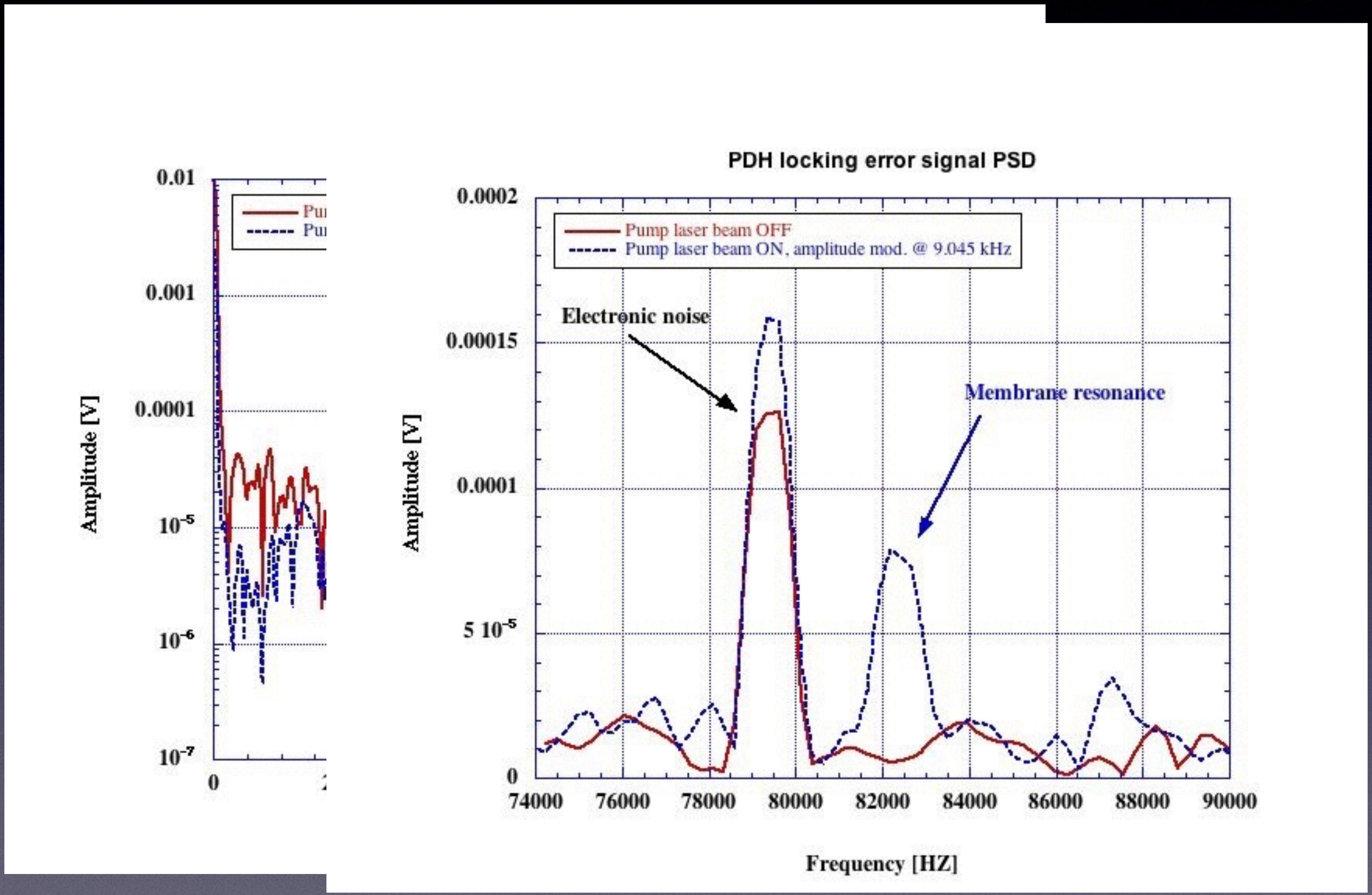
Membrane mechanical resonance

- Pre-stessed membrane is equivalent to a drumhead with resonant frequency in the 10's of kHz range

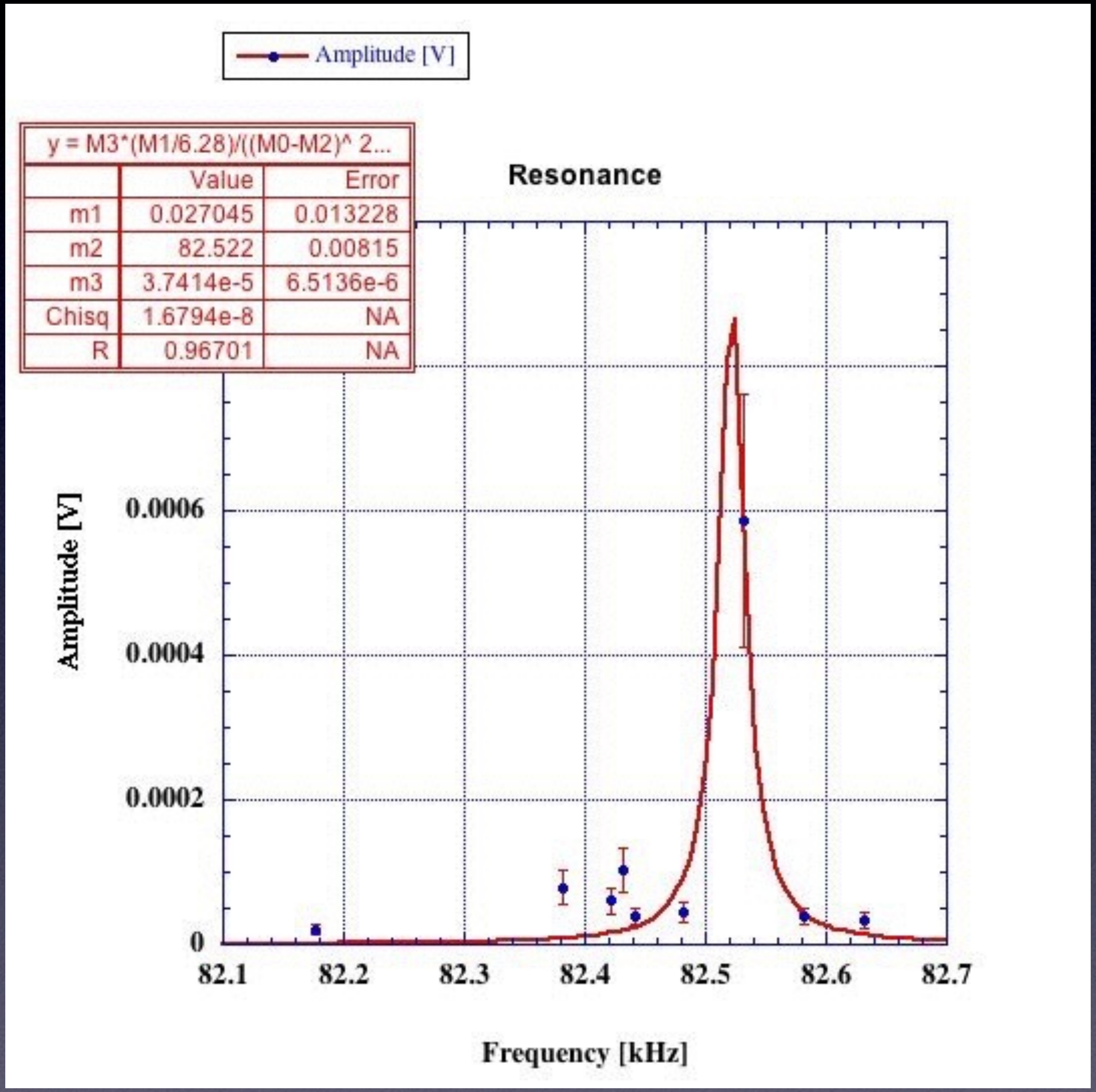


Membrane mechanical resonance

- Pre-stessed membrane is equivalent to a drumhead with resonant frequency in the 10's of kHz range

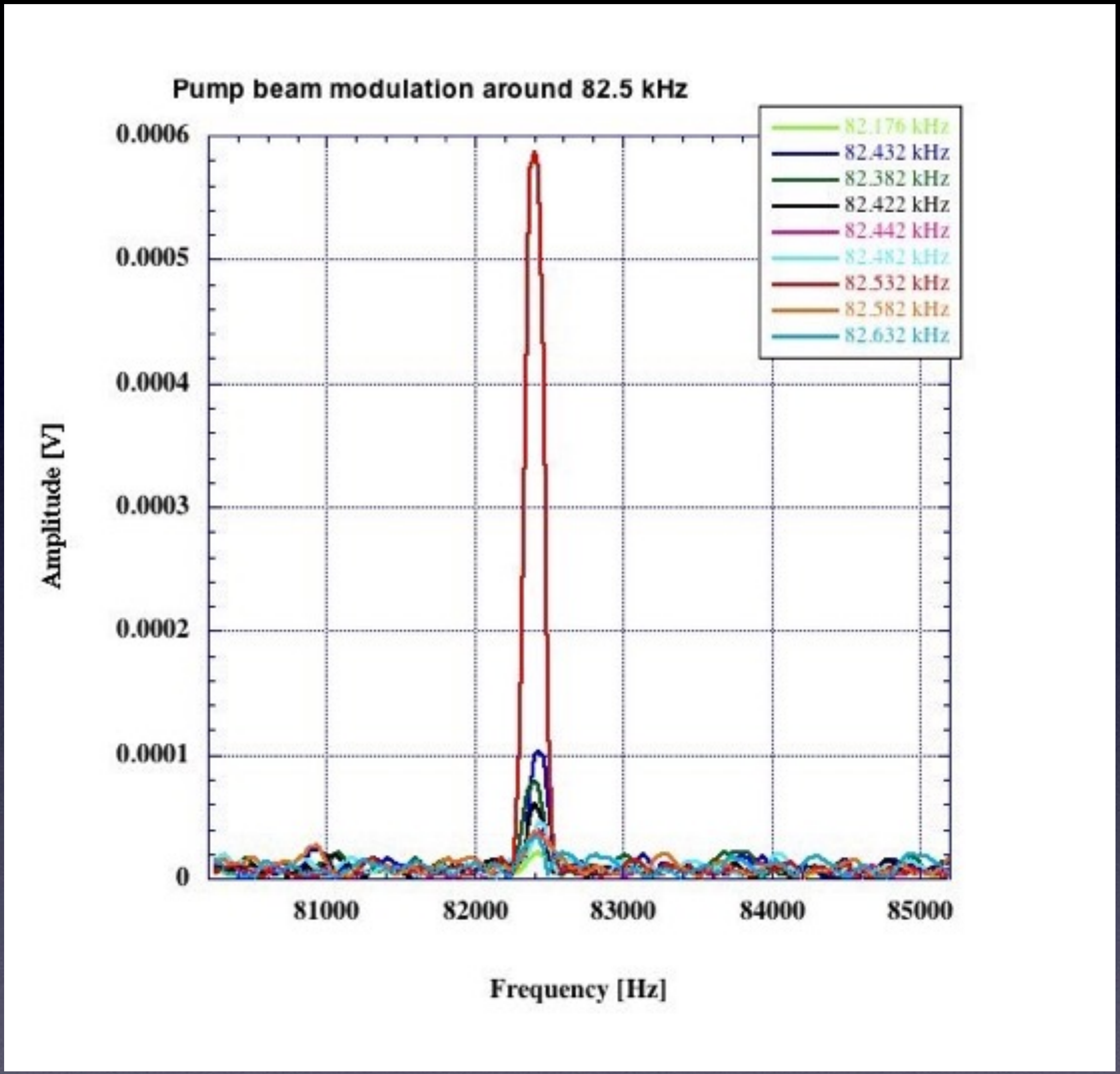


Measuring the membrane mechanical Q



- To find the membrane mechanical Q-factor the pump beam is modulated at constant amplitude around the resonance frequency
- Recorded force amplitudes are then fitted with a Lorentzian curve
- Fit results:
  - resonance frequency: 82.522 kHz
  - FWHM: 27 Hz
- Membrane mechanical Q ~3000

Amplified force response at resonance



- When the pump beam is modulated (with constant amplitude) at/near the membrane mechanical resonance frequency the response to the force is amplified by a factor Q
- Consequently the sensitivity is enhanced also by a factor Q
- Sensitivity at resonance: $1.7 \cdot 10^{-17}$ N/√Hz

Results summary

- Sensor under stable lock and working with 5x5 mm^2, 100 nm thick membrane
- Force sensitivity measured directly with pump beam:
  - off resonance: $5 \cdot 10^{-14}$ N/$\sqrt{Hz}$
  - on resonance: $1.7 \cdot 10^{-17}$ N/$\sqrt{Hz}$
- Key point ⟹ solar Chameleon flux must be amplitude-modulated
  - Need a "Chameleon chopper": built in Trieste following an original idea(*)

(*) K. Zioutas, M. Karuza, G. Cantatore, paper in preparation

Chopping a Chameleon beam

- **Key concept:** at the interface between two media of different densities:
    - grazing incidence -> total reflection
    - normal incidence -> transmission

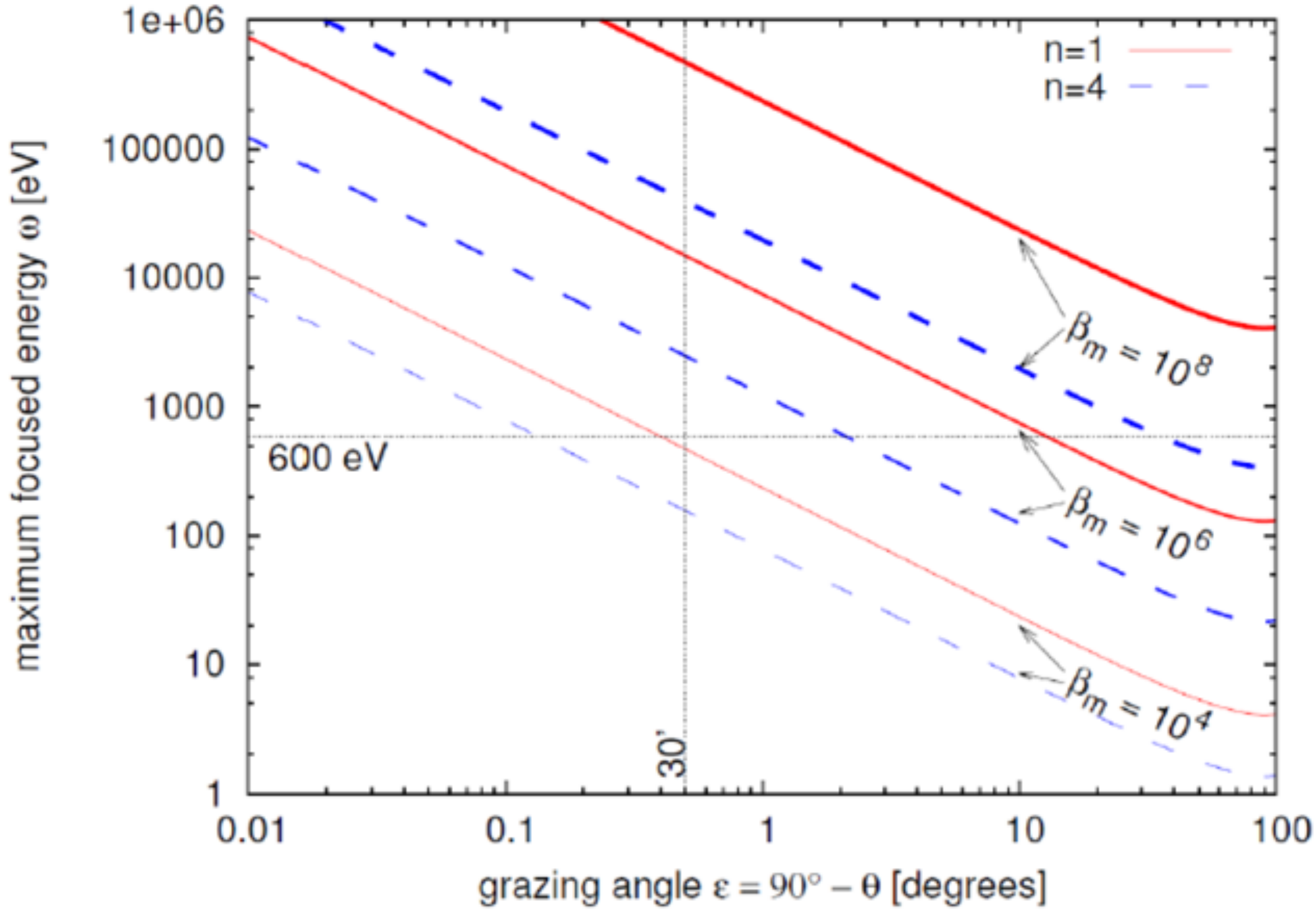
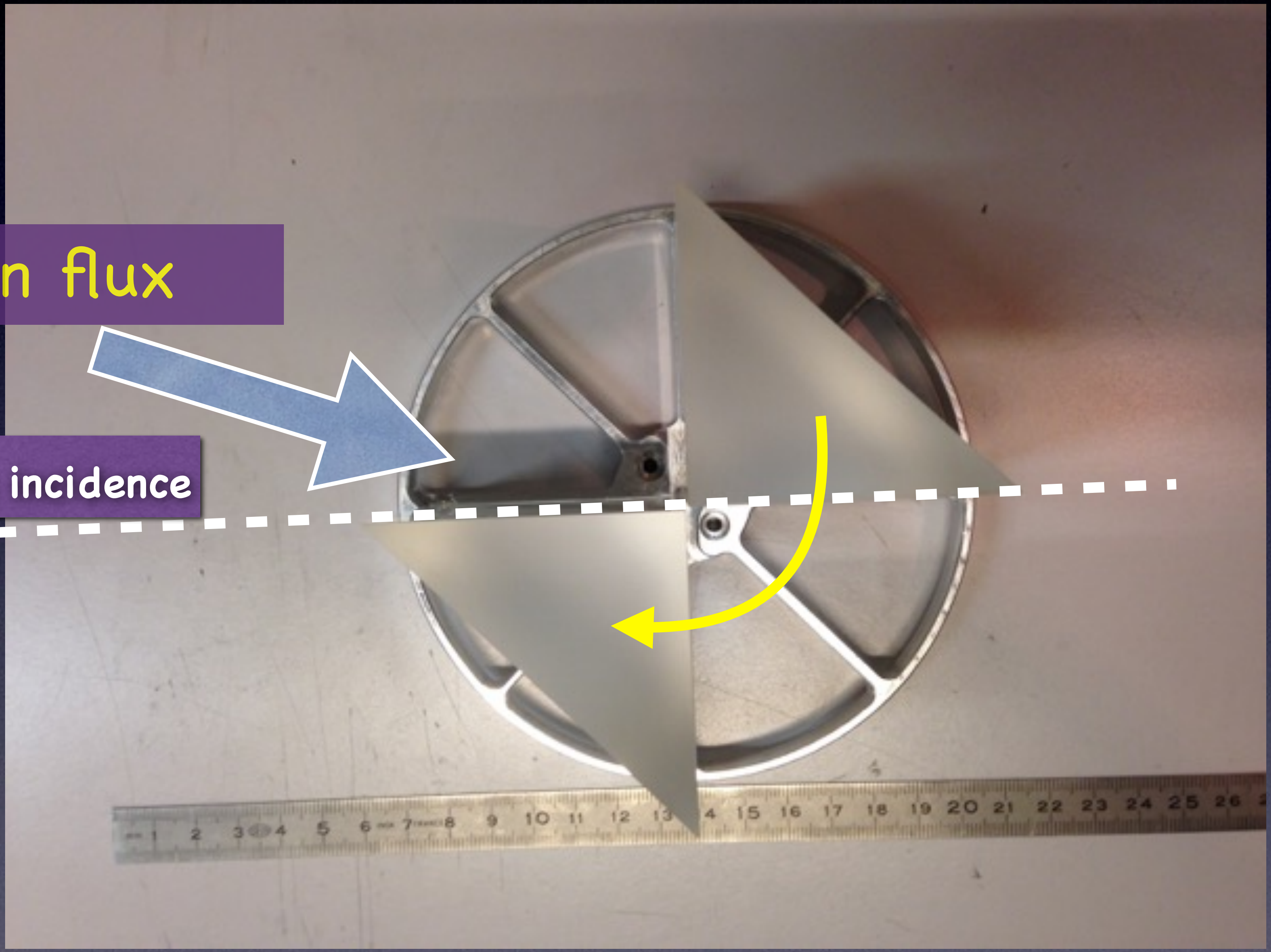


Figure 2 Maximum energy at which a chameleon particle can be focused by an X-ray mirror with density 10 g/cm^3 (≈ the density of a Ni-coated X-ray telescope) and grazing angle ε, for several different chameleon models. The dotted horizontal and vertical lines illustrate one example of a 600 eV chameleon incident on a mirror of focusing angle 30', which is, for example, equal to the field-of-view of XMM/Newton. The chameleon will be focused by this mirror if n=4 and $\beta_m=10^6$, but will pass through the mirror if n=1 and $\beta_m=10^4$.

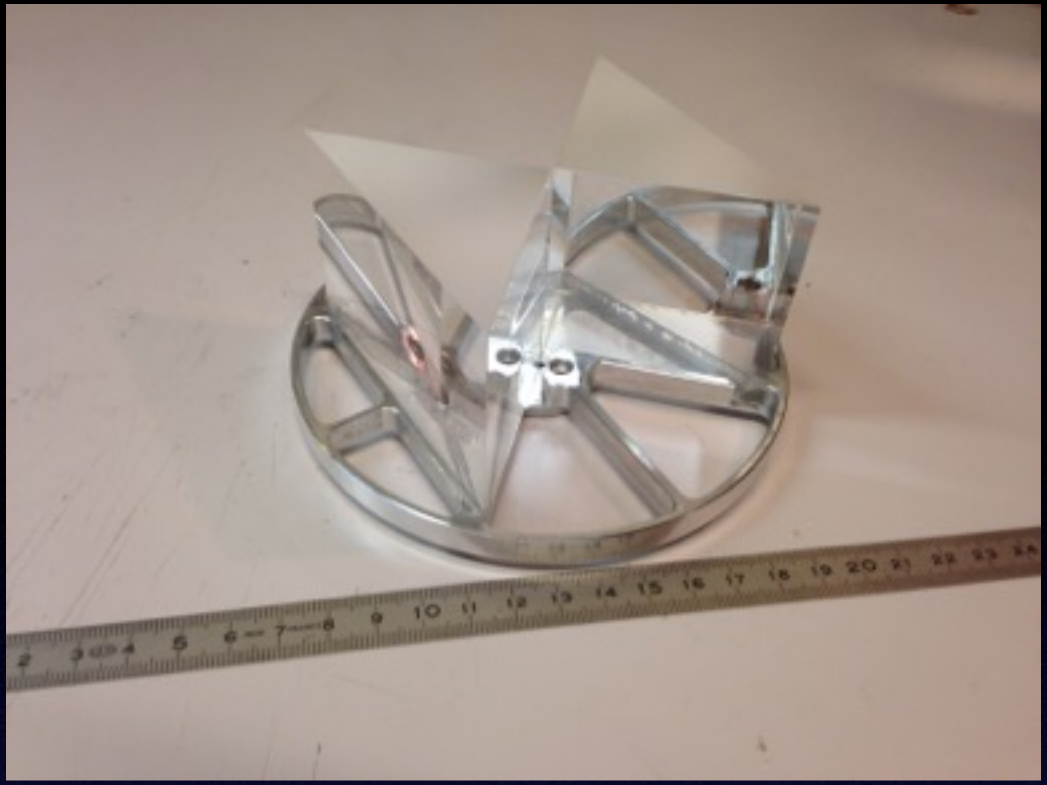
K. Baker, A. Lindner, A. Upadhye, K. Zioutas, *A chameleon helioscope*, http://xxx.lanl.gov/abs/1201.0079 **3**

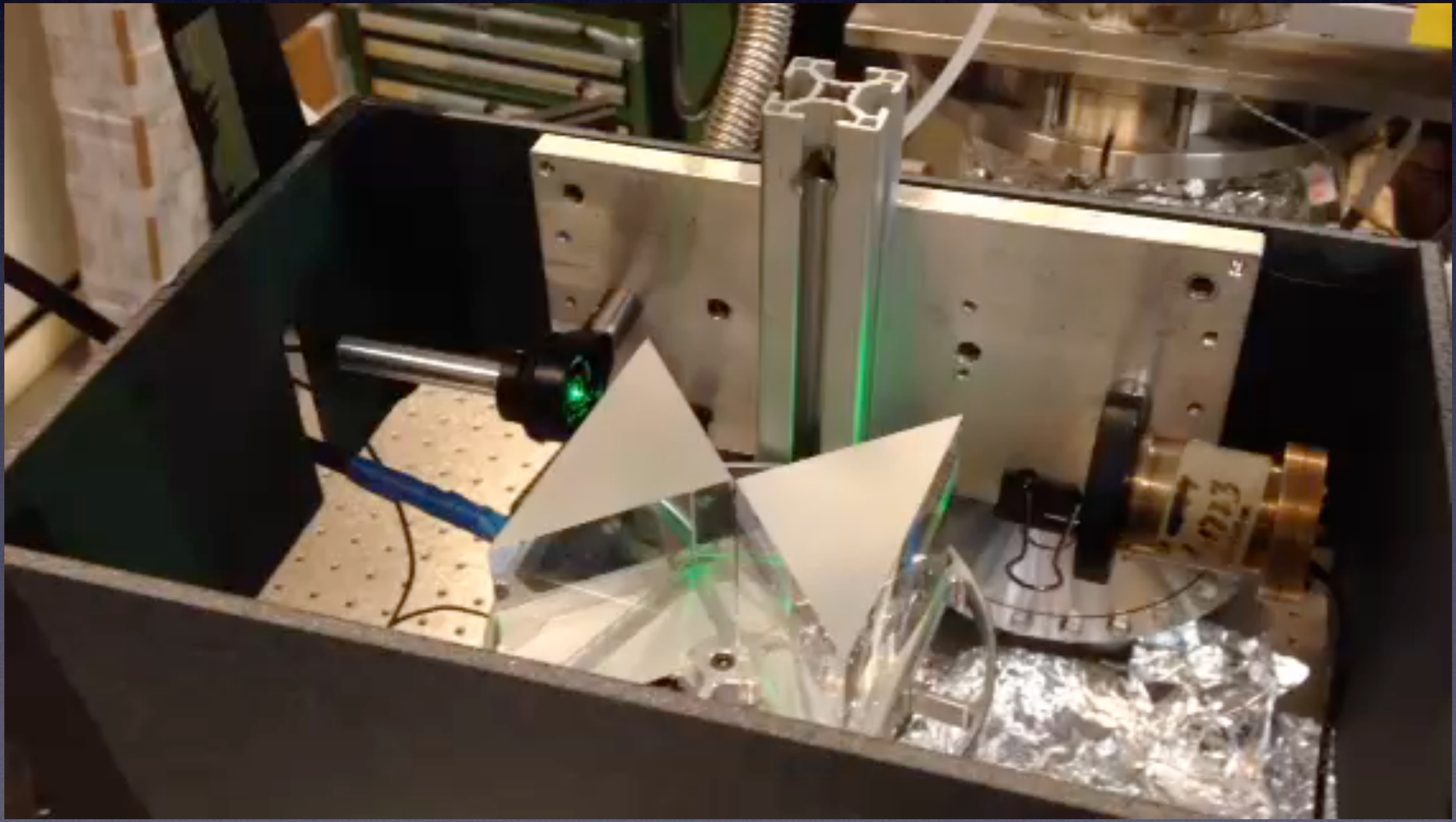
Slide courtesy of K. Zioutas

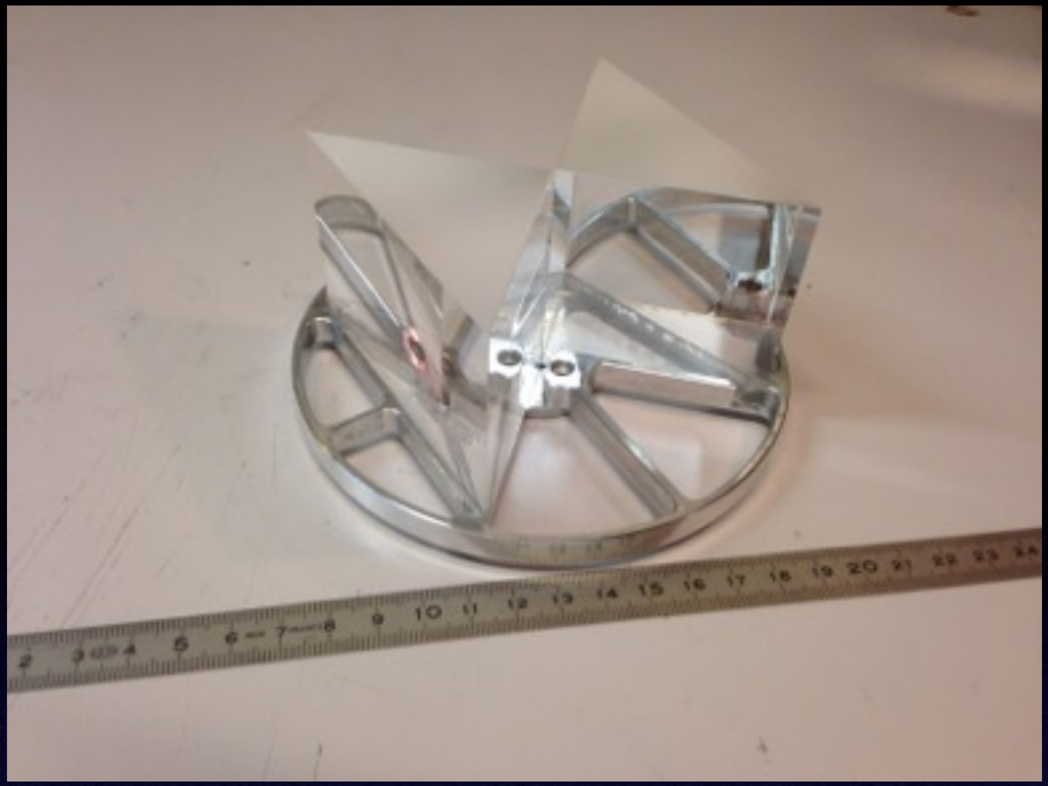
Chameleon chopper v.1

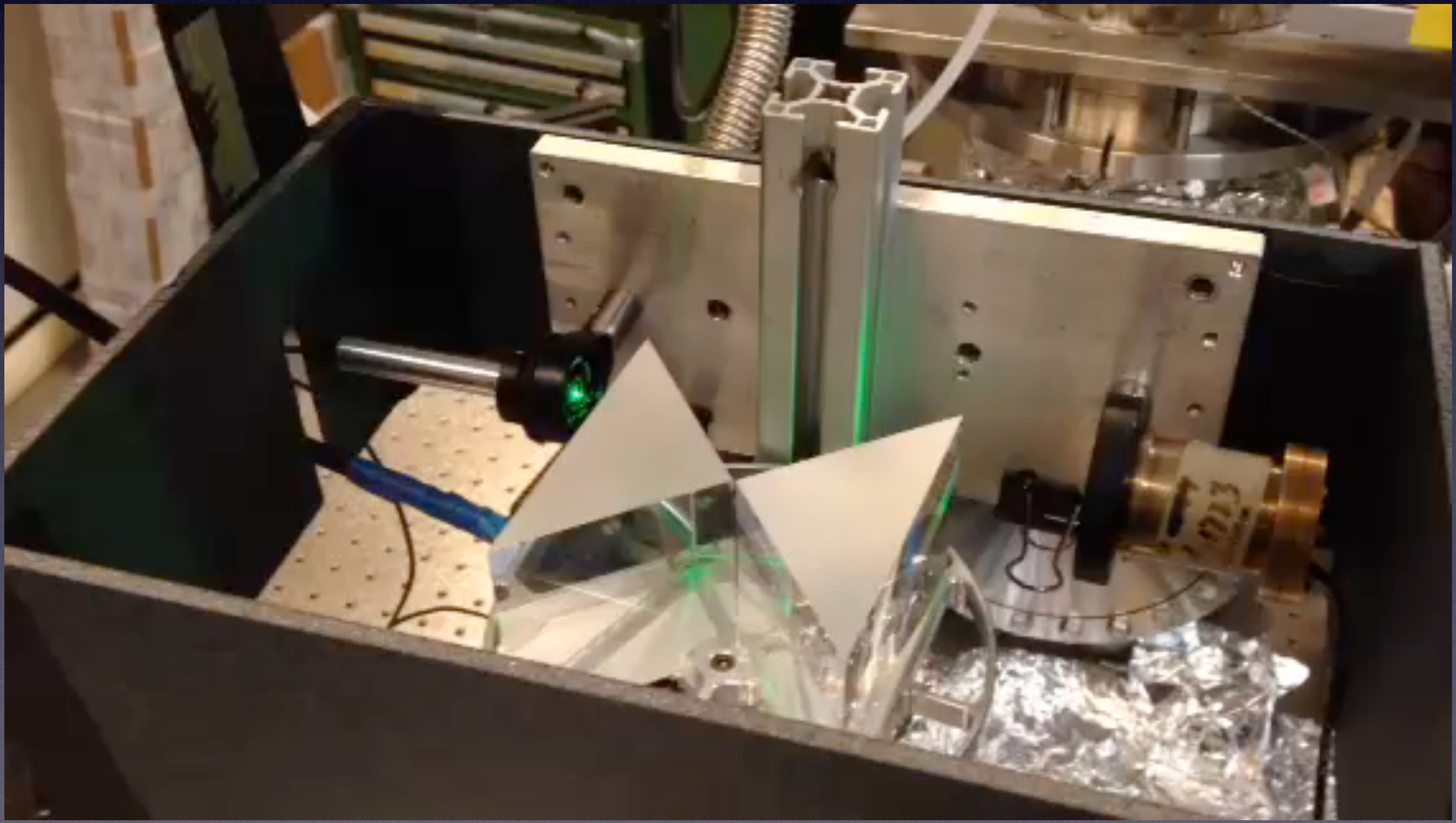


Chopping frequency ~200 Hz

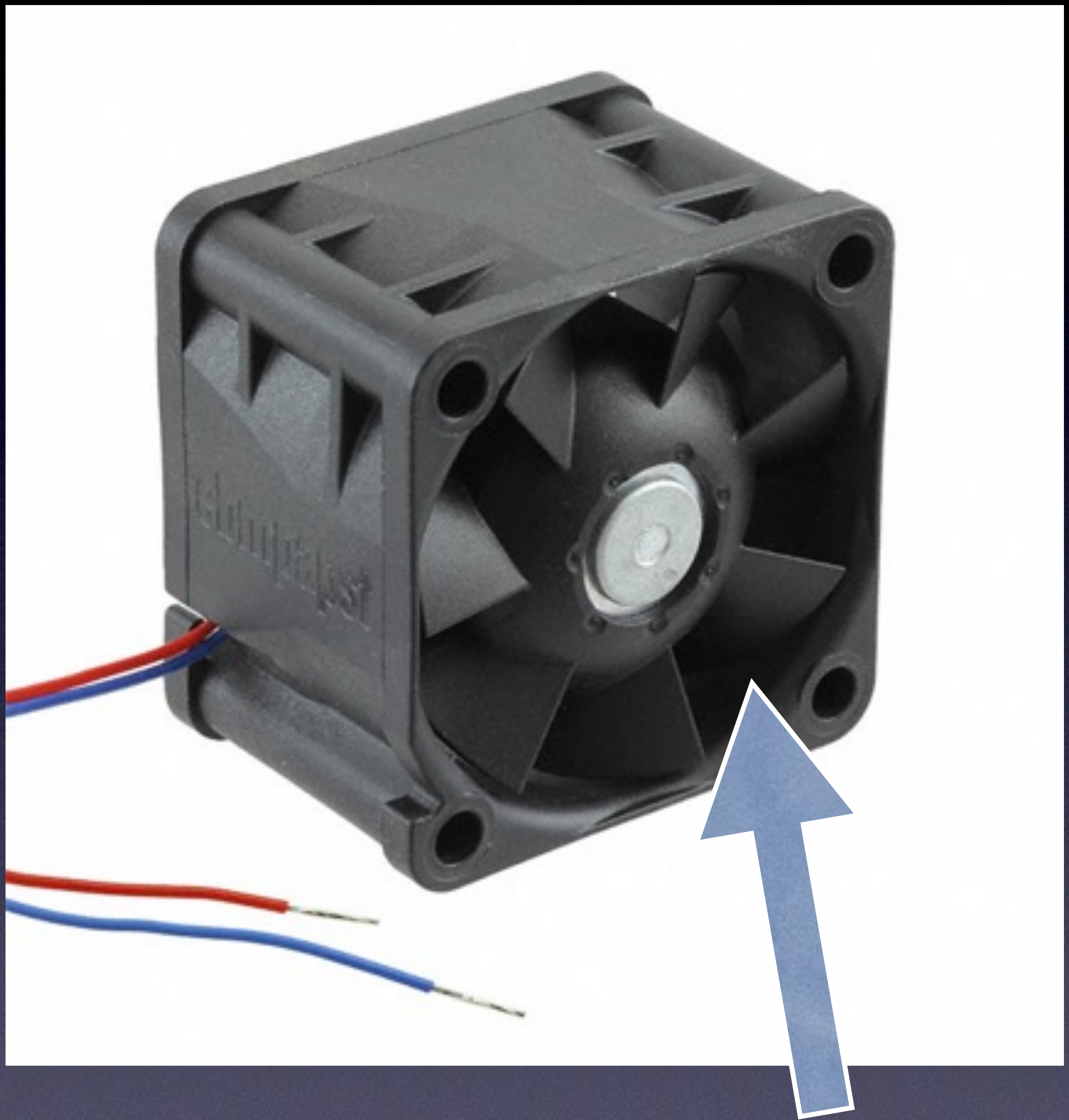








Higher Frequency Chameleon chopper

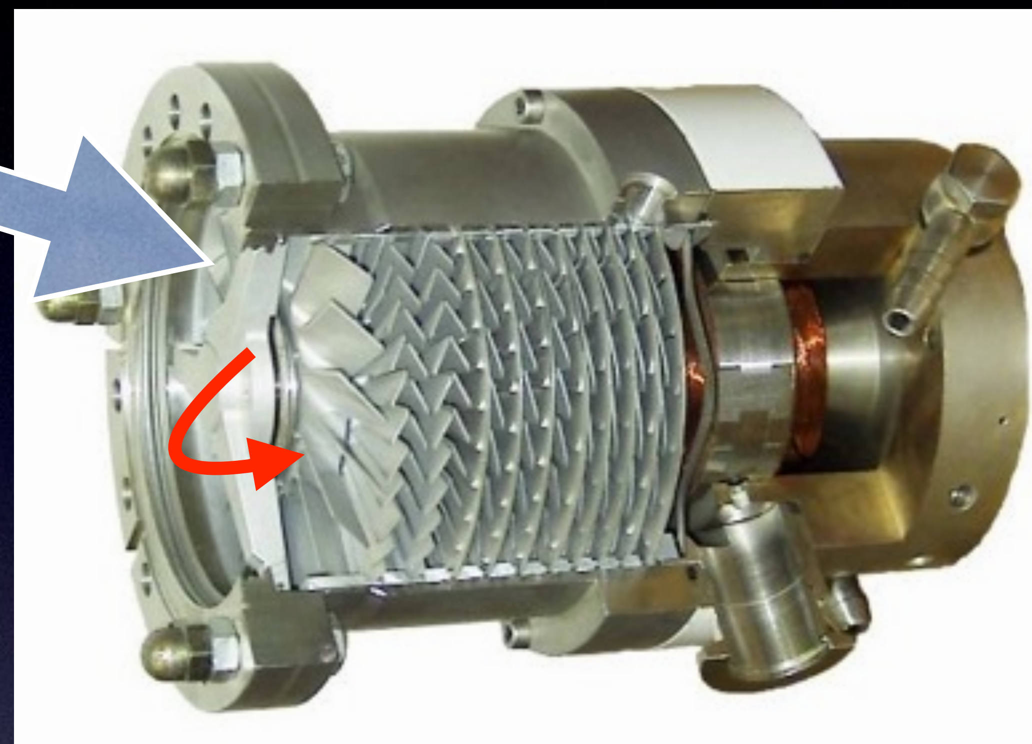


Chopping frequency
~2 kHz

Chameleon flux

Even Higher Frequency Chameleon chopper

Chameleon flux

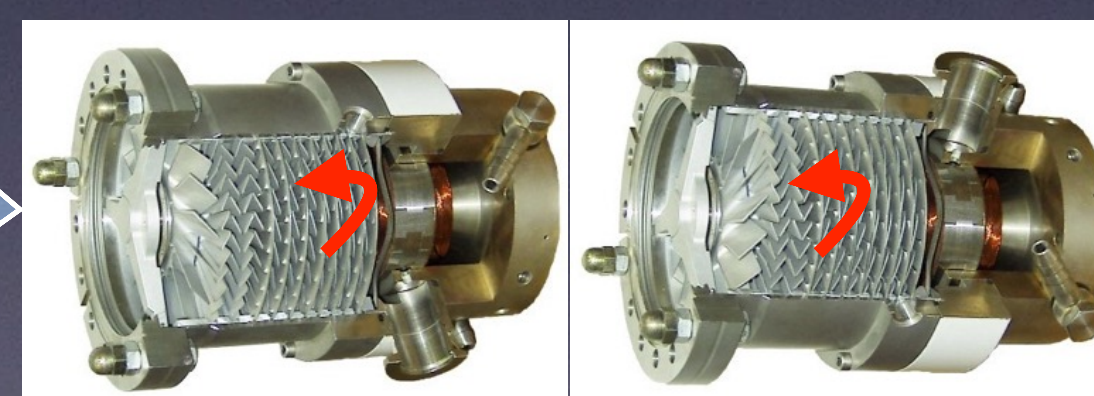


Chopping frequencies
~100 kHz

Vacuum turbo
pump turbine

Chameleon flux

Gain a further factor 2 … (suggestion by S. Hofmann)



2 counter-rotating turbines

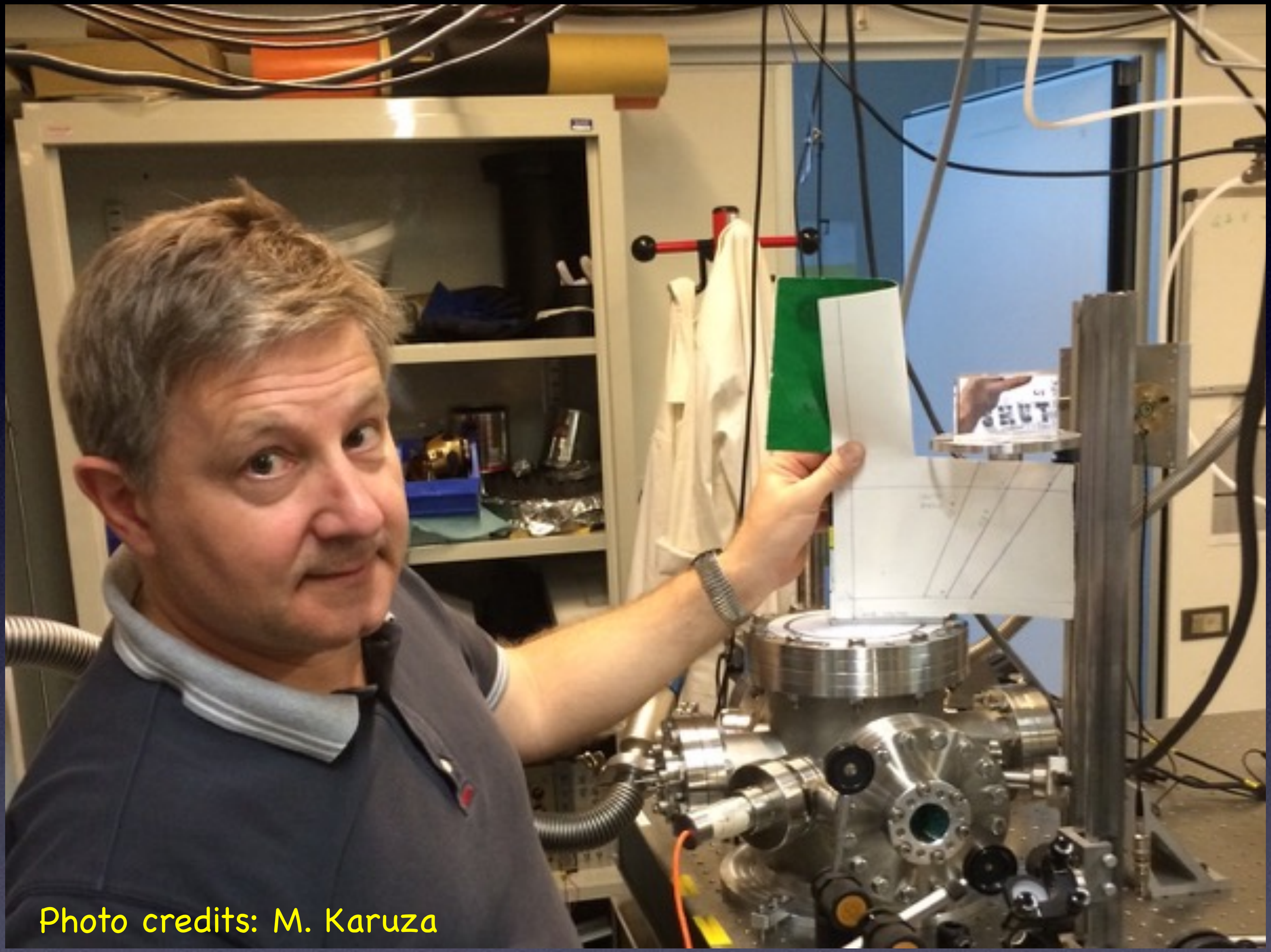
Preliminary tests in Trieste with the chameleon chopper

- Chameleon chopper built and tested mechanically up to 100 Hz
- Coarsely aligned with the sun position with respect to the KWISP membrane
  - alignment done with … *Solar Geometrical Calculator*
  - selected grazing incidence angles 0-20°
  - two-hour window for solar runs
- Preliminary test solar runs with Chameleon chopper

Setting up with the… SGC(*)!

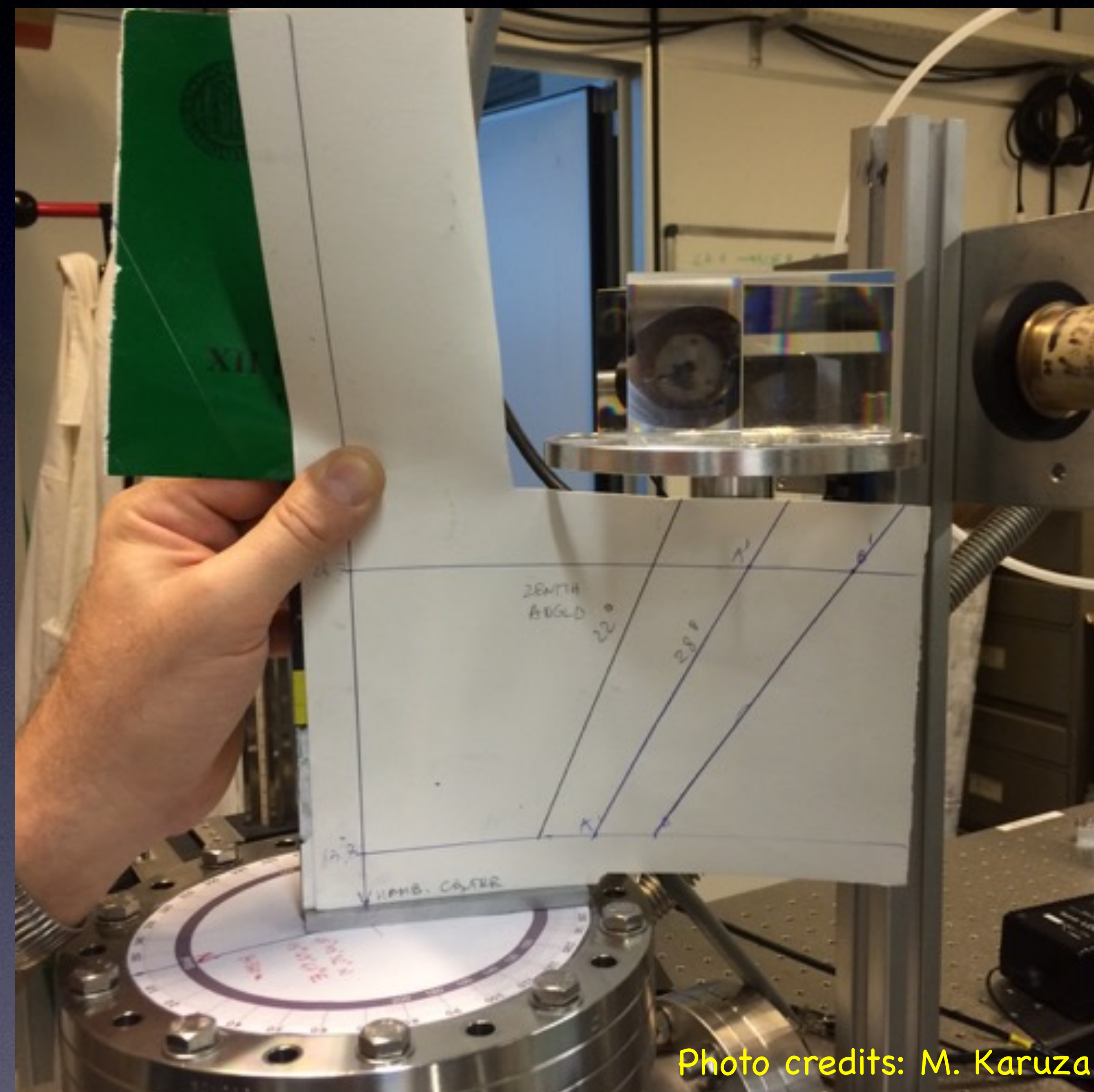
(*) Solar Geometrical Calculator

Setting up with the… SGC(*)!



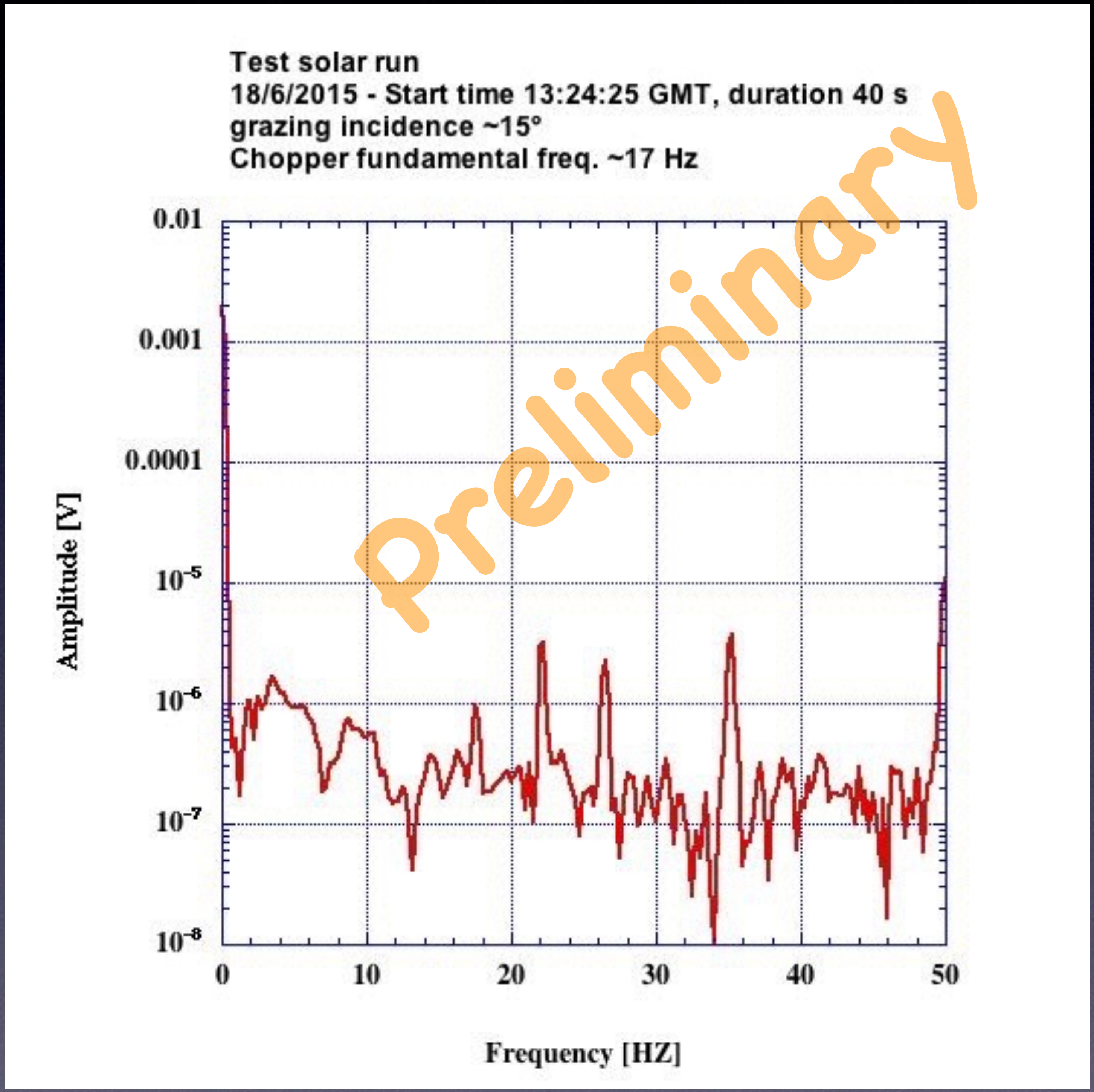
(*) Solar Geometrical Calculator

Setting up with the… SGC(*)!



(*) Solar Geometrical Calculator

Sample spectrum from test solar Chameleon run



Conclusions and plans

- The KWISP force sensor has been calibrated with a directly applied force, also determining the membrane mechanical Q-factor. Measured sensitivity:

  off resonance: $5 \cdot 10^{-14}$ N/√Hz

  on resonance: $1.7 \cdot 10^{-17}$ N/√Hz

- Key concept: amplitude modulation of a Chameleon beam
  - built a first version of a Chameleon chopper
  - tested with preliminary "solar" runs
- New in-house technologies under development
  - homodyne detection (differential two-beam readout)
  - membrane cooling
  - membrane coatings for better photon detection
- **Detecting the solar chameleon flux at CAST with KWISP (*):**
  - sensor coupled to the CAST MPE X-ray telescope ⟹ factor ~100 increase in flux
  - **exploit solar tracking capability for unique signal ID**
  - **searching for _real_ Chameleon interaction (as opposed to *virtual*)**
  - **possibility for a first glimpse at the Dark Energy sector**

(*) see the CAST proposal to the CERN SPSC at https://cds.cern.ch/record/485291

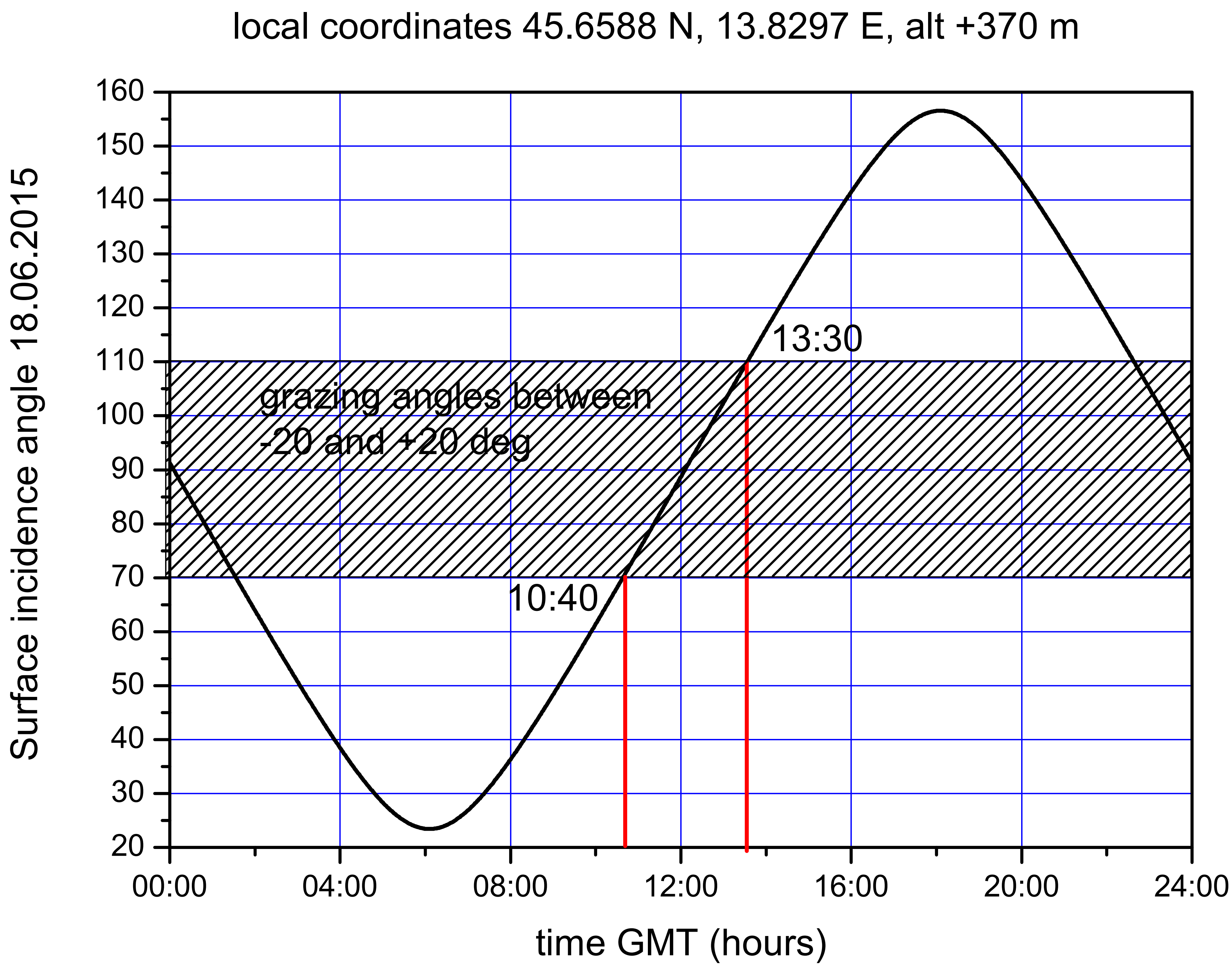
Suggestions for further reading

G. Cantatore et al., Rev. of Sci. Instr., 66(4) 2785–2787 (1995)
on frequency locking Fabry-Perot cavities

M. Karuza et al., J. Opt. 15, 025704 (2013), M.Karuza et al. New J. of Phys 14 (2012) 095015
on detecting micro-membrane displacements

S. Baum, G. Cantatore, D.H.H. Hoffmann, M. Karuza, Y.K. Semertzidis, A. Upadhye, K. Zioutas, Physics Letters B 739, 167–173 (2014)
on detecting solar Chameleons with an opto-mechanical force sensor

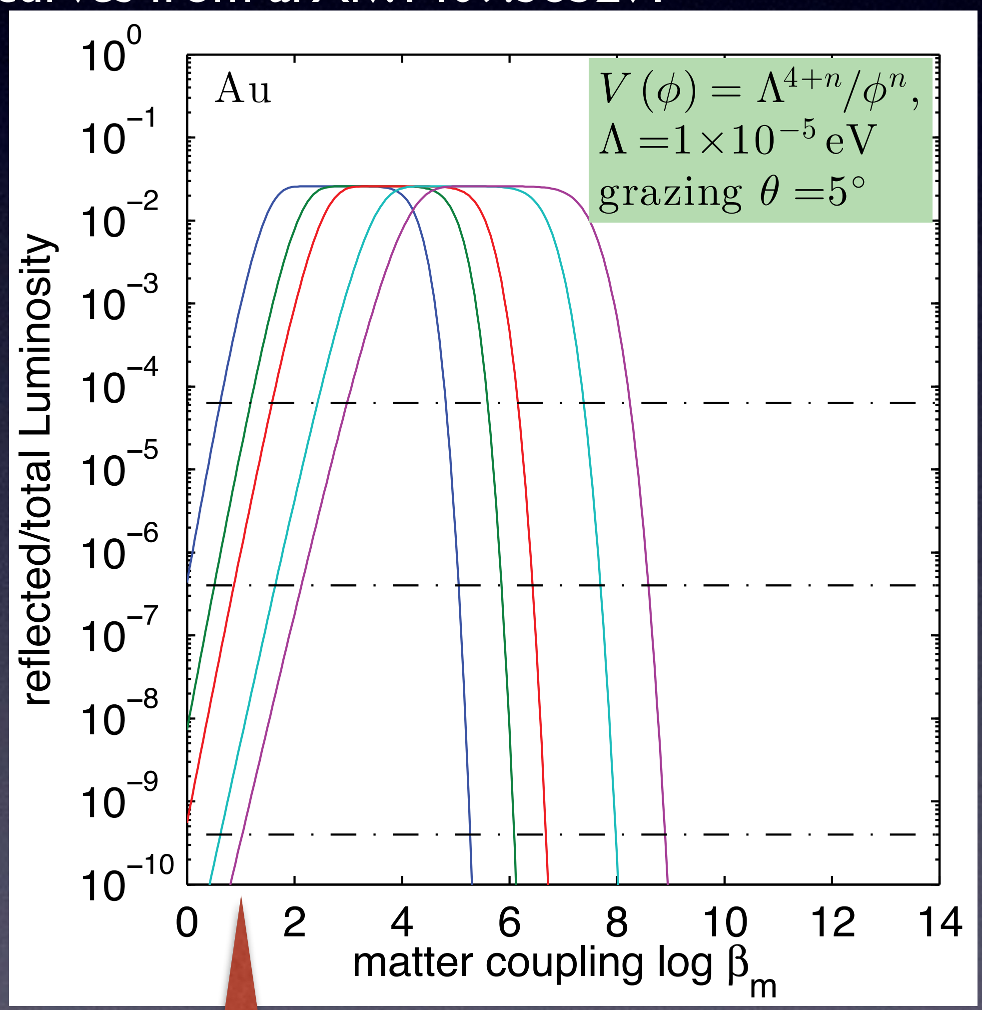
BACKUP SLIDES

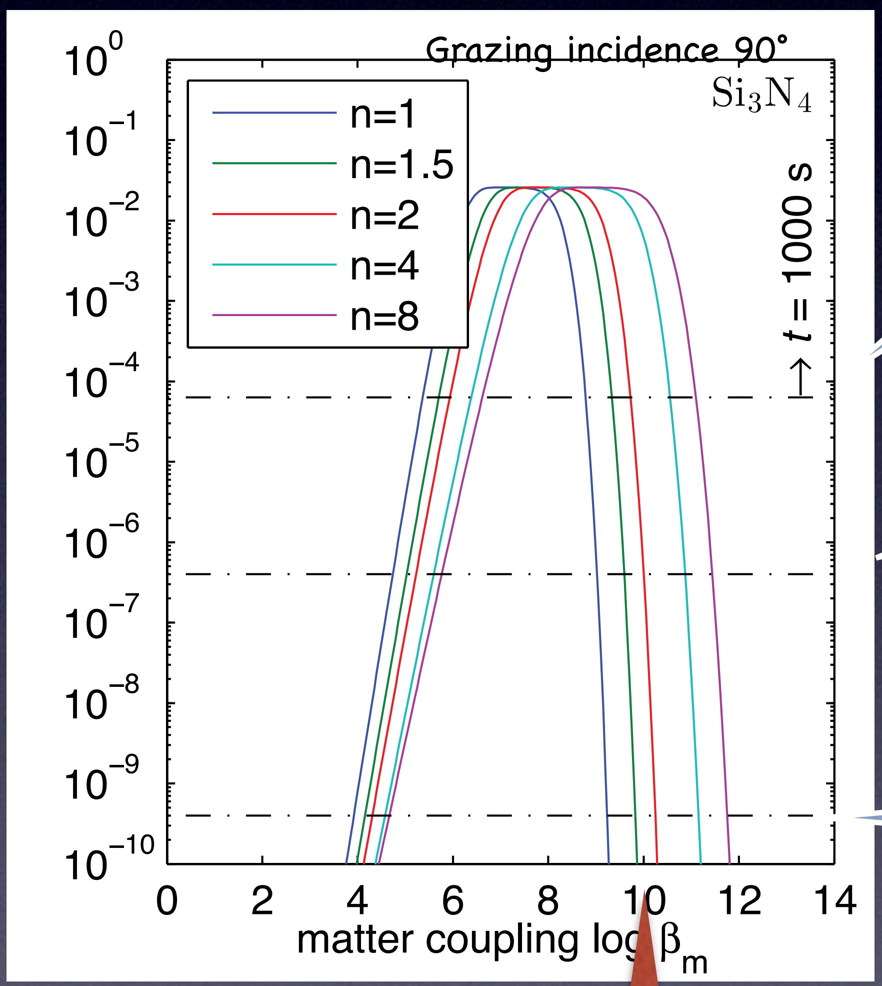

local coordinates 45.6588 N, 13.8297 E, alt +370 m
Surface incidence angle 18.06.2015
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
13:30
grazing angles between
-20 and +20 deg
10:40
00:00
04:00
08:00
12:00
16:00
20:00
24:00
time GMT (hours)

Physics reach of the KWISP force sensor

- Curves below represent, for different *n* and Λ parameters in the Chameleon potential the fraction of the total incident flux reflected by the Si_3N_4 membrane ("Au" plot refers to a gold coated membrane)
- Dashed lines indicate, for different measurement conditions, the minum fraction detectable by KWISP with the current expected force sensitivity of $5 \cdot 10^{-14}$ N/√Hz (assuming $L_{ch}/L_{sol} = 0.1$)

curves from arXiv:1409.3852v1





- T_{mis} = 1000 s
- No XRT

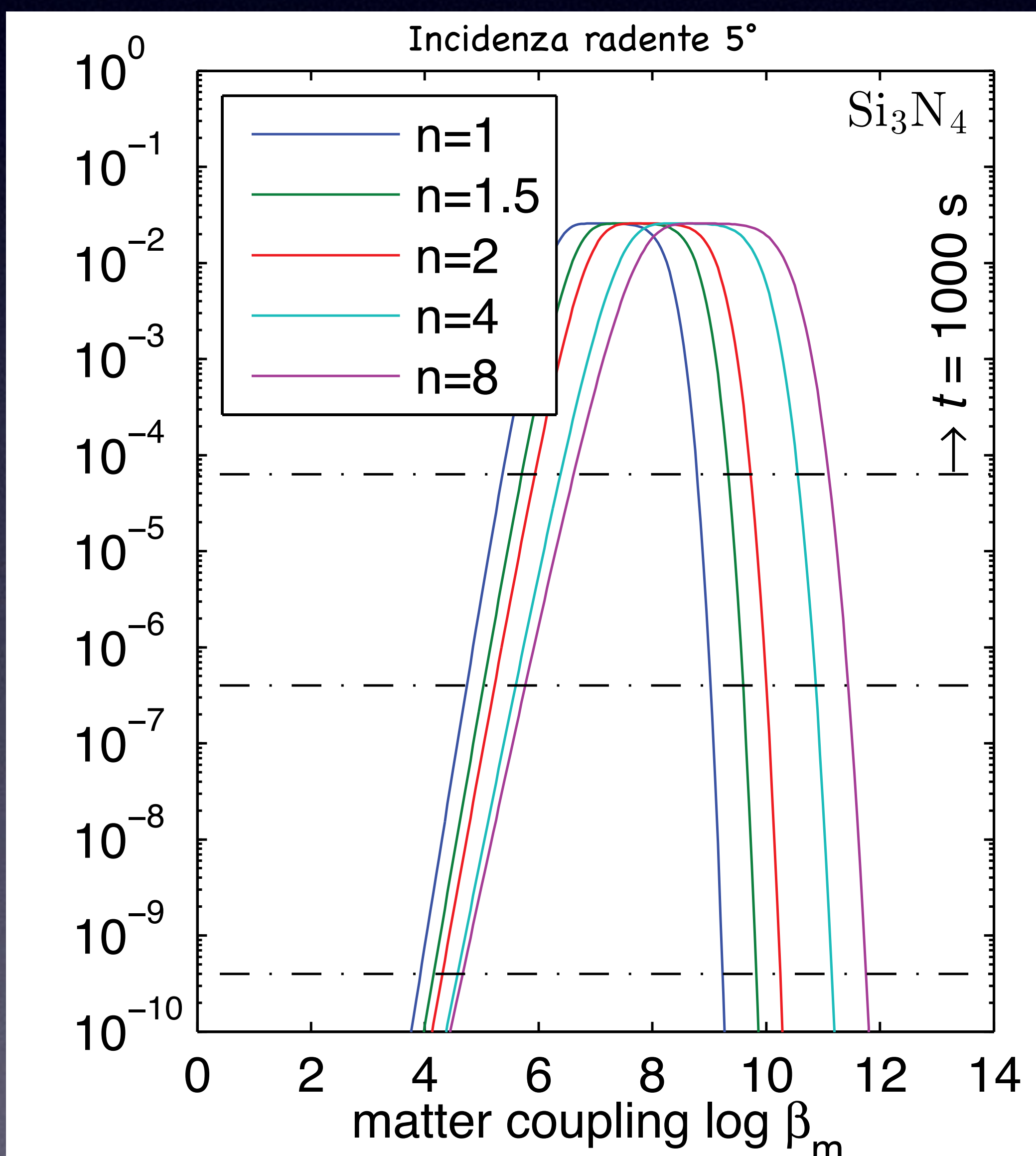
- T_{mis} = 100 s
- sensor in the CAST XRT focus

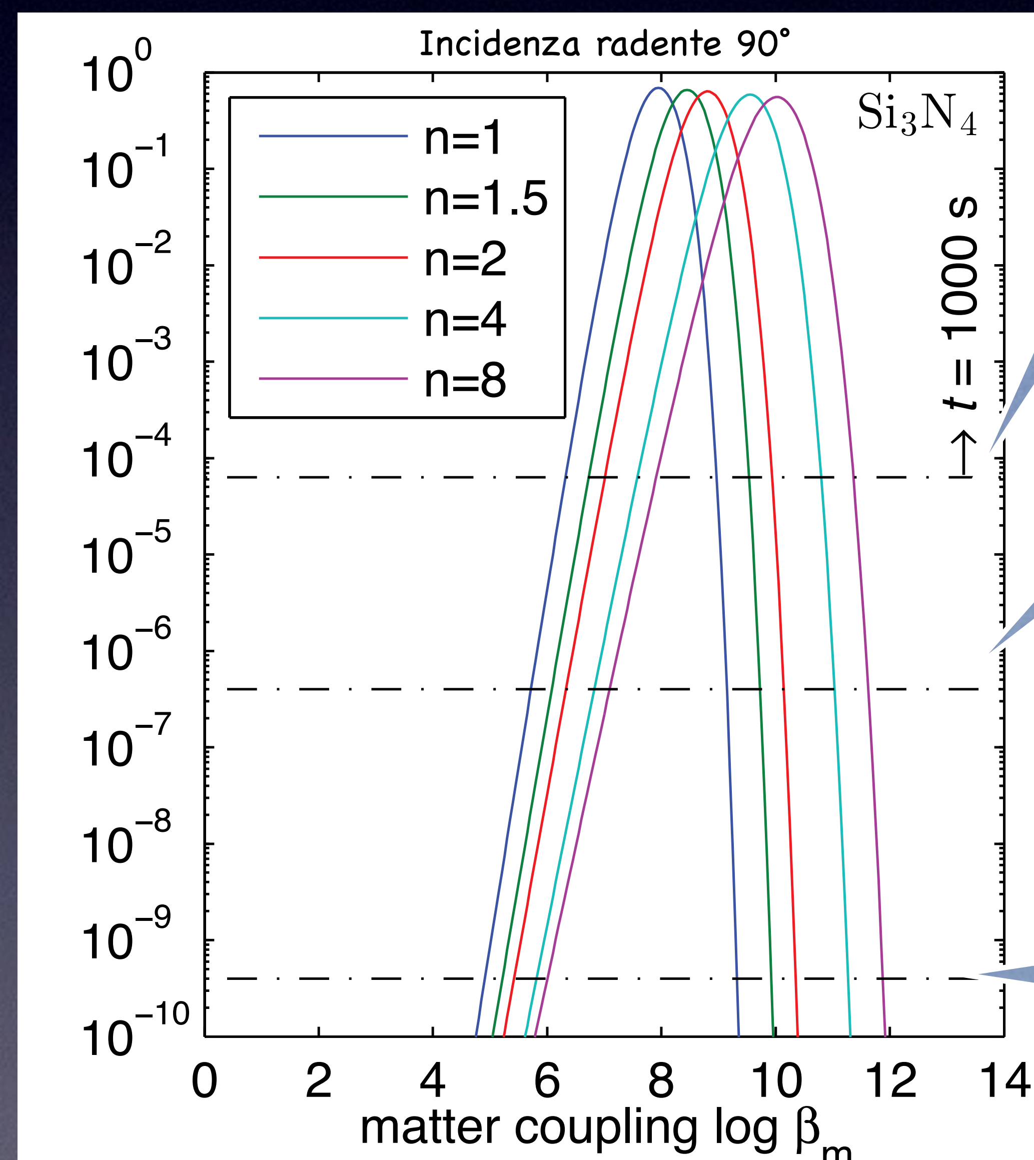
- T_{mis} = 100 s
- sensor in the CAST XRT focus
- membrane at < 1 K
- chopper

Wide β_m reach from < 10 to > 10^{10}

Curve di sensibilità del sensore KWISP

- Le curve dànno, per diversi *n* nel potenziale e per $\Lambda = 2.4 \times 10^{-3}$ eV, la frazione del flusso di chameleon riflessi dalla membrana di Si_3N_4
- Le linee tratteggiate indicano, per diverse condizioni di misura, la frazione minima rivelabile da KWISP con la sensibilità aspettata corrente di 5×10^{-14} N/√Hz (assumendo $L_{ch}/L_{sol} = 0.1$)





- T_{mis} = 1000 s
- No XRT

- T_{mis} = 100 s
- sensore nel fuoco del CAST XRT

- T_{mis} = 100 s
- sensore nel fuoco del CAST XRT
- membrana a < 1 K
- chopper

Short terms plans and SPSC proposal

- Remaining measurements in Trieste
  - determine membrane mechanical resonant frequency ν_m
  - modulate pump beam at ν_m: sensitivity increases by a factor $Q \sim 10^4 - 10^5$
  - repeat test runs
- At CERN (short term)
  - setup of the off-beam bench starts as soon as equipment arrives
- CAST proposal to SPSC
  - CAST new physics proposal to SPSC submitted yesterday
  - KWISP is a substantial part of this program developing over three years

2016	2017	2018
• **solar tracking with room temperature membrane** • **study homodyne detection**	• **solar tracking with homodyne detection** • **study membrane cooling**	• **solar tracking with cooled membrane and homodyne detection**