Latest results with the KWISP force sensor at CAST

G. Cantatore - University and INFN Trieste

CAST Collaboration
KWISP Working Group: G. Cantatore, H. Fischer, A. Gardikiotis, D. H. Hoffmann, M. Karuza, Y. Semertzidis, I. Tsagris, K. Zioutas

Summary

- CAST and its new physics program
- KWISP detection principle
- First search for solar Chamelons at CAST with KWISP
- More to come…

CAST at CERN

- 21 institutes, 48 authors, 12 countries…
- Probing the mysteries of the Universe since 2003 !!!

http://cast.web.cern.ch/CAST/CAST.php

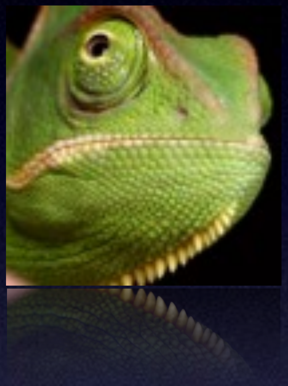
The new CAST physics program

- CAST has terminated its solar axion search program at the end of 2015
  - while analysis of the latest vacuum data is still in progress, CAST is still a benchmark reference for axion searches
- A new physics program for CAST has been approved by CERN (*)
- CAST expands its horizons from Dark Matter to Dark Energy with three new research lines
  - solar Chameleon searches with KWISP (direct coupling to matter)
  - solar Chameleon searches with InGrid (two-photon coupling)
  - relic axion searches with CAPP@CAST

(*) see G. Cantatore, L. Miceli, K. Zioutas, "Search for solar chameleons and relic axions with CAST", CERN-SPSC-2015-021

Chameleon searches at CAST

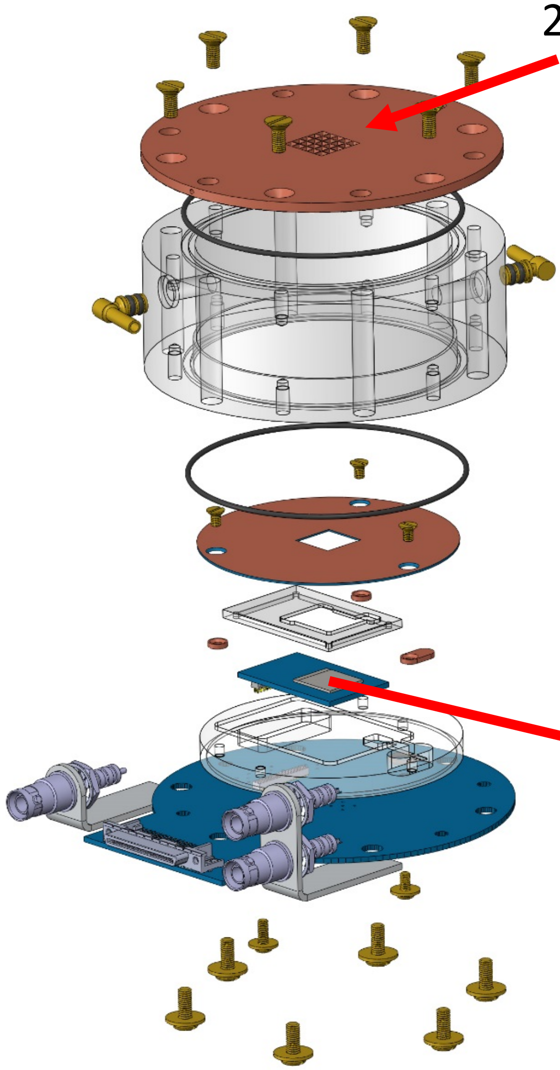
- Chameleons are a type of scalar WISPs having an effective mass dependent on the local energy density. Solar Chameleons are Primakoff-produced inside the magnetic field of the Sun and then stream to Earth



- Two couplings, two detection possibilities:
  - **inverse Primakoff conversion inside a magnetic field** $\Longrightarrow$ photon coupling β_γ
  - **force exerted at grazing incidence on a surface** $\Longrightarrow$ direct coupling to matter β_m
- Photon channel: InGrid low-threshold photon detector
- Matter channel: **KWISP** (Kinetic WISP detection) opto-mechanical force sensor
  - first force-sensor prototype built and absolutely calibrated at INFN Trieste
  - KWISP-type sensors tested at CERN and used for the first ever direct matter-coupling based search

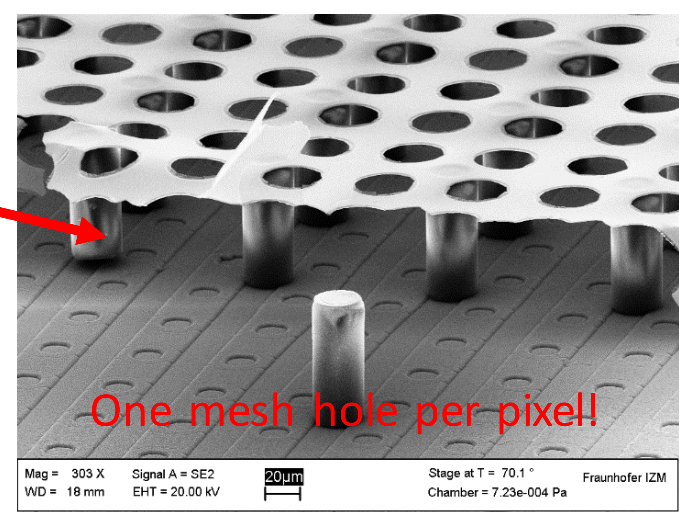
The InGrid based X-ray detector

2 μm Mylar entrance window

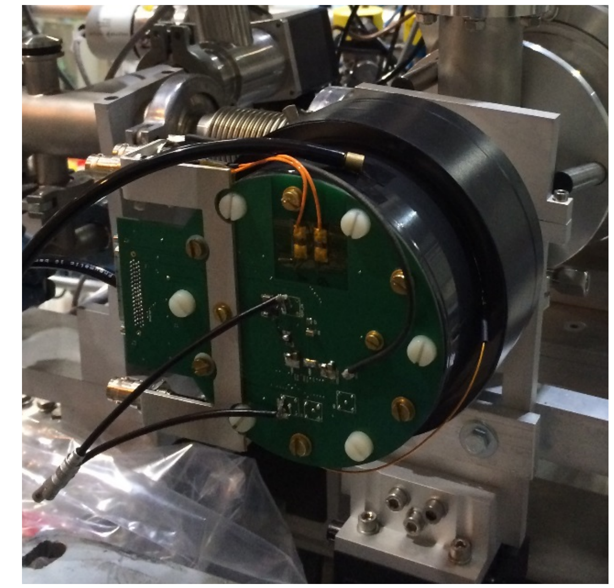


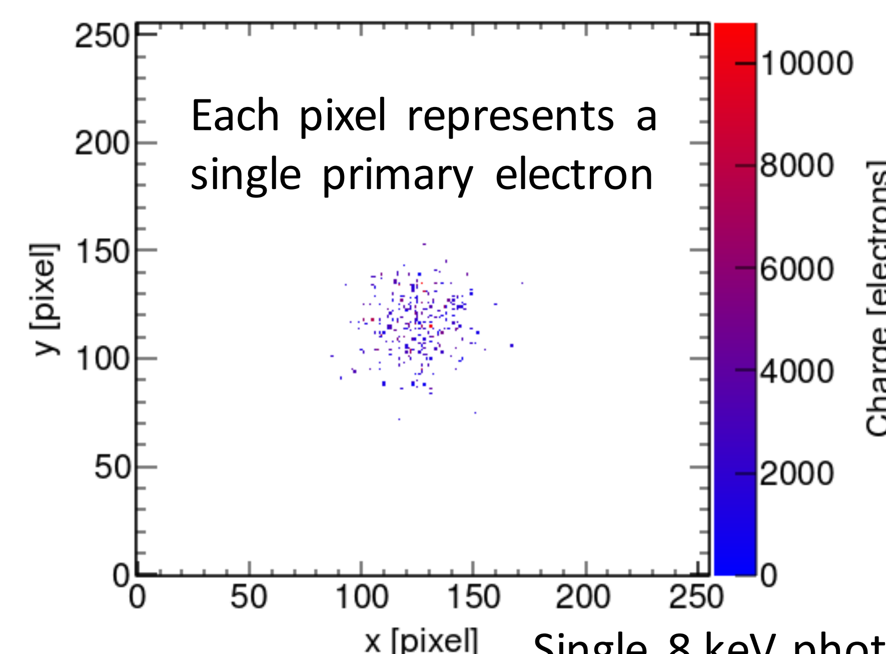
Detection of photons down to 277 eV (Carbon K_α line) possible

Timepix ASIC combined with integrated Micromegas stage (InGrid)



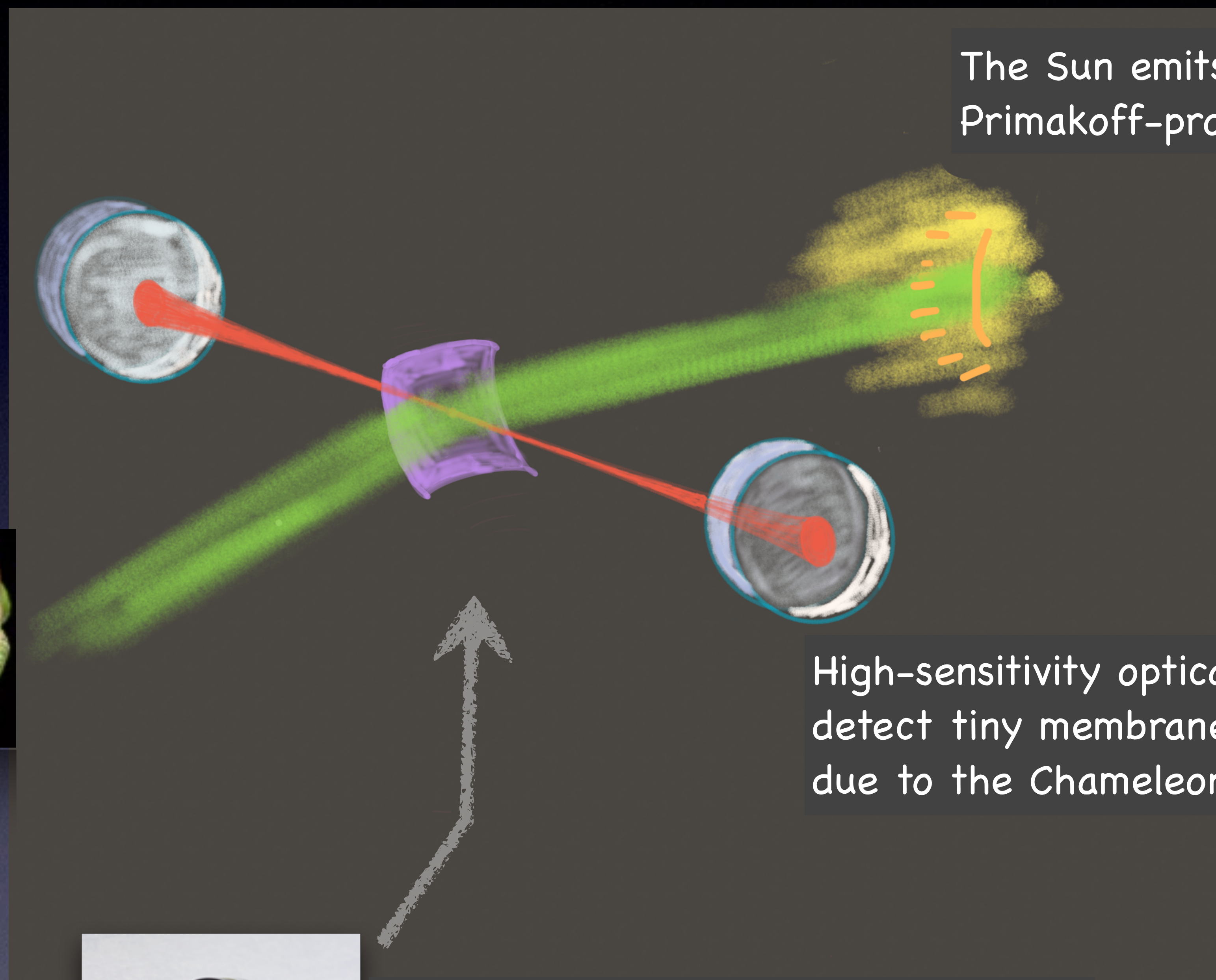
InGrid based X-ray detector



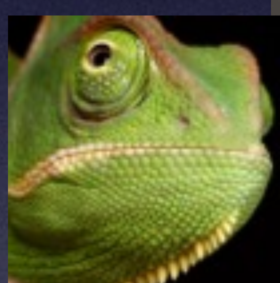


Single 8 keV photon

The KWISP principle



The Sun emits a stream of Primakoff-produced Chameleons

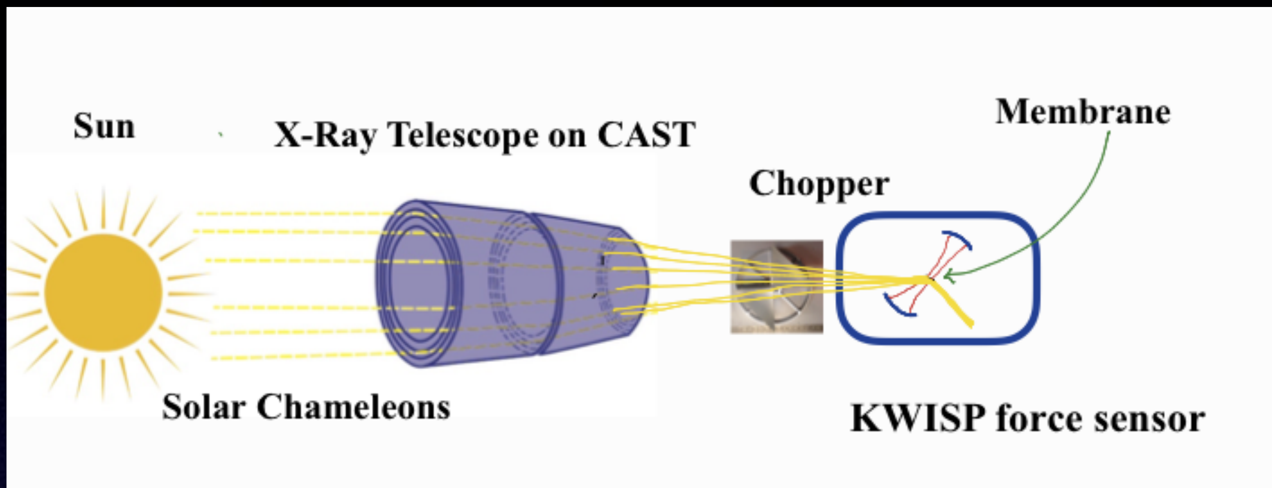


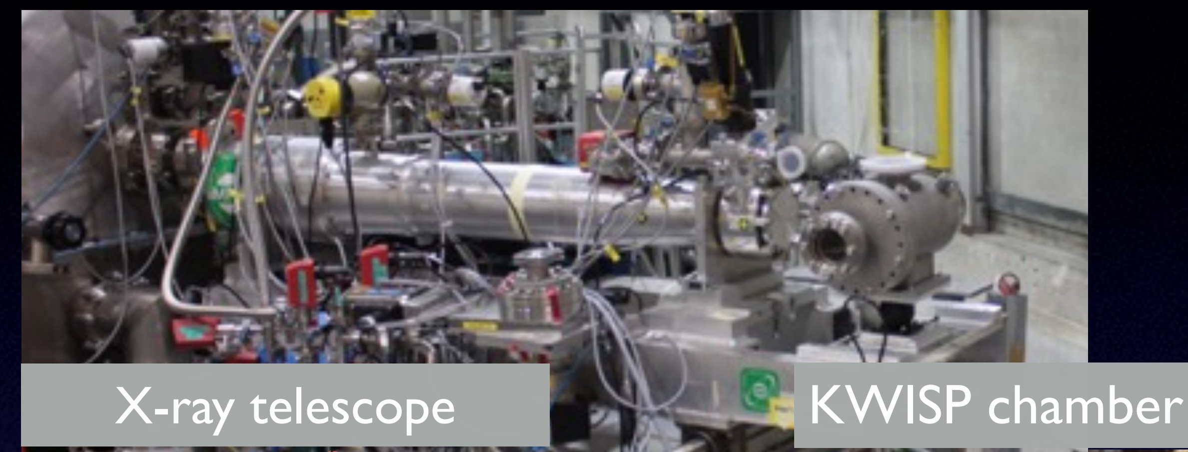
High-sensitivity optical techniques detect tiny membrane displacements due to the Chameleon wind force

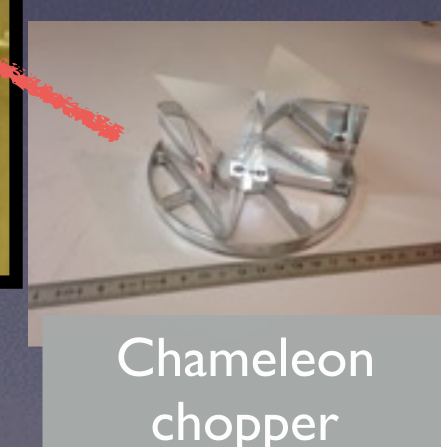
An ultra-thin taut membrane flexes as a sail under the Chameleon wind

Curious? See January-February 2016 CERN Courier http://cerncourier.com/cws/article/cern/63705

KWISP at CAST

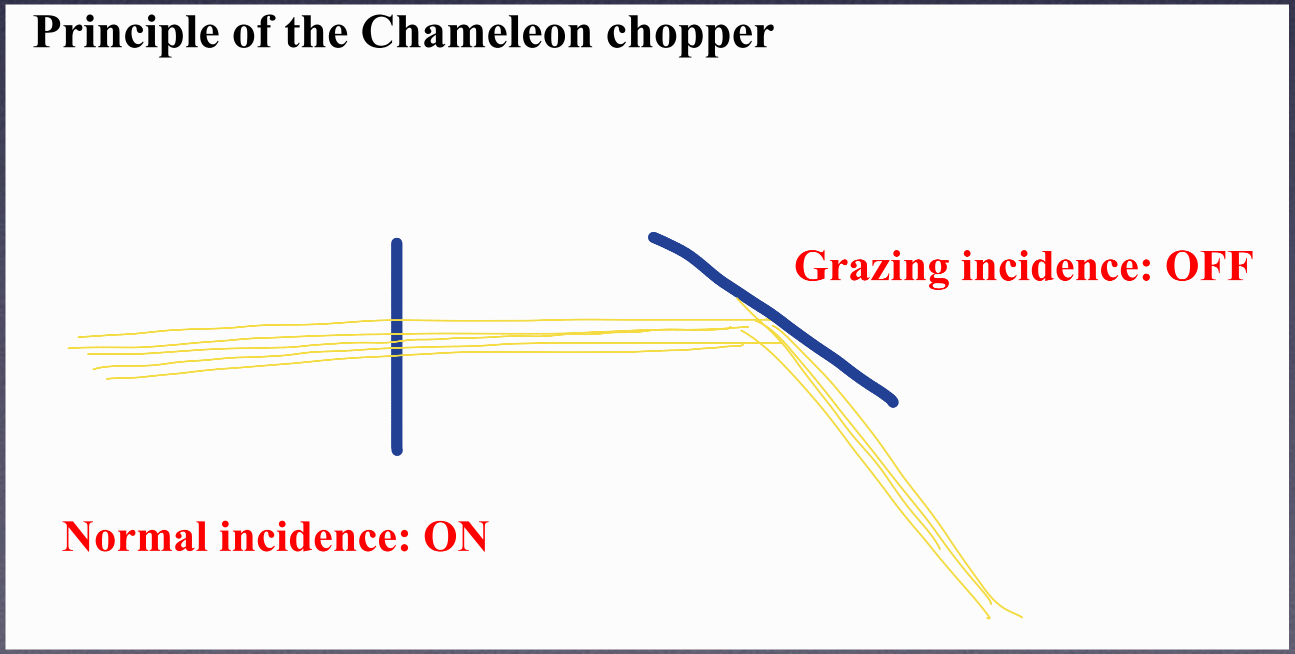






The Chameleon chopper

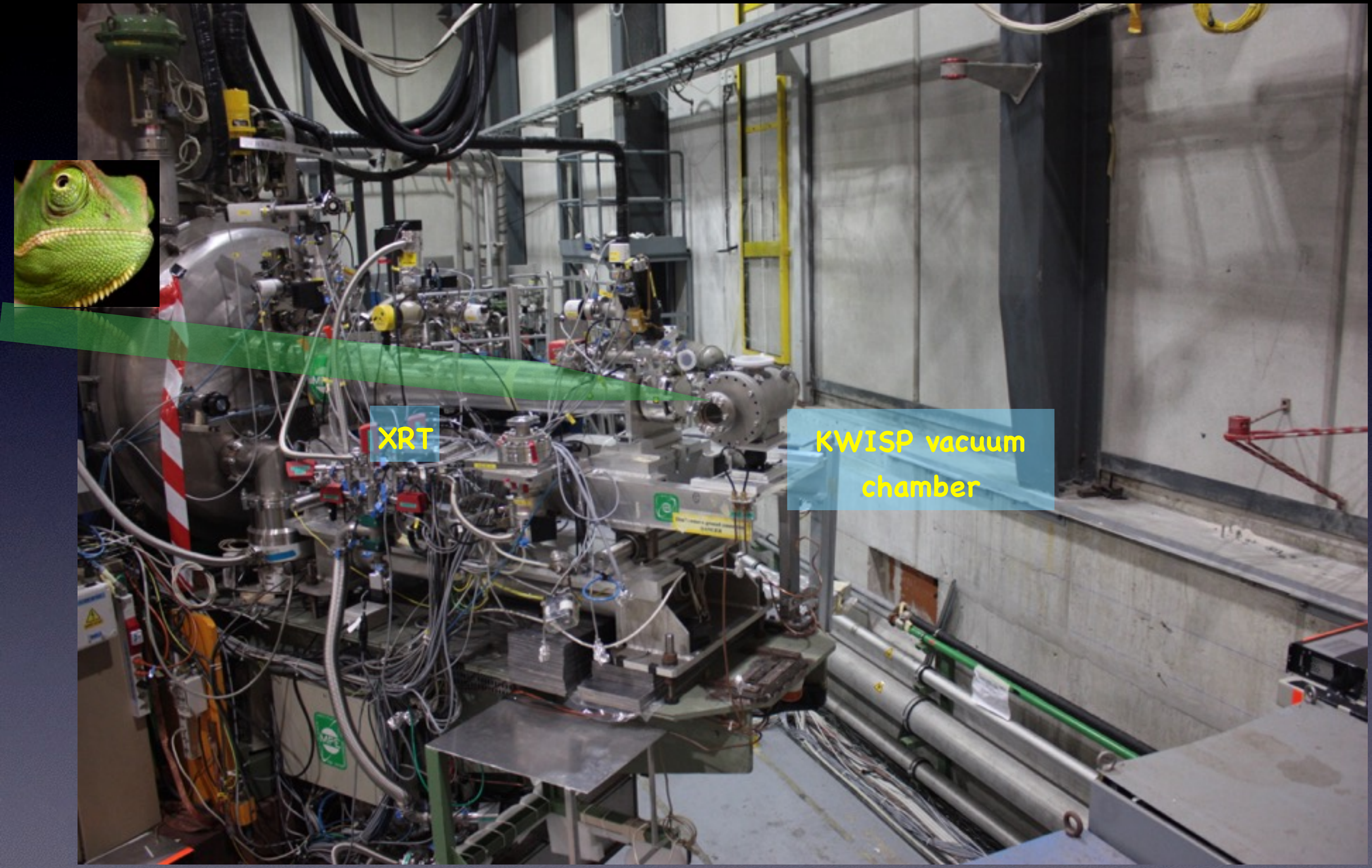
- Why does one need a chopper?
  - the sensor detects *relative* displacements, thus a *static* displacement is not seen
  - a time dependence must then be introduced in the membrane excitation
- Modulating the amplitude of something you cannot even see… the Chamelon chopper!
  - rests on the principle of grazing-angle reflection of Chameleons (see http://arxiv.org/abs/1201.0079)
  - key element: no detection is possible without



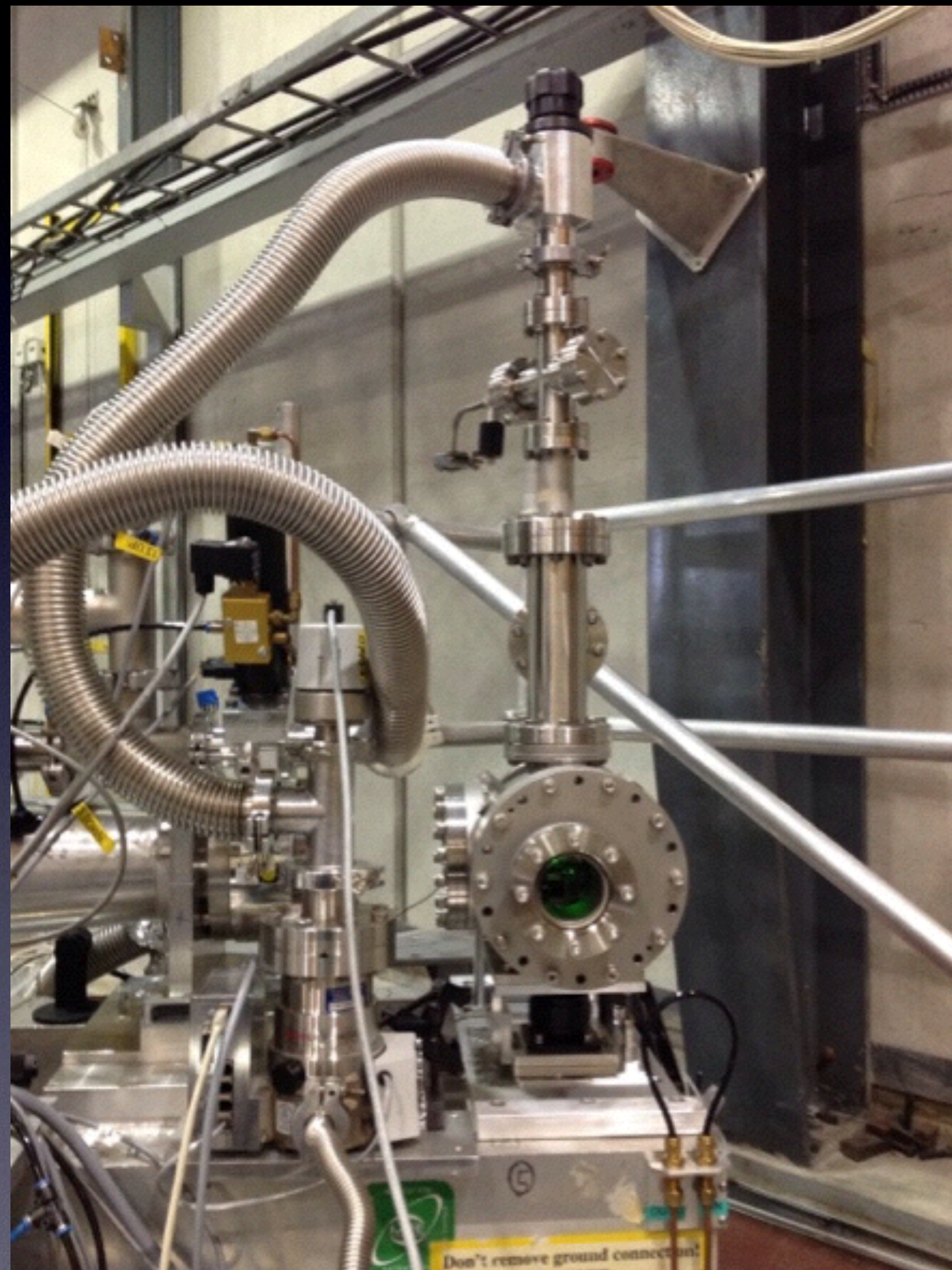
On-beam assembly

- The KWISP vacuum chamber is coupled to the CAST beamline with *xyz* movements and the membrane is aligned in the focal plane of the XRT
- The internal optics assembly is modular: it can accommodate different optical setups
- The vacuum system is turbo pumped, reaching residual pressure in the 10^{-6} mbar range

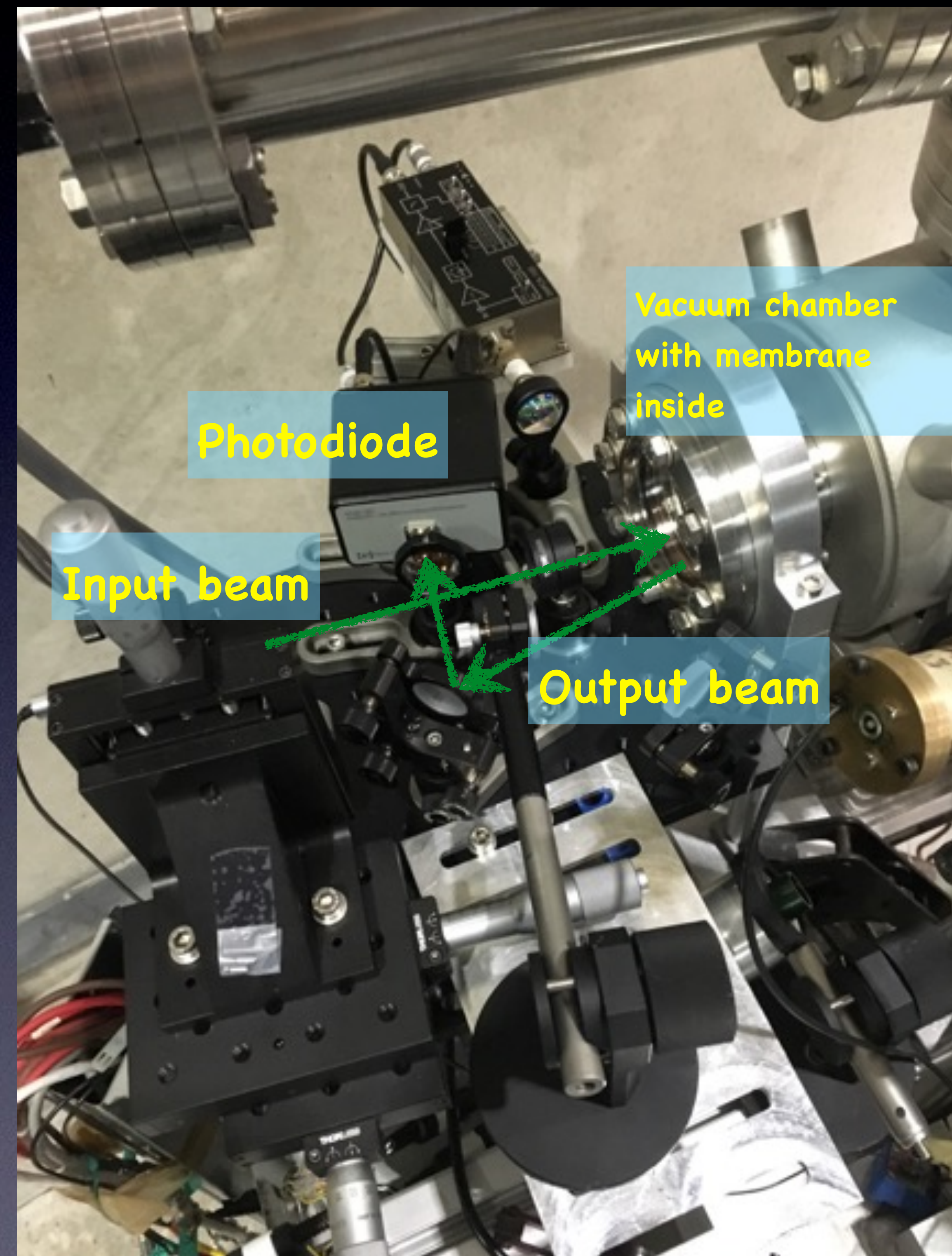
KWISP gallery I



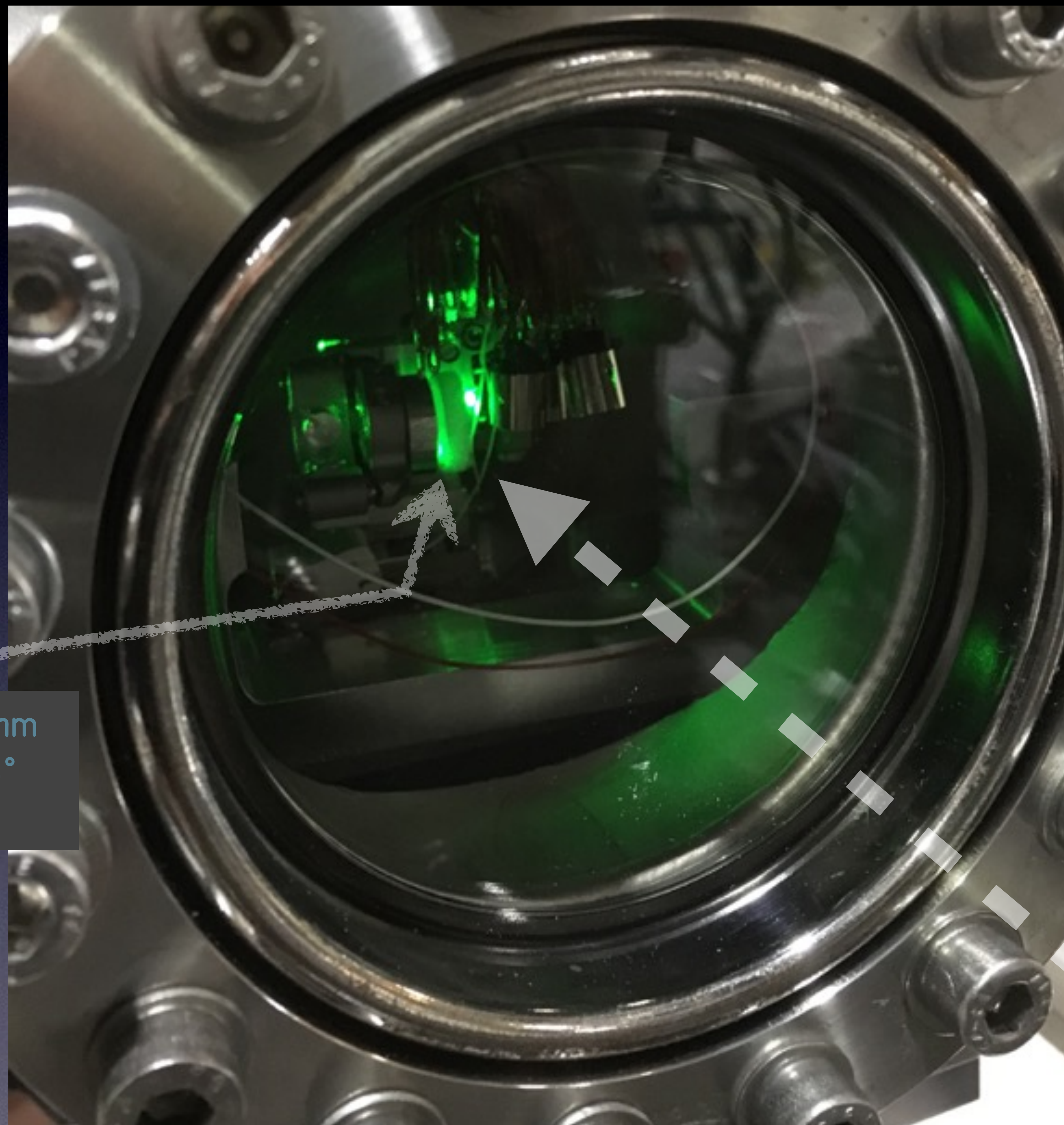
KWISP gallery II



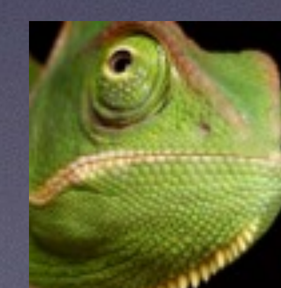
KWISP gallery III



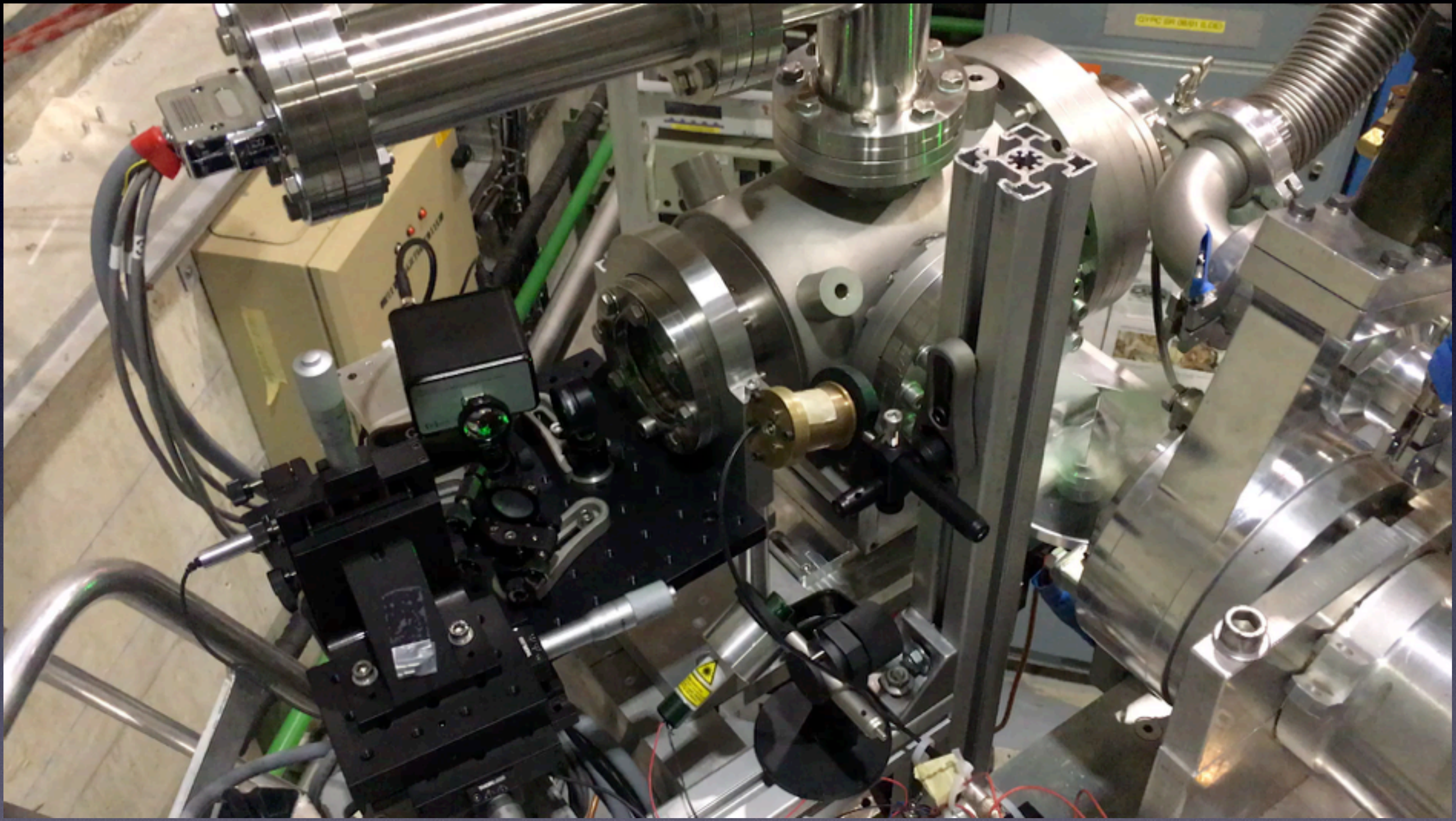
KWISP seen by Chameleons …



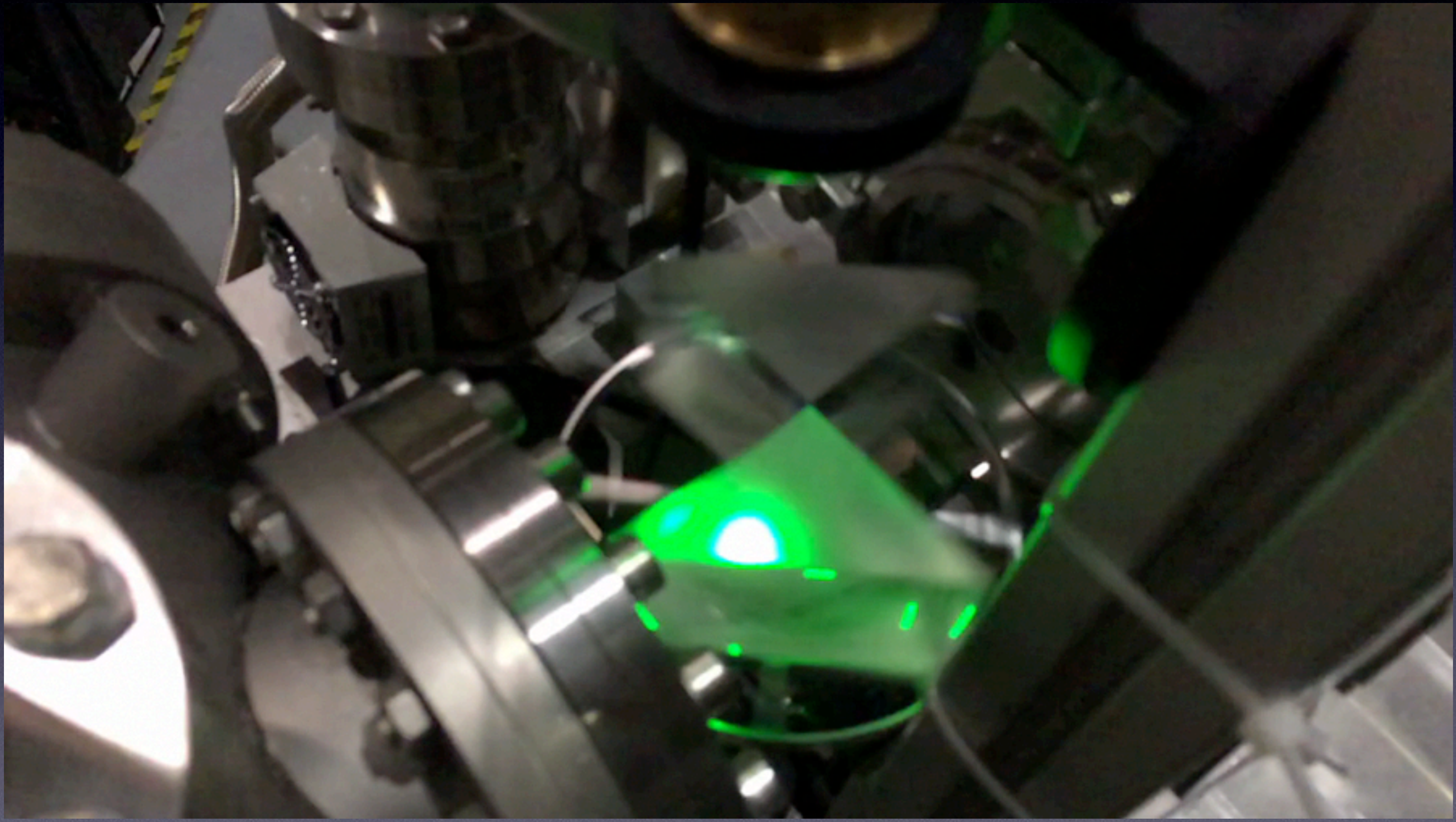
5x5 mm^2 Si_3N_4, 100 nm thick membrane at 5° incidence angle



KWISP bird's eye view

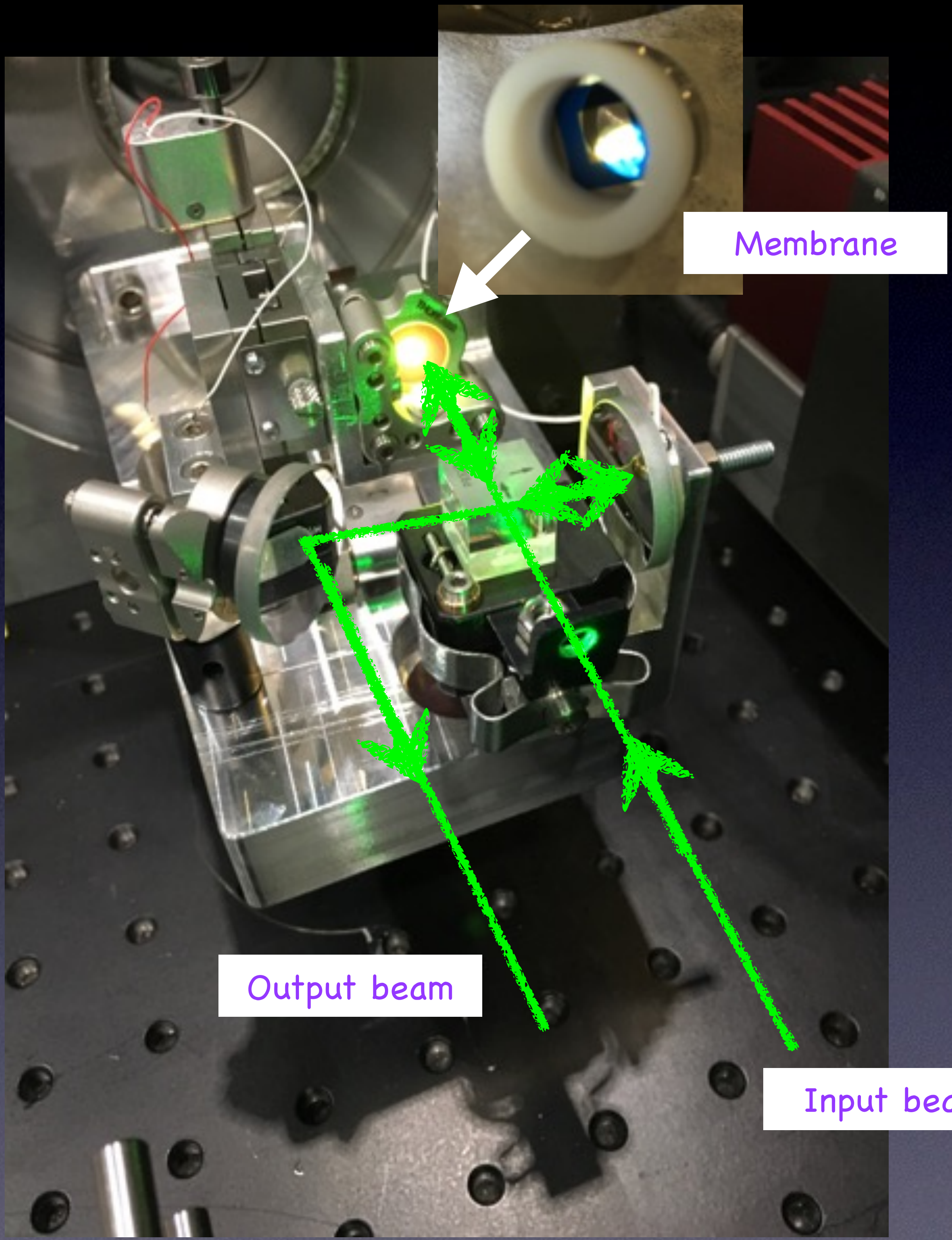


Chameleon chopper slow motion



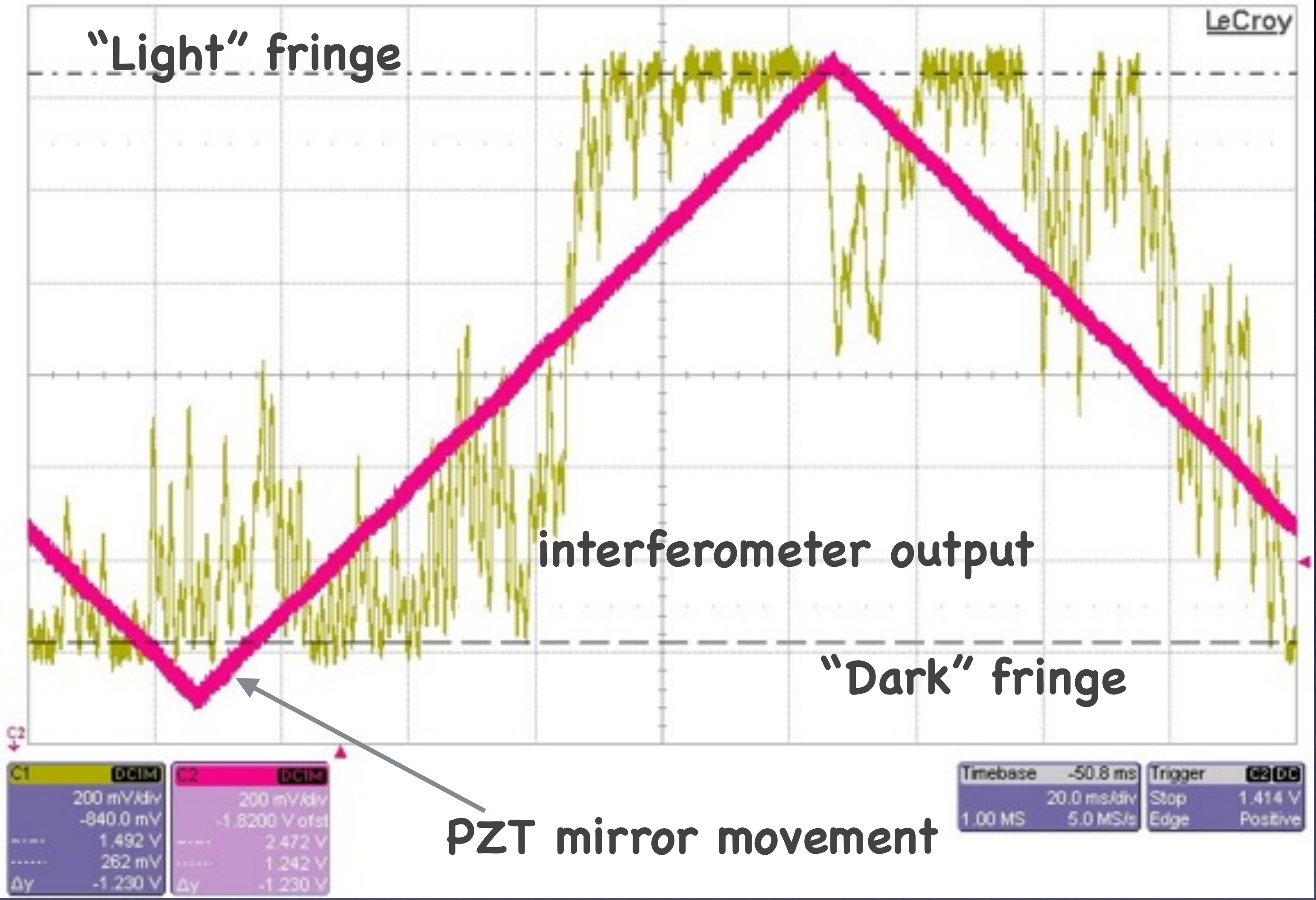
KWISP on-beam initial optics setup

- Michelson-type interferometer setup
  - equivalent to single-pass FP
  - realtively low sensitivity, but high stability
  - 5x5 mm^2, 100 nm thick membrane in one interferometer arm, PZT-moveable mirror in the other arm for calibration



Interferometer calibration (example)

- In response to externally-actuated mirror movement, the interferometer output shifts from “dark” fringe to “light” fringe



- the measured difference in voltage corresponds to a displacement of λ/2 (λ = 532 nm)
  - in this example

$$C = \frac{532 \text{ nm}}{2 \cdot 1.23 \text{ V}} = 216 \text{ nm/V}$$

Measurement procedure

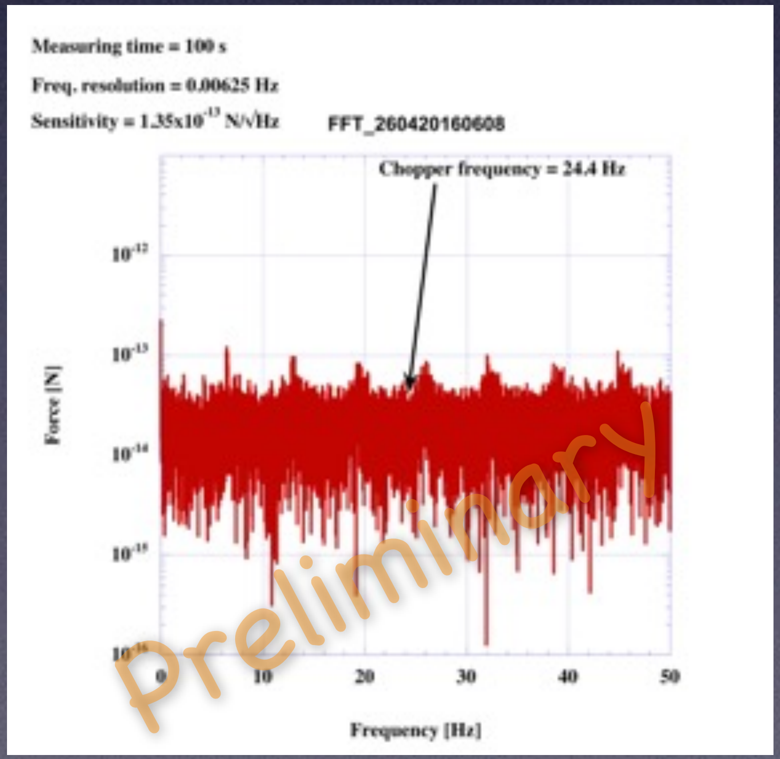
- Interference fringes in the sensor output beam are detected by a photodiode (PD): fringe shifts follow membrane movements.
- Information on membrane displacements as a function of time is encoded in the PD output voltage
- The Chameleon chopper provides both a reference frequency and a trigger signal for data acquisition
- A Chameleon signature should appear as a peak at the chopper frequency in the PD signal power spectrum
- The chopper also allows for
  - extended integration time (separate time records are taken in phase)
  - signal ID as a function of the chopper angular position (in case of positive signature)

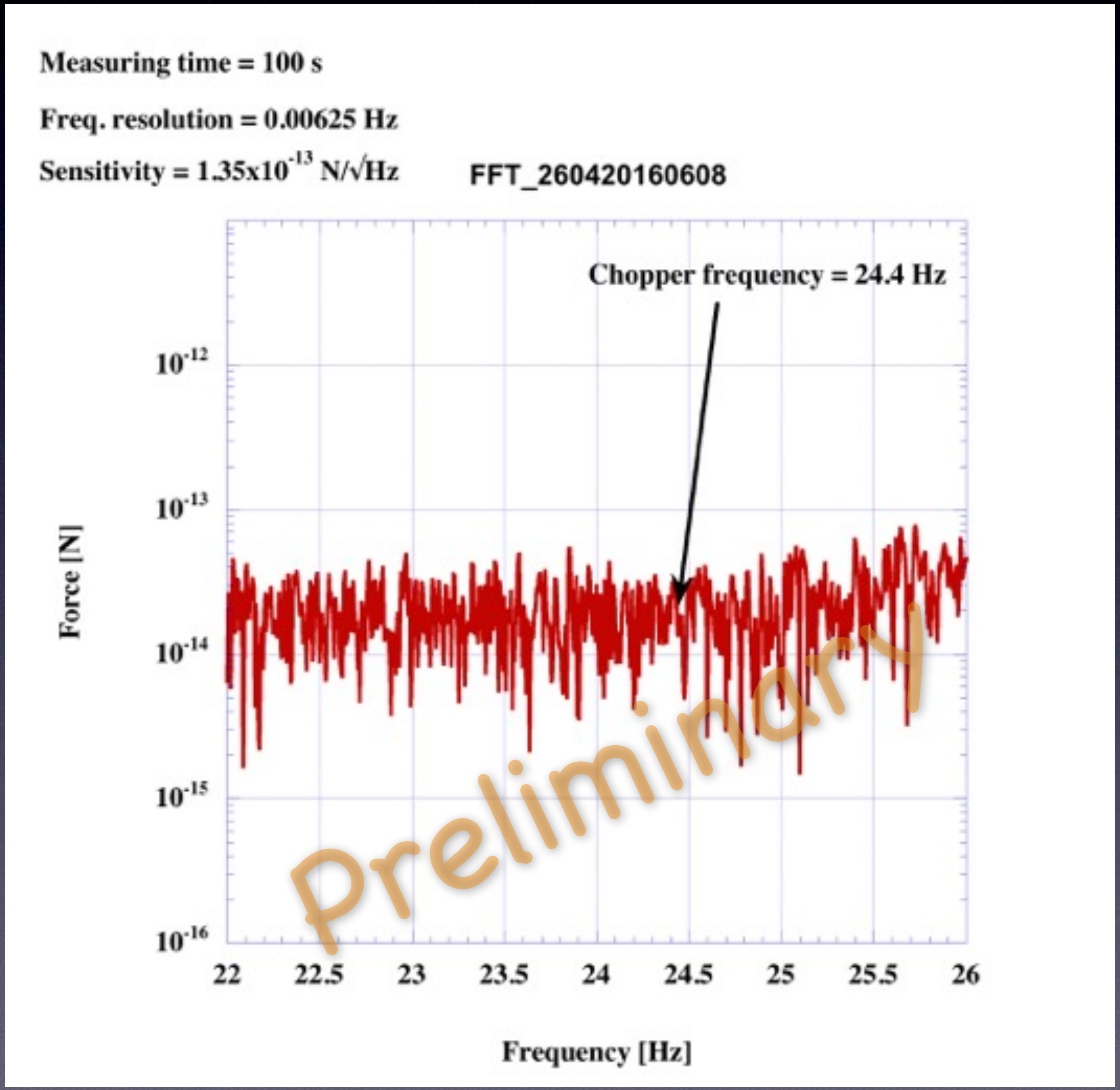
April 2016 KWISP solar run at CAST

- **First run ever with a force sensor looking for solar Chameleons**
- Morning sun-trackings 21-28 April 2016
  - preliminary phase (2 days, DAQ with spectrum analyzer)
  - full DAQ phase with automated LabView based data daking and optimized optics
- Data taking strategy
  - time domain data acquired in 100 s-long time records
    - both the interferometer output signal and the trigger signal are acquired
  - a calibration signal is briefly injected at the beginning of each time record to obtain instantaneous senistivity
  - data are taken continuously both during sun-tracking and off-tracking
- April 2016 run summary statistics
  - 7 days of running
  - 9000 s of sun-tracking data (90 time records)
  - 121400 s of background data (1214 time records)

Data samples from KWISP April 2016 run

- Full data analysis is in progress
  - single-record spectra are inspected for peaks at the chopper frequency taking into account variations due to the CAST magnet angular position
  - spectra are then combined and vector–averaged to lower stochastic backgtound
  - background data spectra are inspected for spurious peak due to possbile noise sources





Upcoming steps in 2016

- Detector upgrade
  - upgrade IR laser temperature control
  - Fabry-Perot optics
  - redesign on-beam chamber
    - larger volume
    - vibration isolation
    - provisions for cryogenic cooling
  - implement homodyne detection technique
  - procure new mirrors and membranes
- DAQ upgrade
  - optimize analog FP locking, move to digital locking
  - adapt DAQ program to upgraded sensor
- Chopper upgrade
  - use high-RPM DC motors salvaged from discarded laser printers (suggestion by M. Karuza)
  - chopping rotors built from commercial low-cost optical flats
- **Goal: be ready for a possible data taking window in December 2016**

Key KWISP technologies

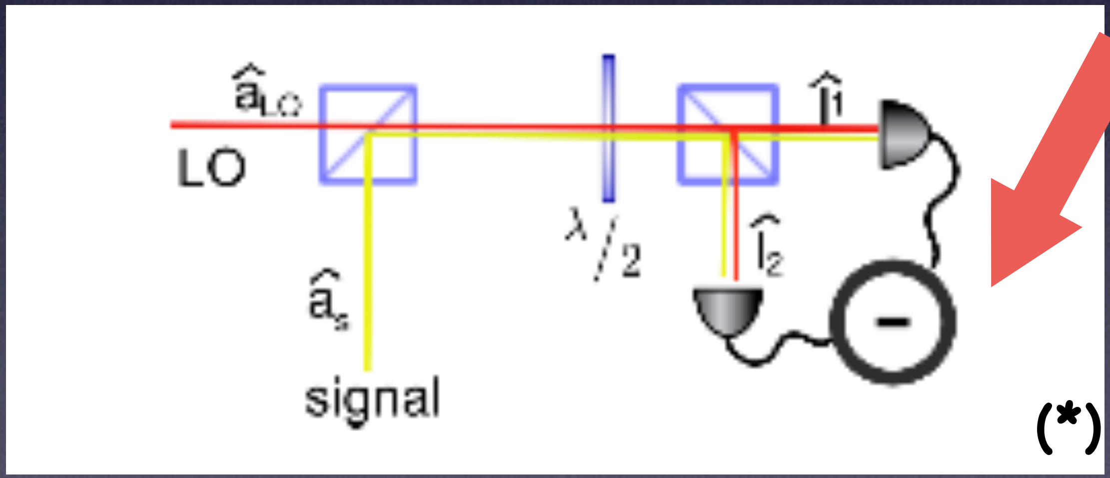
- Enabling technologies
  - Opto-mechanical force sensing with nano-membrane
  - Double resonator concept: membrane Q and FP finesse
  - Chameleon chopper: flux modulation and phase-locking for unique particle detection and identification
  - Sun-tracking and X-ray telescope
- Upgrading technologies
  - direct homodyne detection
  - membrane customisation
  - Chameleon concentrator and recycler
  - membrane cooling

Direct homodyne detection

- The laser beam is split into two beams:
  - a local oscillator beam
  - a sensing beam passing through sensor and carrying the signal information
- The two beams are then combined again before detection and sent to a two-input balanced photodetector
- This approach rejects the common mode noise from
  - laser amplitude fluctuations
  - frequency-locking feedback loop
  - electronic noise in detection

local oscllator (LO)
directly from the laser

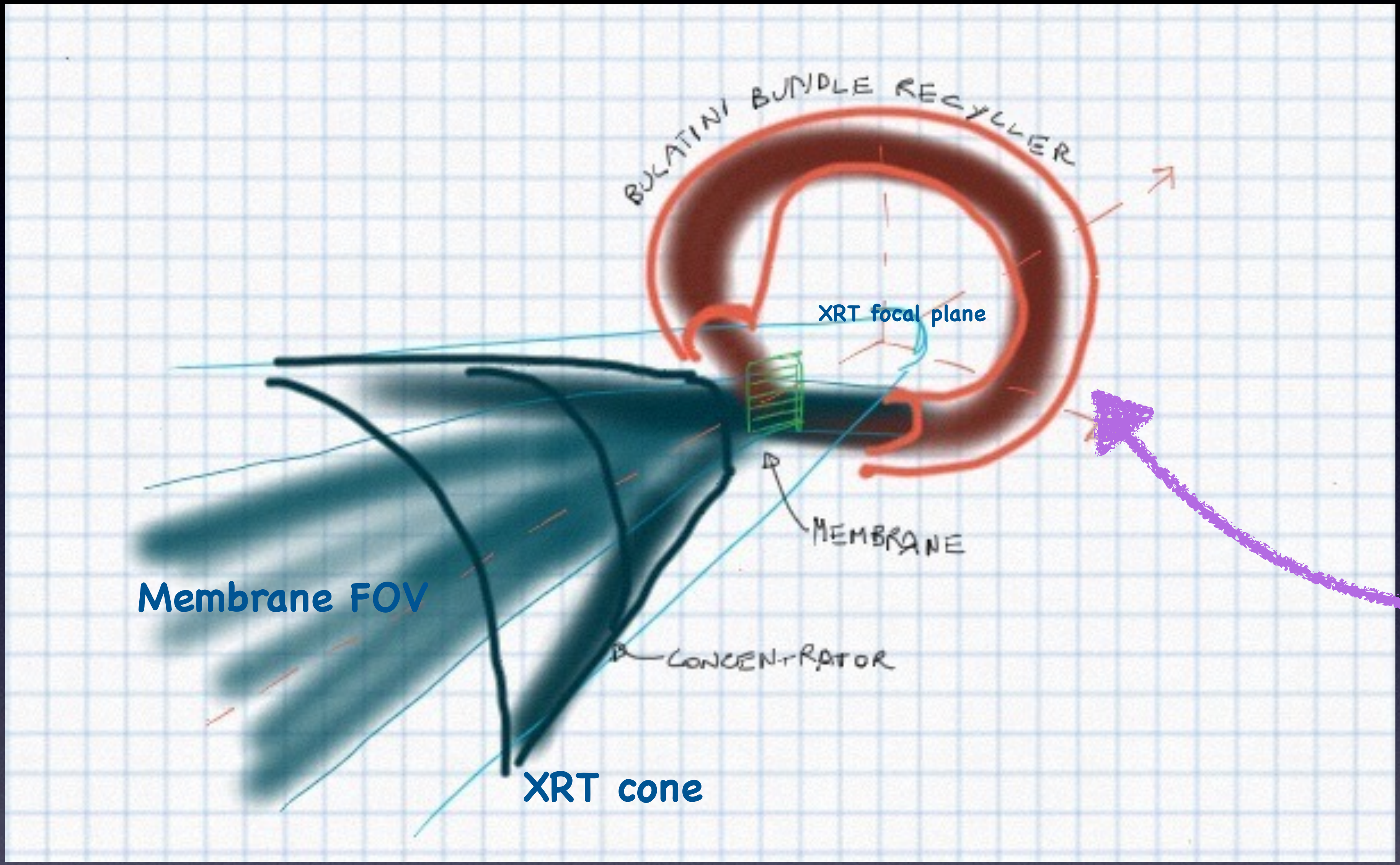
balanced photodetetctor



"signal" - beam exiting the FP cavity and carrying the information on membrane displacements

(*) from P. Piergentili, "Optical cooling of a mechanical micro-oscillator revealed by homodyne detection", Tesi di Laurea Magistrale, Univ. di Camerino (2013)

Concentrator and "bucatini"-recycler concepts

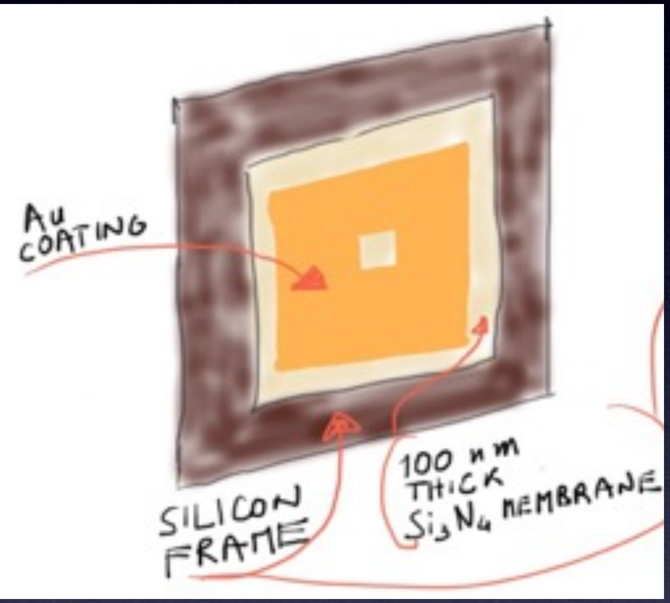


from discussions with K. Zioutas

(*) best if prepared "all'amatriciana"

Membrane customisation

- Membrane design is flexible and can be highly customised during the production stage at a relatively low cost
- Key parameters
  - resonant frequency
  - mechanical quality factor "Q"
  - equivalent spring constant
- Already working on custom prototypes with
  - the company producing membranes (Norcada Inc.)
  - a CERN group expert in thin-layer coatings



Membrane cooling

- Cooling the membrane down to an as low as possible equivalent temperature brings the sensitivity to the ultimate limit
- Cooling takes place in two stages
  - cryogenic cooling: the physical temeprature of the membrane is lowered by standard means, such as contact with a cold finger
  - optical cooling: energy is transferred from thermally excited phonons in the membrane to photons in a laser beam (*)
- **Optical cooling can lower the equivalent temperature by a factor of 1000**
  - the mK range is accessible starting from LHe cryo-cooling at 4 K

(*) see for instance M. Karuza et al., New Journal of Physics, 14(9) (2012)

Conclusions

- KWISP completed the **first ever** solar tracking run searching for solar Chameleons with a force sensor
  - week-long run done with a stable, but reduced-sensitivity setup
  - analysis is in progress
- We move now towards a second generation sensor
  - optimized detector design optimized to adequately counter noise in the CAST experimental hall
  - better designed mechanics and vacuum enclosure
  - upgraded laser and optical components
  - homodyne detection technique
- CAST took a **small step** in DE energy territory… perhaps **giant leap** is just around the corner!

Thank you!

Suggestions for further reading

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

G. Cantatore, M. Karuza and K. Zioutas, Cern Courier January-February 2016
for a general introduction to the CAST physics program

M. Karuza, G. Cantatore, A. Gardikiotis, D.H.H. Hoffmann, Y.K. Semertzidis, K. Zioutas, Physics of the Dark Universe, 12 (2016) 100-104
on the performance and calibration of the KWISP force sensor