advanced-KWISP

Investigating short-range interactions at sub-micron scales with an optomechanical sensor

G. Cantatore (Univ. and INFN Trieste)

<u>**also with:**</u>

H. Fischer (Univ. of Freiburg)

A. Garidkiotis (Univ. of Patras)

D.H.H. Hoffmann (TU Darmstadt)

M. Karuza (Univ. of Rijeka and INFN Trieste)

Y.K. Semertzidis (CAPP, Korea)

D.Vitali (Univ. of Camerino)

K. Zioutas (CERN and Univ. of Patras)

S. Zippilli (Univ. of Camerino)

Summary

- The idea
- The force sensor and its key technologies
- KWISP at CAST-CERN
- The *a*KWISP project
- Conclusions

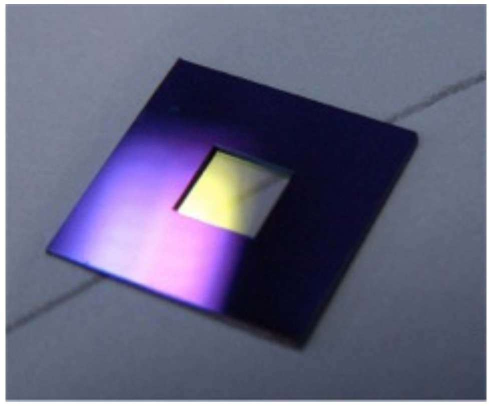
The idea

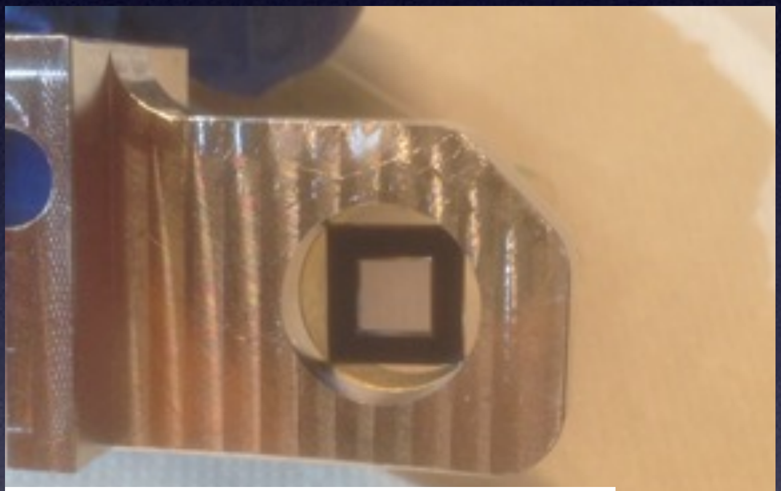
- Build an opto-mechanical device to combine the large quality factors of two resonators and achieve sensitivity to extremely tiny forces and sub-nuclear size displacements
- Use the sensor as a novel and unique particle detector to investigate the dark energy sector at CAST-CERN (KWISP - Kinetic WISP detection)
- Push the sensitivity to the limit by exploiting frontier technologies ⇒ ***a*KWISP**
- Explore with *a*KWISP uncharted territory in short range physics possibly accessing new sectors such extra dimensions, scalar dark matter, moduli, dilatons…

Opto-mechanical force sensors

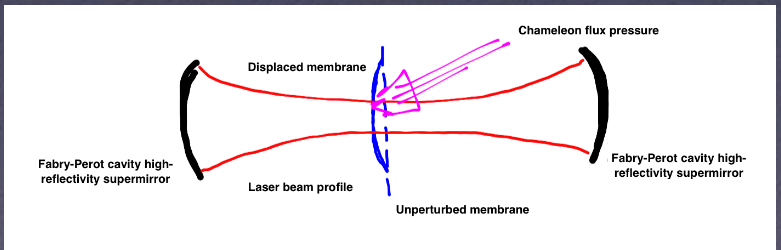
- A nano-membrane (a few 10's of nm thick Si_3N_4) is centred and aligned inside an optical Fabry-Perot resonant cavity
- Membrane displacements in response to an externally applied force shift the cavity mode frequencies
- When a laser beam is frequency-locked to the cavity using a feedback loop, the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





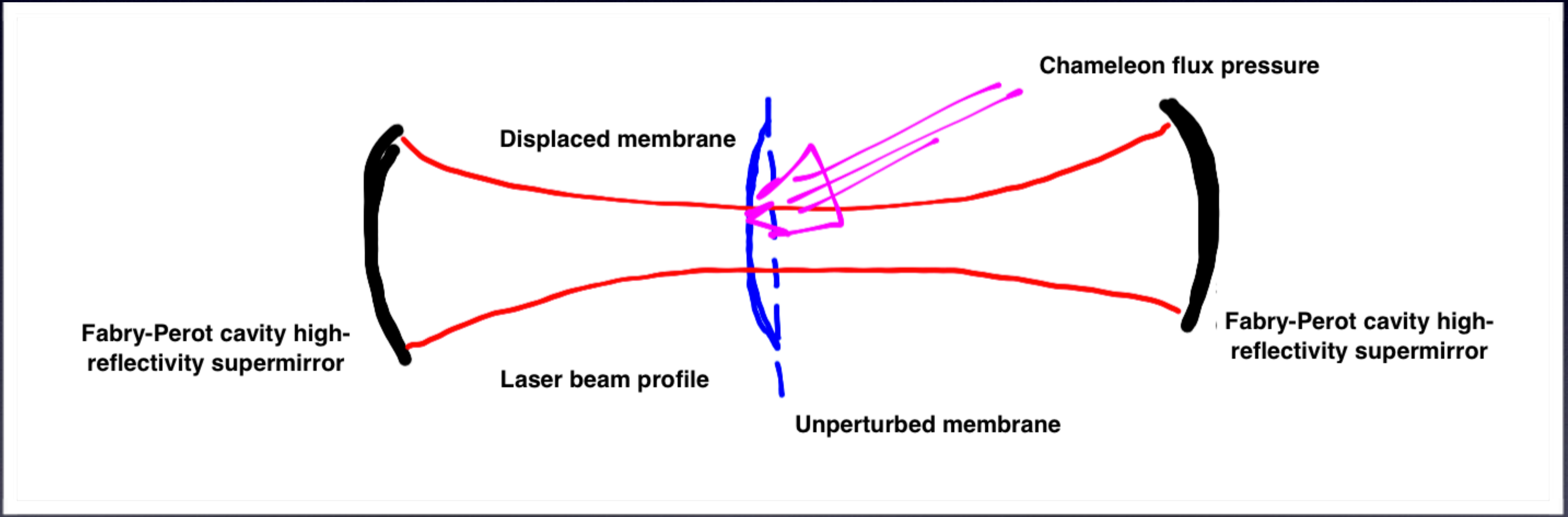
(5 mm)x(5 mm) 100 nm thick SiN_4 nano-membrane set inside its holder



KWISP timeline

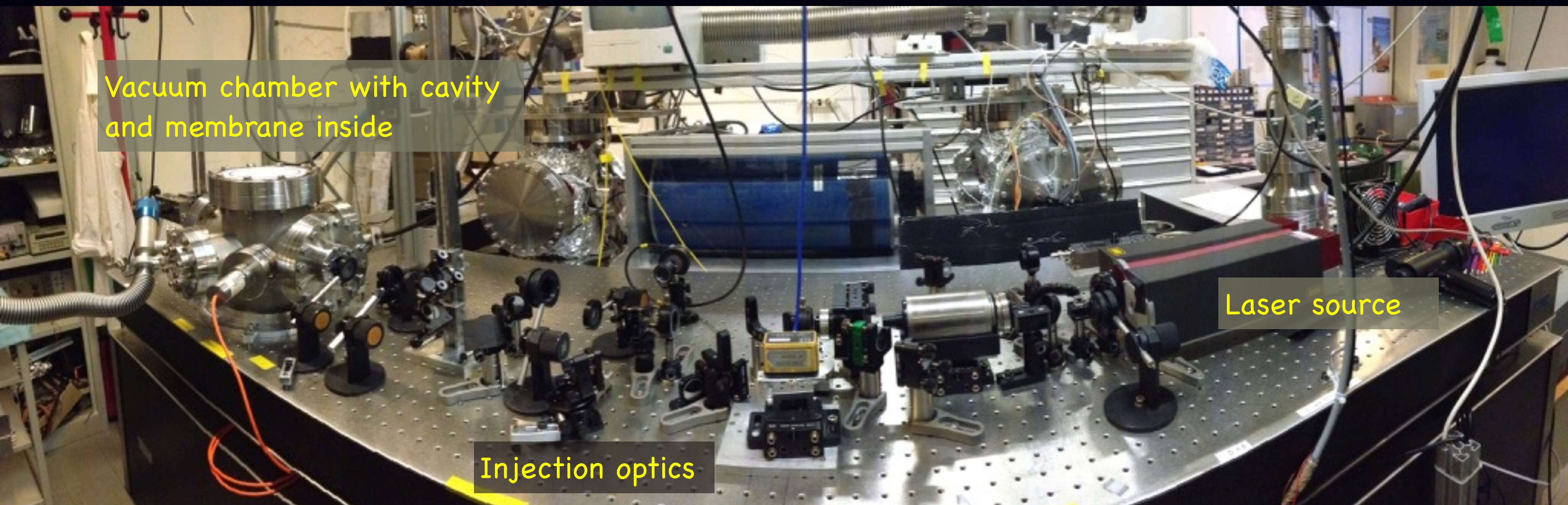
- Prototype sensor built and calibrated in Trieste with the original “pump beam” setup
- Sensor cloned at CERN and now in use in the CAST experiment as a novel detector for astroparticle physics

KWISP force sensor cartoon

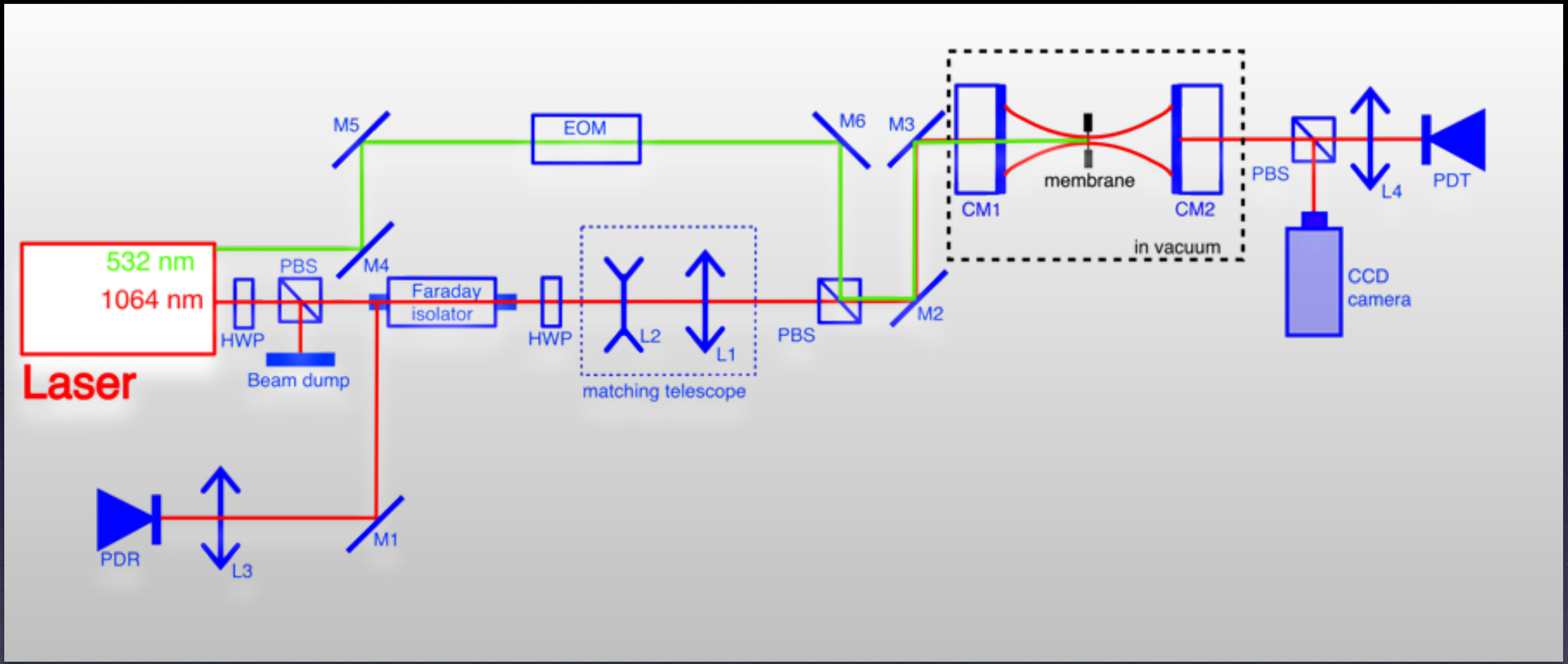


5x5 mm^2 Si_3N_4 membrane

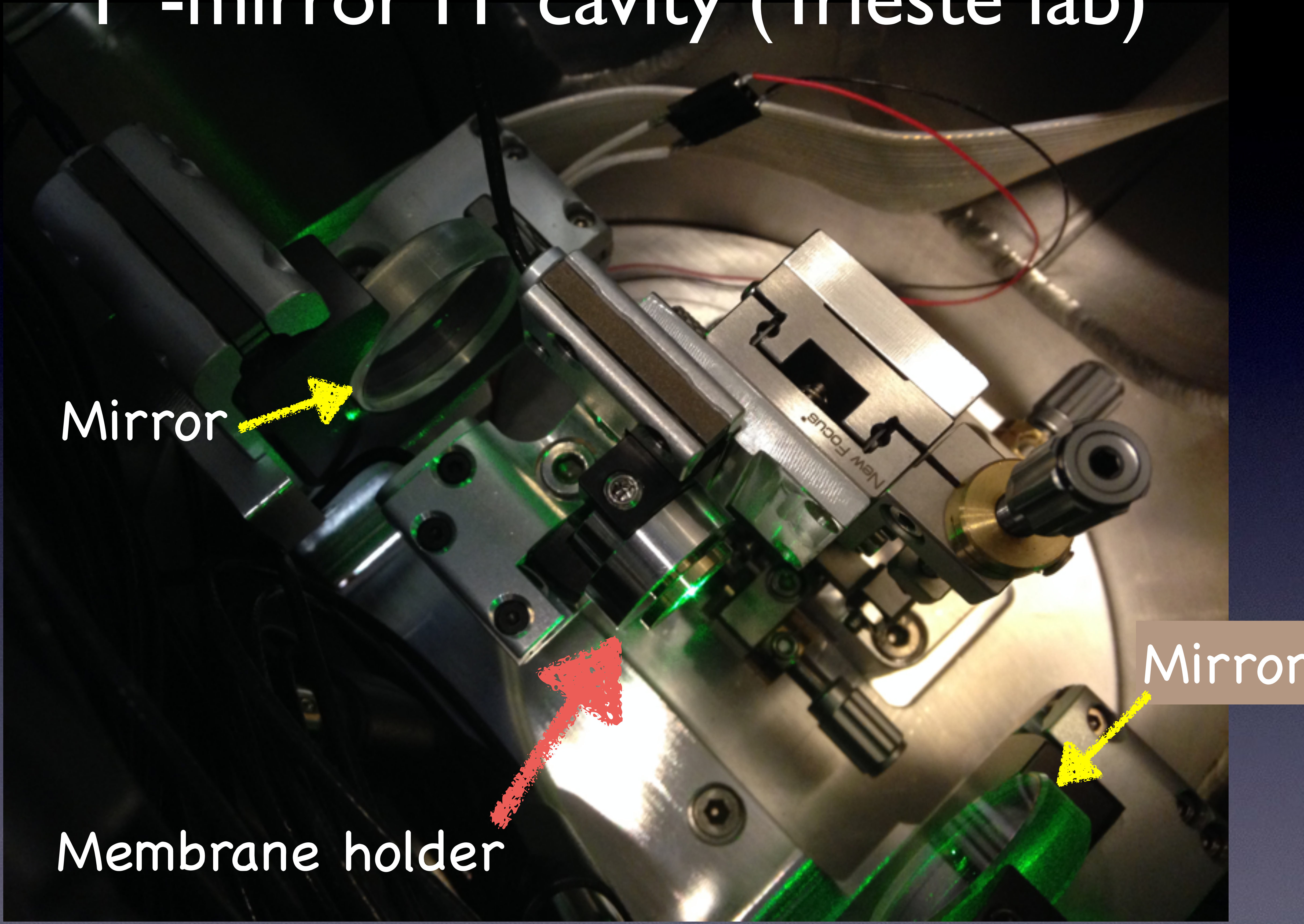
Trieste optical bench panorama



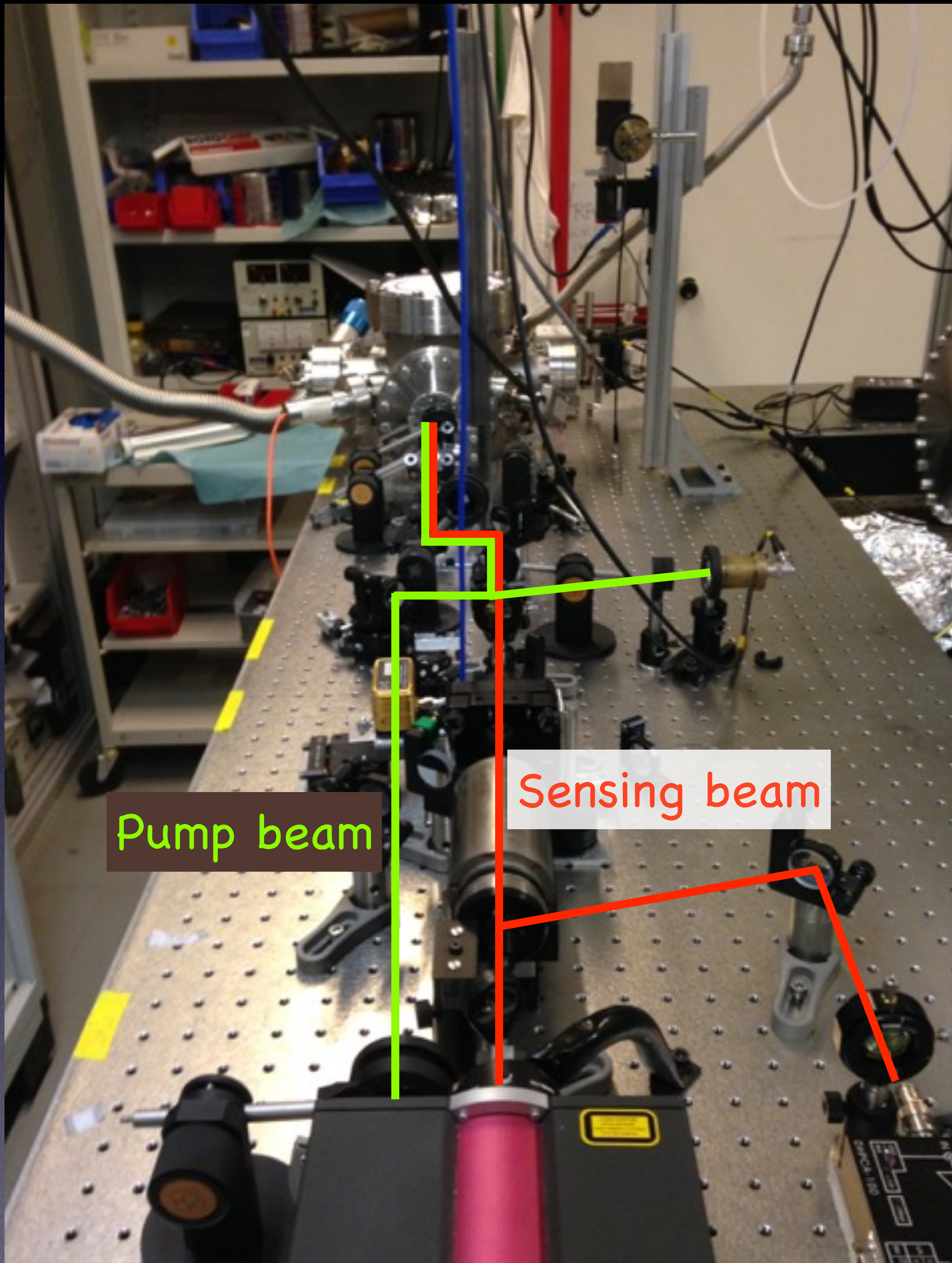
KWISP optics layout

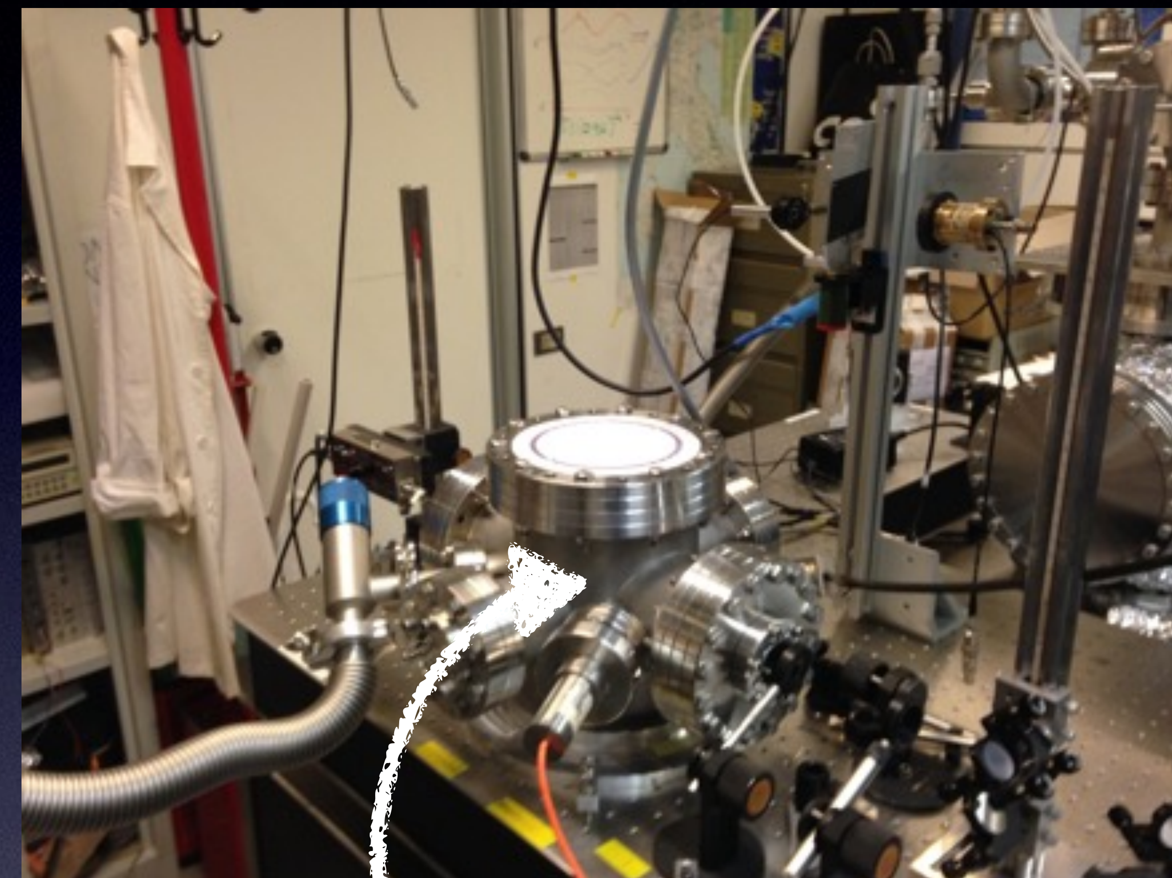


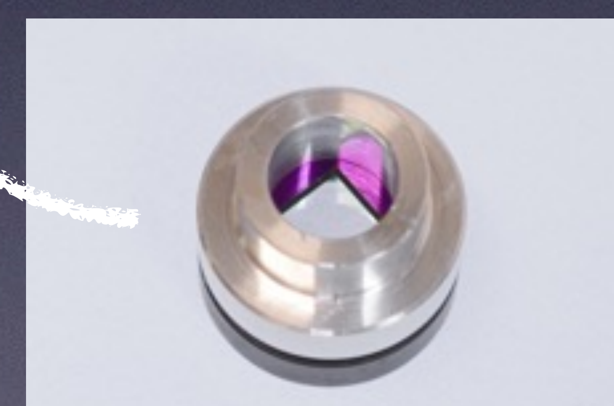
1”-mirror FP cavity (Trieste lab)



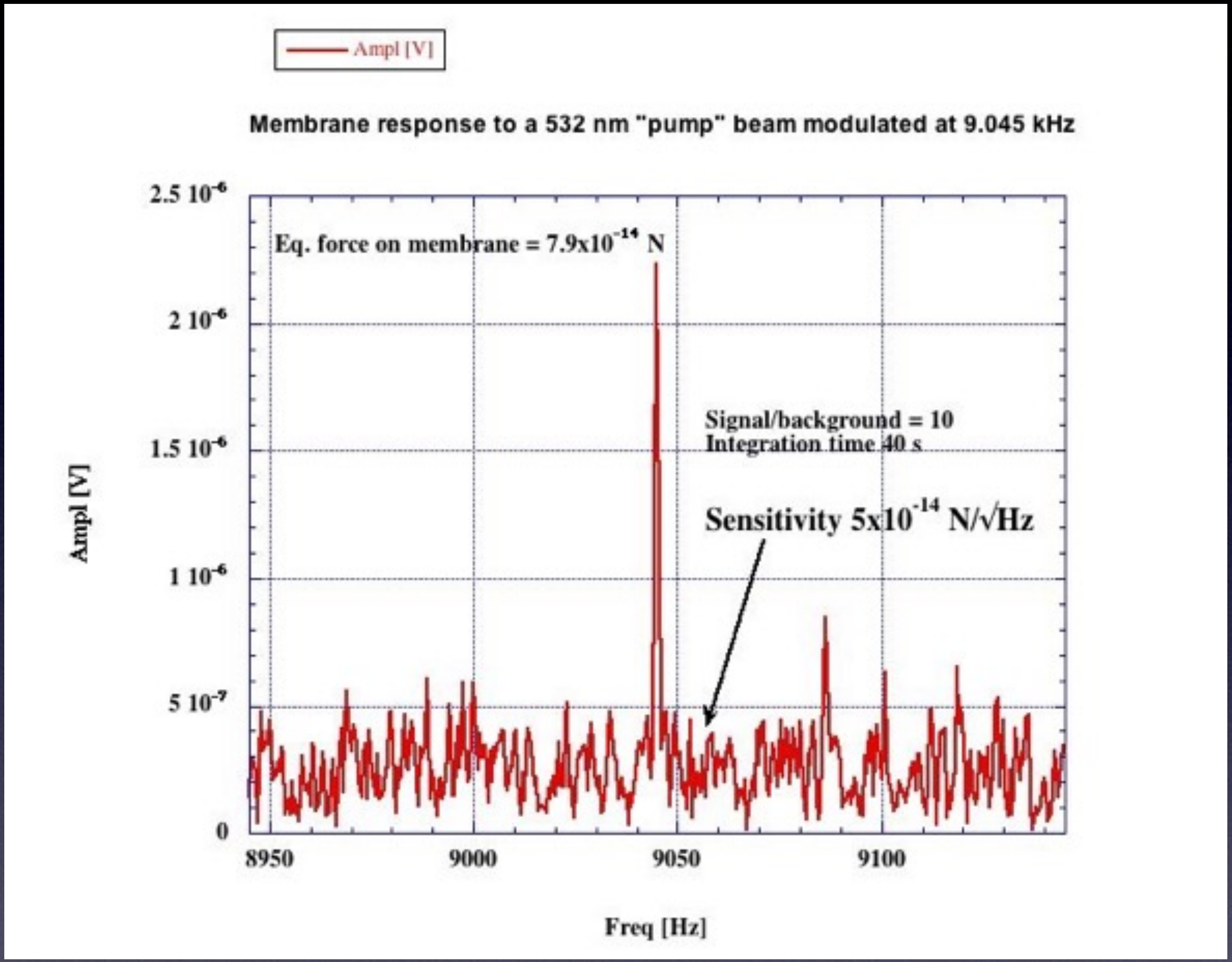
Two-beam setup







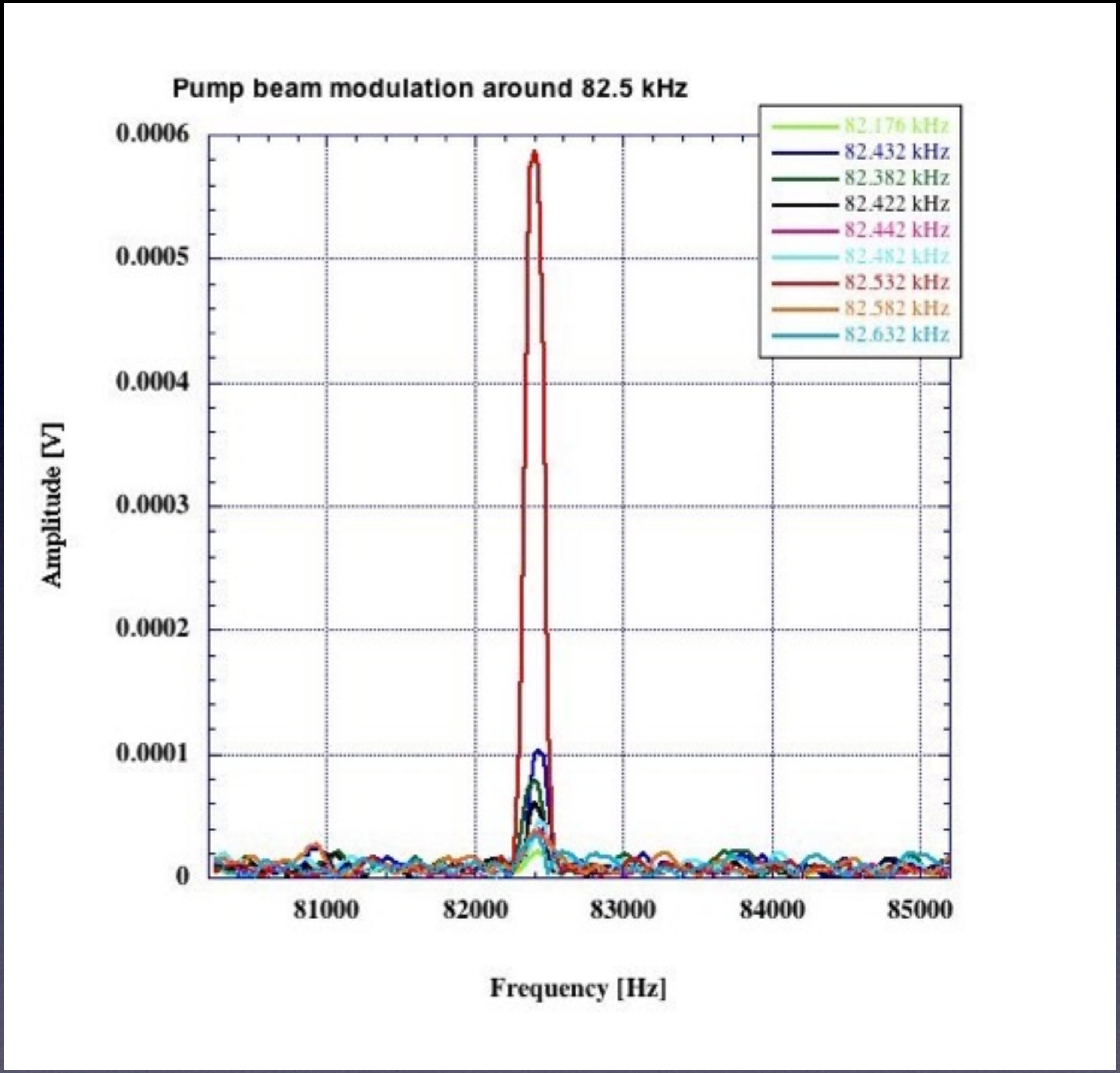
Direct force calibration of KWISP sensor with 532 nm pump beam



- 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

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

Sensor running in Trieste

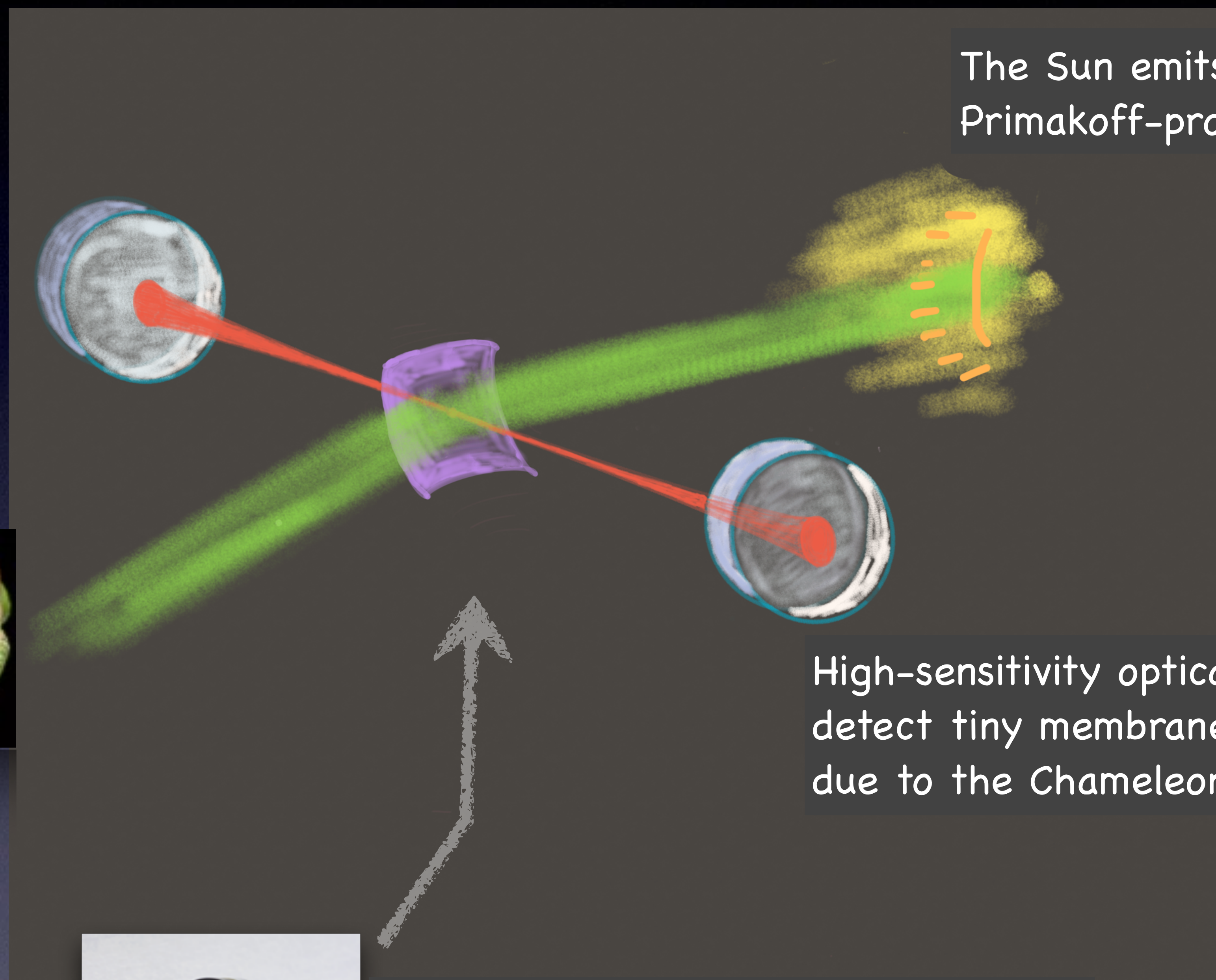
- Summary of the results from the KWISP sensor running in the INFN Trieste Laboratory
  - absolute force calibration of the sensor with the "pump beam" technique
  - preliminary measurements of the membrane resonant frequency and mechanical Q with the "pump beam" technique
  - **sensitivity results**:

Off-resonance: S_{f}, off-res. = $5.0 \cdot 10^{-14}$ N/√Hz ($2.5 \cdot 10^{-15}$ m/√Hz in terms of displacement)

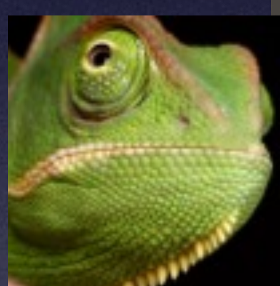
On-resonance: S_{f}, on-res. = $1.5 \cdot 10^{-14}$ N/√Hz ($7.5 \cdot 10^{-16}$ m/√Hz in terms of displacement)

- Note:
  - **The on-resonance sensitivity is already at the 300 K thermal limit.**
  - Displacement sensitivities are comparable to those achieved at large gravitational wave interferometric detectors
  - Designed and built prototype chameleon chopper for “trial” solar runs
  - Results are published in
    - Physics of the Dark Universe, 12 (2016) 100-104
    - arXiv:1510.06312

The KWISP particle detector 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

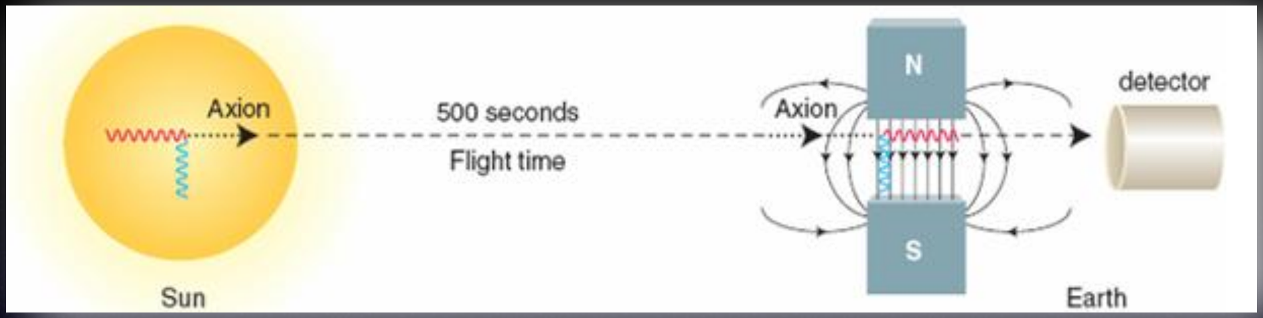
Curious? See January-February 2016 CERN Courier http://cerncourier.com/cws/article/cern/63705

CAST at CERN

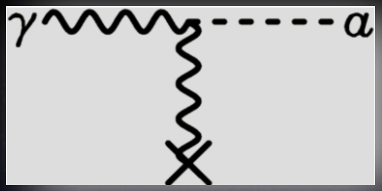
- 21 institutes, 48 authors, 12 countries…
- Probing the mysteries of the Universe since 2003 !!!

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

Magnetic helioscope principle



Primakoff production



$$L_{eff} = g_{a\gamma\gamma} \left(\vec{\mathbf{E}} \cdot \vec{\mathbf{B}} \right) a$$

- Axion production in the sun
    - Axions are produced by the Primakoff process in hot solar core and stream out freely reaching the Earth
    - Combining the details of Primamoff production in the solar plasam with the knowledge coming from the Standard Solar Model allows the prediction of the expected spectrum of the solar axion flux at Earth’s surface
- Solar axion detection on Earth
    - A magnetic field reverses Primakoff production turning axions back into photons
    - Converted photons carry the same momentum and energy of the original solar axions
    - Photon counters detect an excess of photons at the expected energies
- Possible results
    - **An excess of photons is seen: great discovery!!!!** (Excess photons must match predicted spectrum of course...)
    - No excess of photons is detected: the background counting rate combined with the calculated flux yields an upper bound on the axion-photon coupling

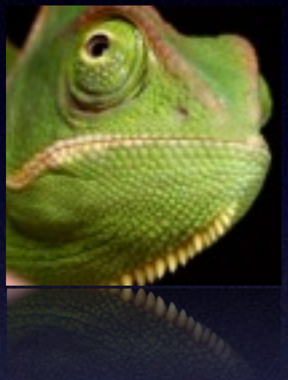
The new CAST physics program

- 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

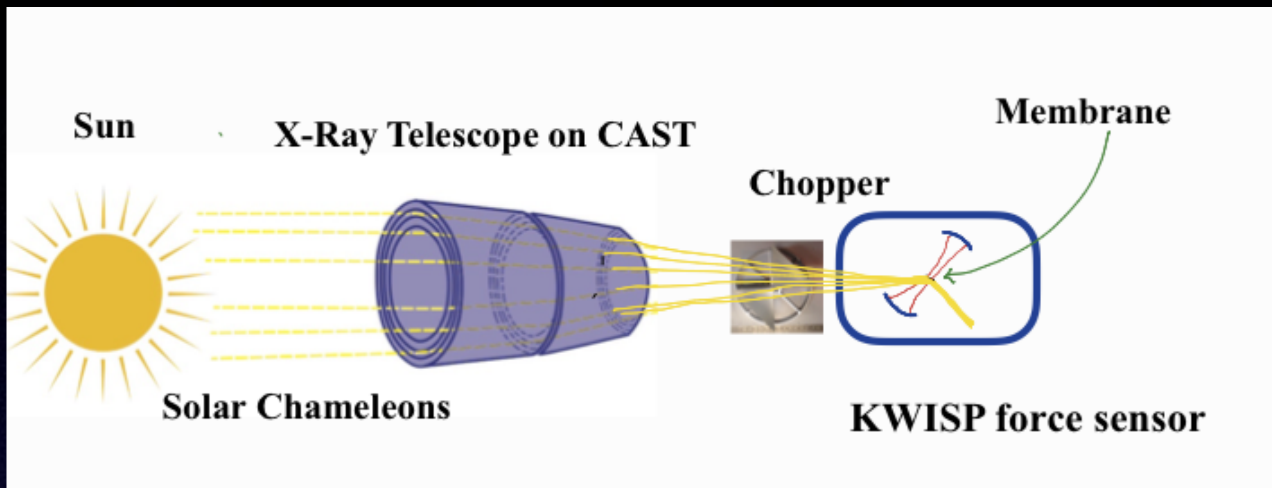
Chameleon searches at CAST

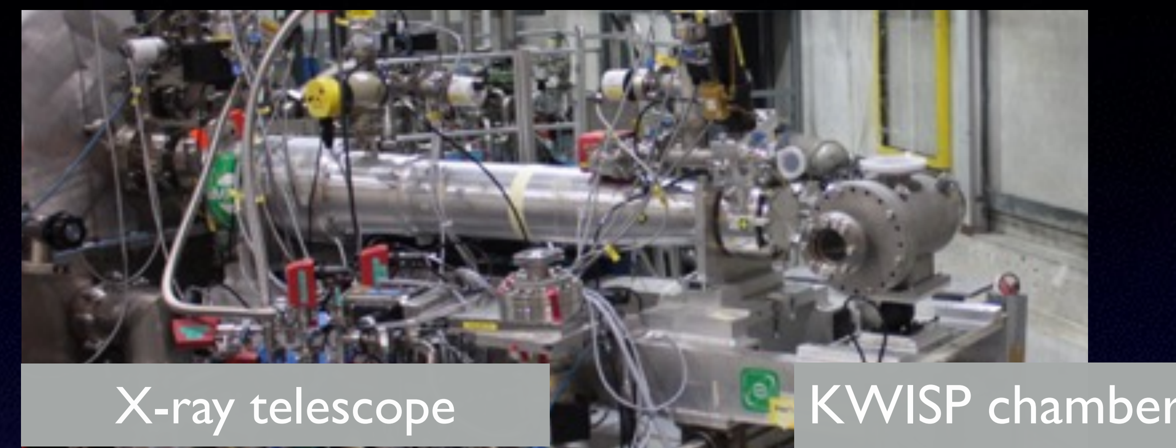
- Chameleons are a type of scalar WISPs having an effective mass dependent on the local energy density. Solar Chameleons are Primakoff-produced inside the magnetic field of the Sun and then stream to Earth



- 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

KWISP at CAST



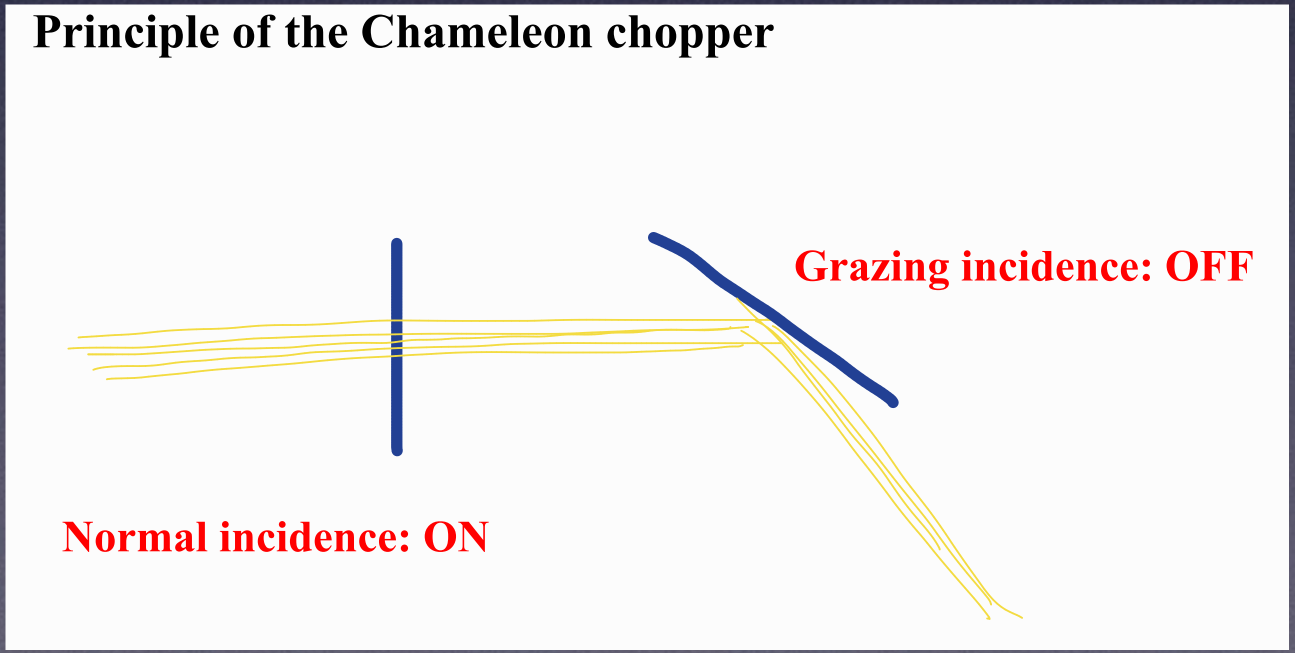


Key KWISP technologies

- Enabling technologies
  - Resonant optical cavity & membrane
  - Pump beam, membrane resonance and Q
  - Chameleon chopper: flux modulation and phase-locking for unique particle detection and identification
  - X-ray telescope
- Upgrading technologies
  - Chameleon concentrator and recycler
  - homodyne detection
  - membrane customisation
  - membrane cooling

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**



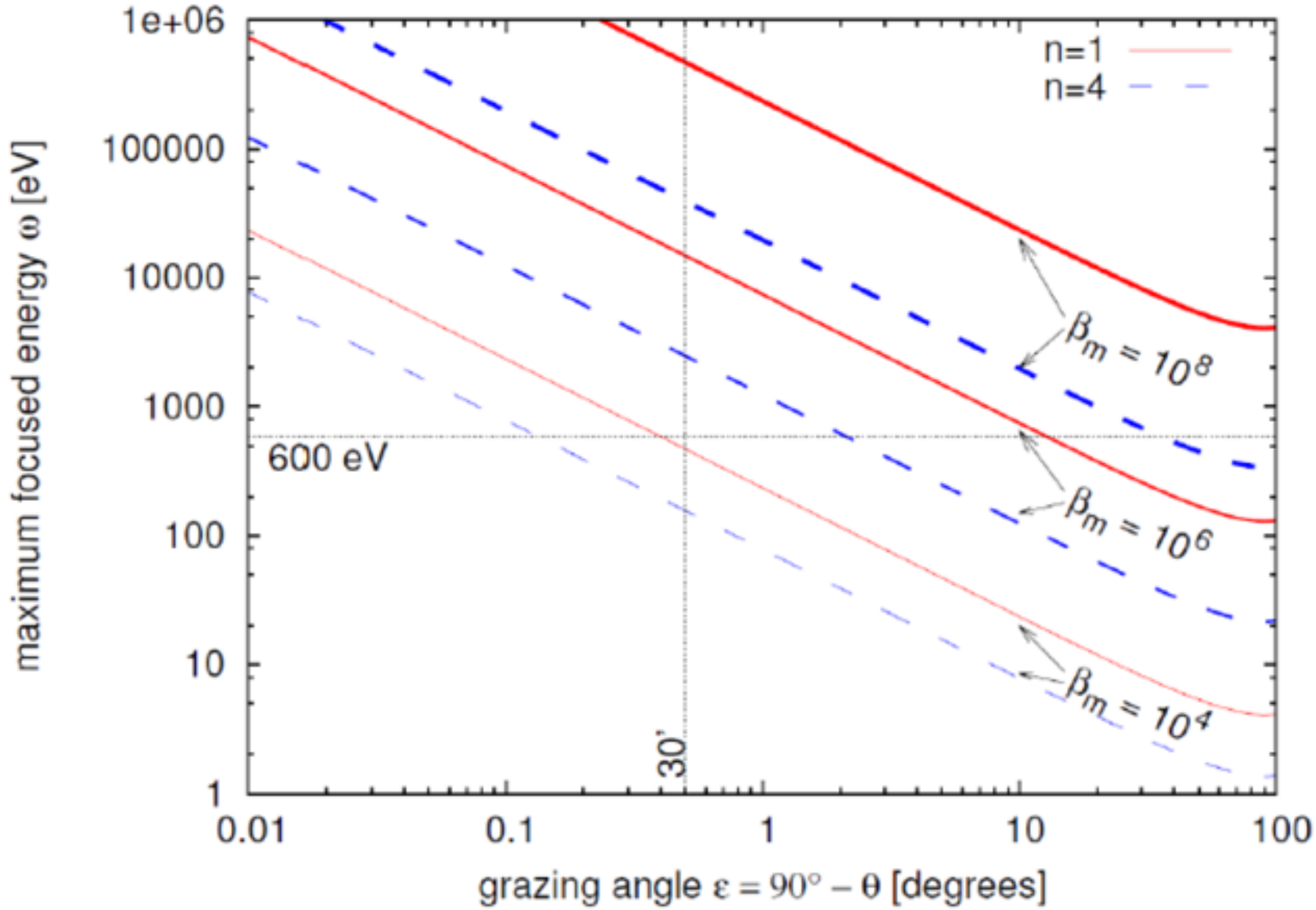


Figure 2 Maximum energy at which a chameleon particle can be focused by an X-ray mirror with density 10 g/cm^3 (≈ the density of a Ni-coated X-ray telescope) and grazing angle ε, for several different chameleon models. The dotted horizontal and vertical lines illustrate one example of a 600 eV chameleon 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

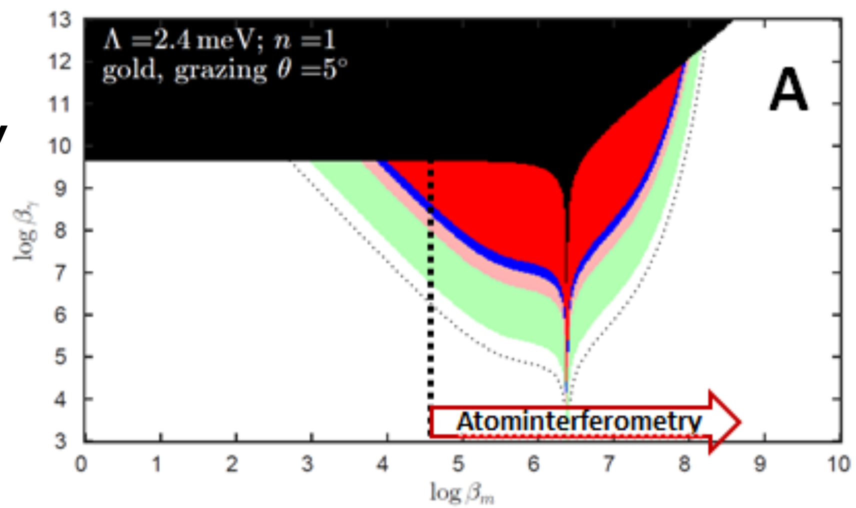
Slide courtesy of K. Zioutas

KWISP physics reach in the DE sector

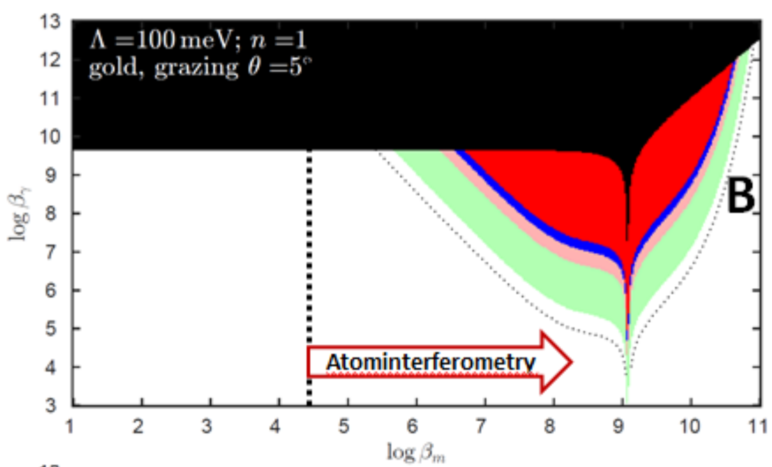
- Main competition: "atom interferometry" (note: different technique, relies on virtual chameleons)
- Comparison heavily dependent on choice of Chameleon potential parameters

choice of Λ

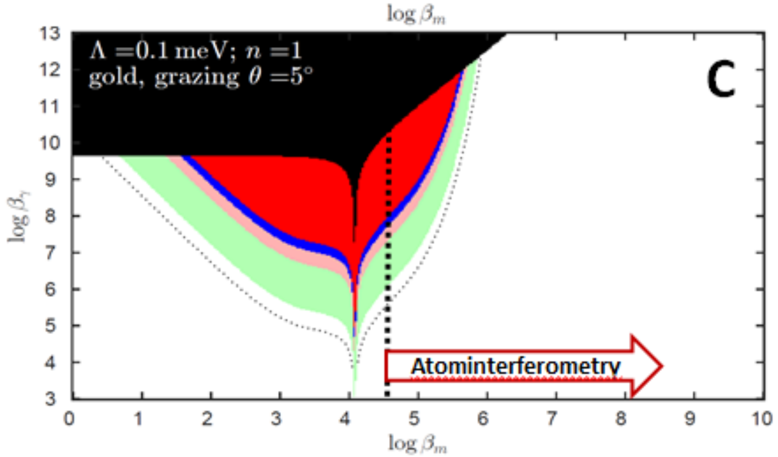
Λ = 2.4 meV



Λ = 100 meV

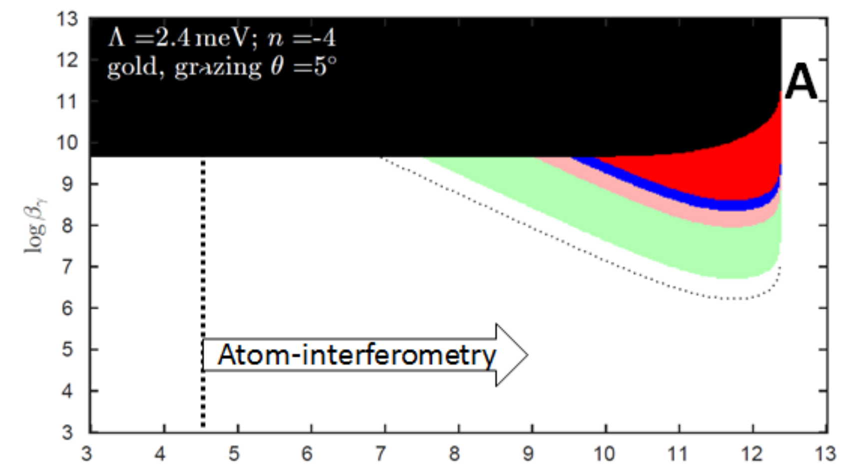


Λ = 0.1 meV

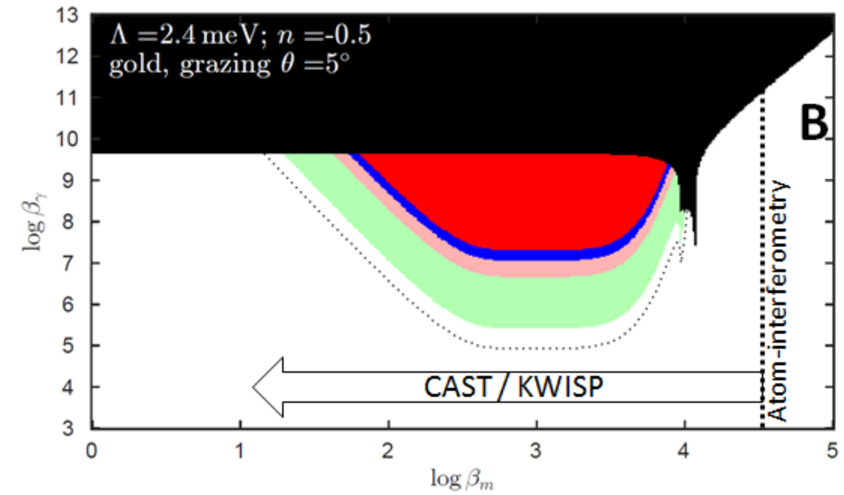


choice of n

n = -4



n = -0.5



Red: 300K, off resonance, force sensitivity $5 \cdot 10^{-14}$ N/√Hz, T = 10^4 s
Blue: 300K, near resonance force sensitivity $1.5 \cdot 10^{-14}$ N/√Hz, T = 10^4 s
Light pink: 300K case assuming Q = 10^5, T = 10^4 s
Light green: projected force sensitivity of $8 \cdot 10^{-18}$ N/√Hz at 30mK, T = 10^4 s

Dotted line: projected 30 mK case with T = 10^6 s

Solar Chameleon production

- Chameleons are a type of scalar WISPs have an effective mass depending on the local matter density
- This makes them candidate constituents for the Dark Energy and allows evading constraints on short range interactions fixed by "fifth-force" measurements.
- Chameleons couple
  - to two photons (Primakoff effect inside a magnetic field)
  - directly to matter (no magnetic field needed)
- To estimate the spectrum of the Chameleon flux emitted by the sun one can assume that production takes place in the solar tachocline region, with a 30 T magnetic field inside it, then linearly decreasing outside.
- In short:
  - Chameleons are produced in the solar magnetic field from the conversion of photons (coupling β_γ)
  - they propagate unhindered to Earth
  - under specific conditions Chameleons interact directly with matter (coupling β_m), in particular by reflecting off a suitable surface

matter coupling

photon coupling

$$V_{\text{eff}}(\phi) = \frac{\Lambda^{4+n}}{\phi^n} + e^{\frac{\beta_m}{M_{\text{Pl}}}\phi}\rho_m + e^{\frac{\beta_\gamma}{M_{\text{Pl}}}\phi}\rho_\gamma,$$

Effective potential

matter coupling

local matter density

$$m_{\text{eff}}^2 = (n+1)\frac{\beta_m \rho_m}{M_{\text{Pl}}}\frac{1}{\phi_{\text{min}}}.$$

Effective mass

solar magnetic field

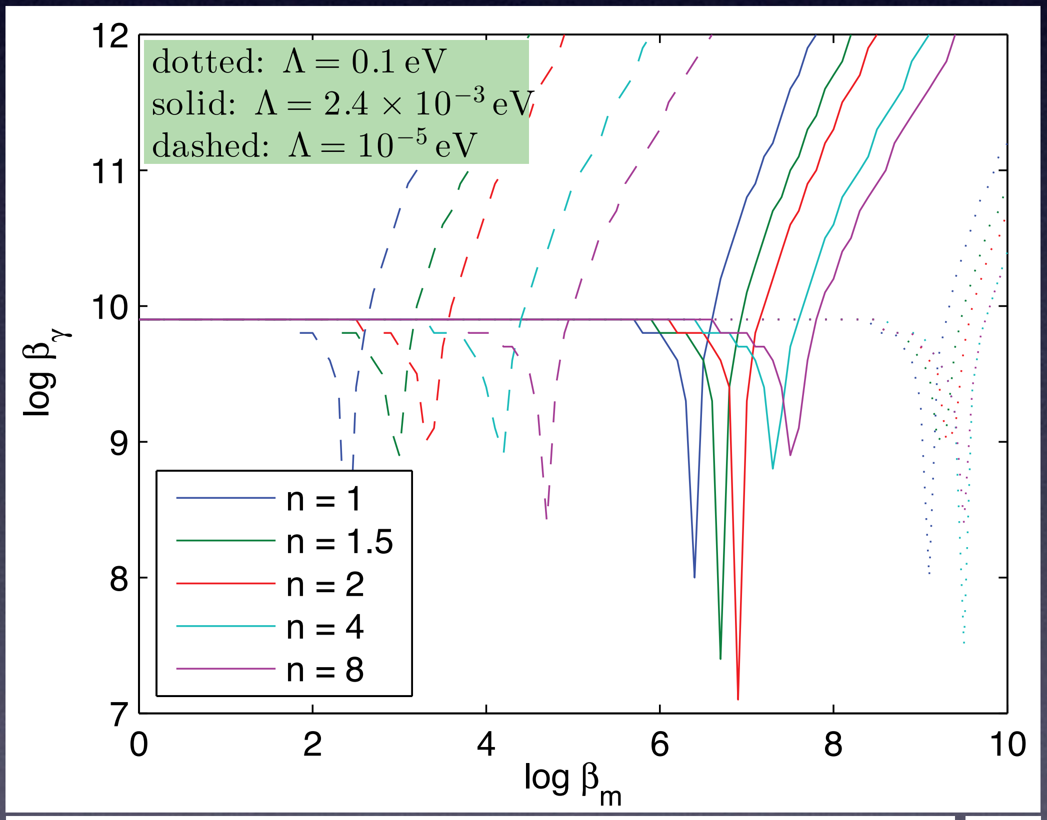
photon coupling

$$P_{\text{chameleon}}(\omega) = 2\theta^2 = 2\left(\frac{\omega B \beta_\gamma}{M_{\text{Pl}}\left(m_{\text{eff}}^2 - \omega_{\text{pl}}^2\right)}\right)^2.$$

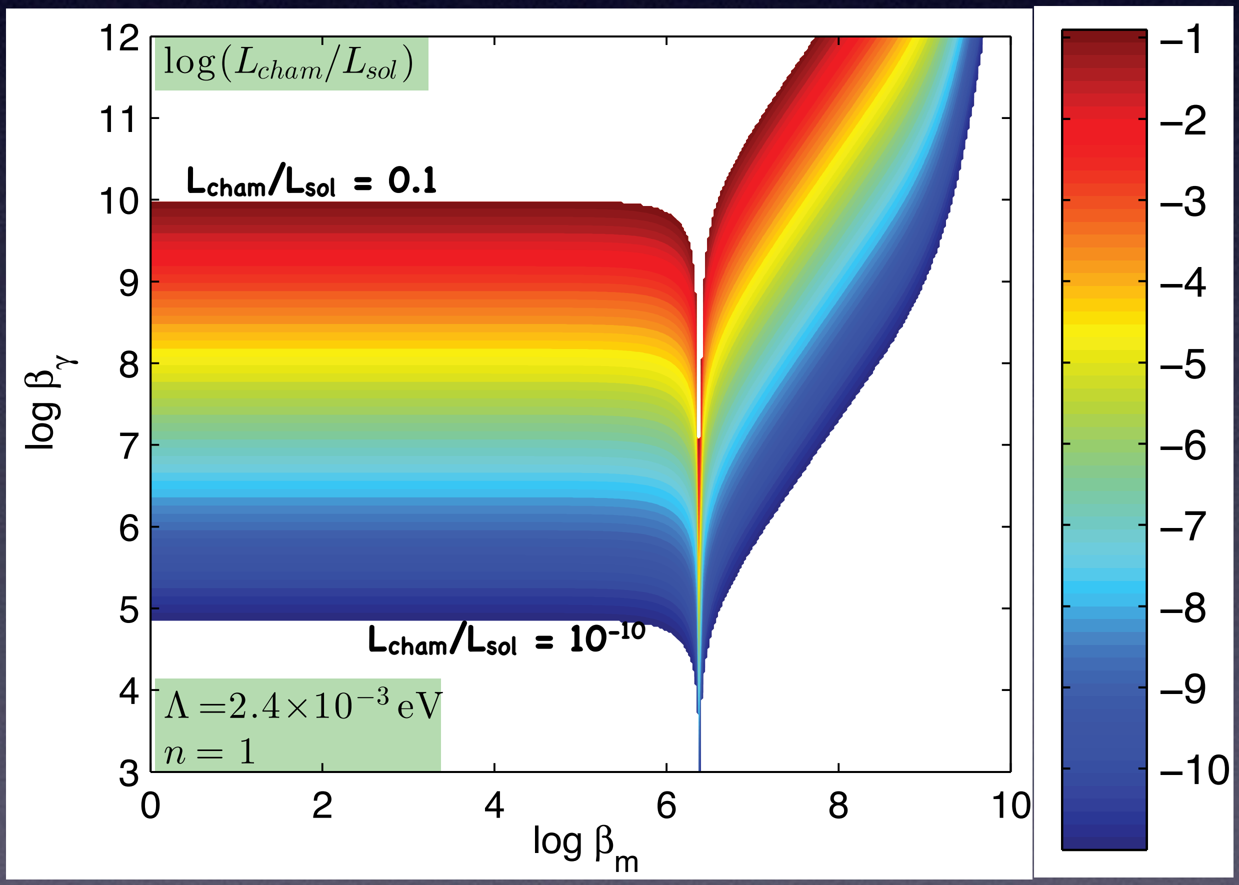
Photon-chameleon conversion probability assuming production in the solar tachocline

Relationship between β_γ and β_m

- The two couplings β_γ and β_m are not independent. Their particular numerical relationship is dictated by the fraction of the total solar luminosity which is emitted as Chameleons
- This fraction can be at most 10% in order to preserve observations on solar age and evolution

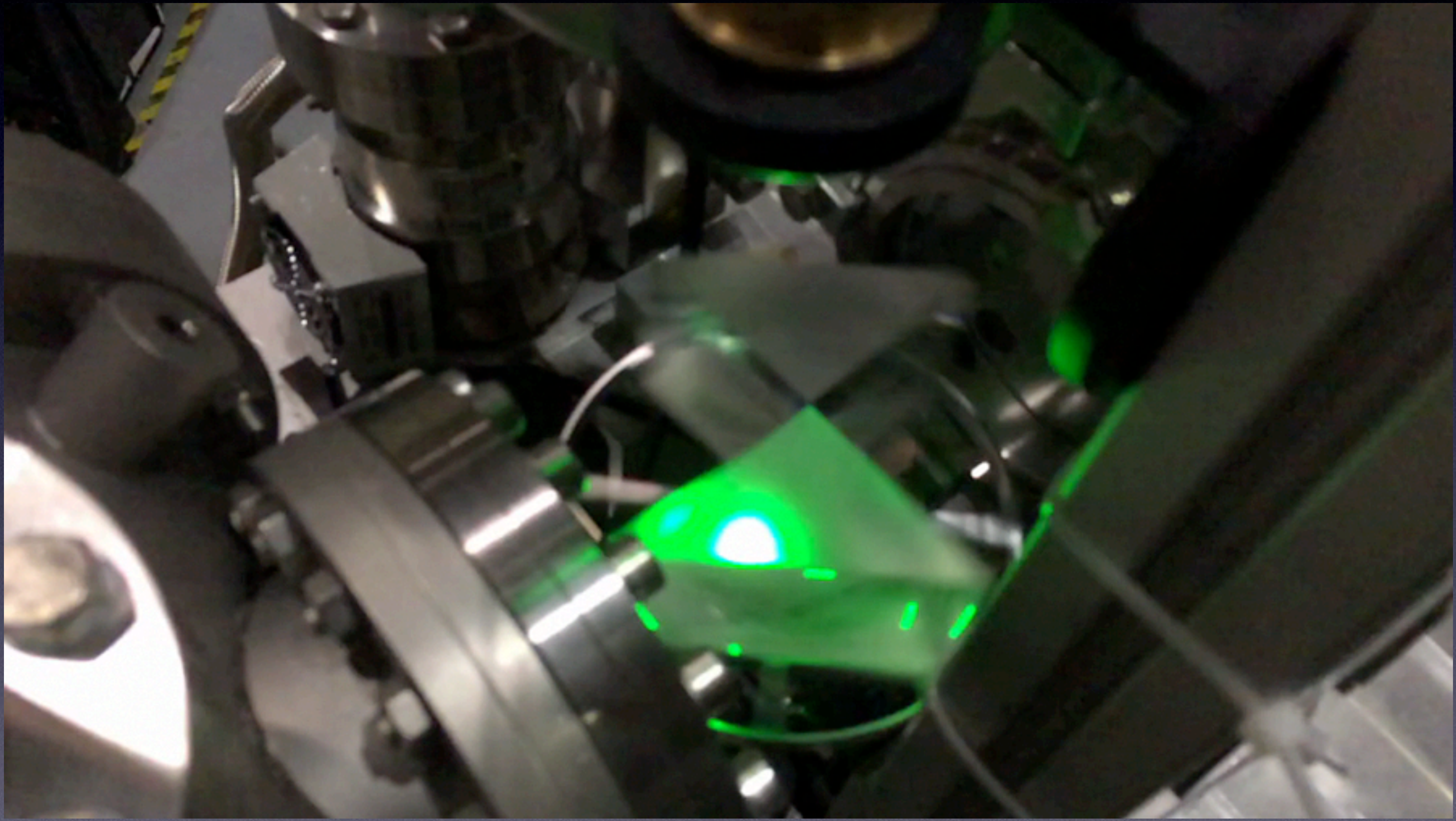


β_γ as a function of β_m for L_{cham}/L_{sol} = 0.1 and for different choices of the potential parameters. The resonance appears when $m_{eff} \sim \omega_{plasma}$

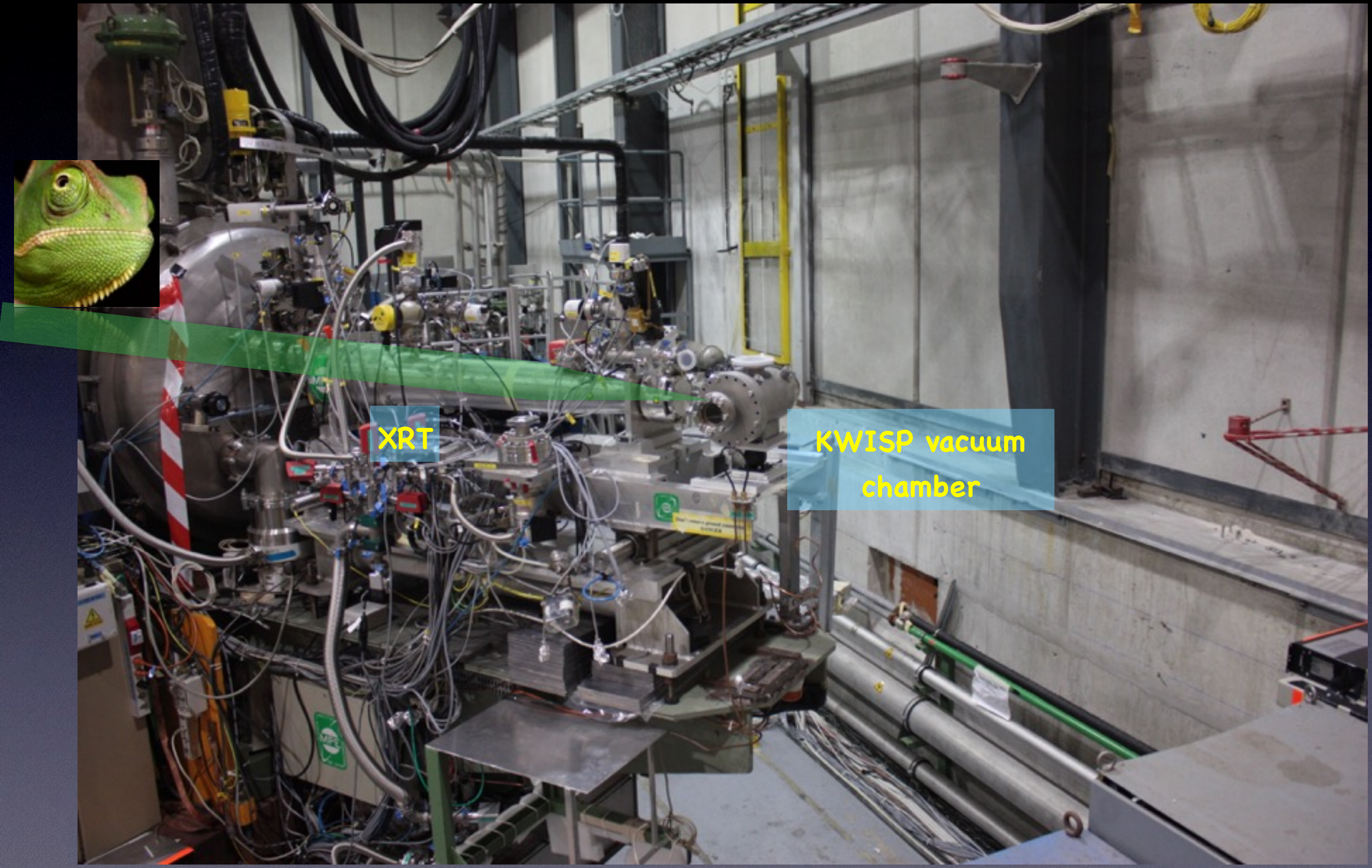


β_γ as a function of β_m for several values of L_{cham}/L_{sol}. n = 1 and Λ = 2.4x10^{-3} eV (dark energy scale) have been set in the potential. The resonance appears when $m_{eff} \sim \omega_{plasma}$

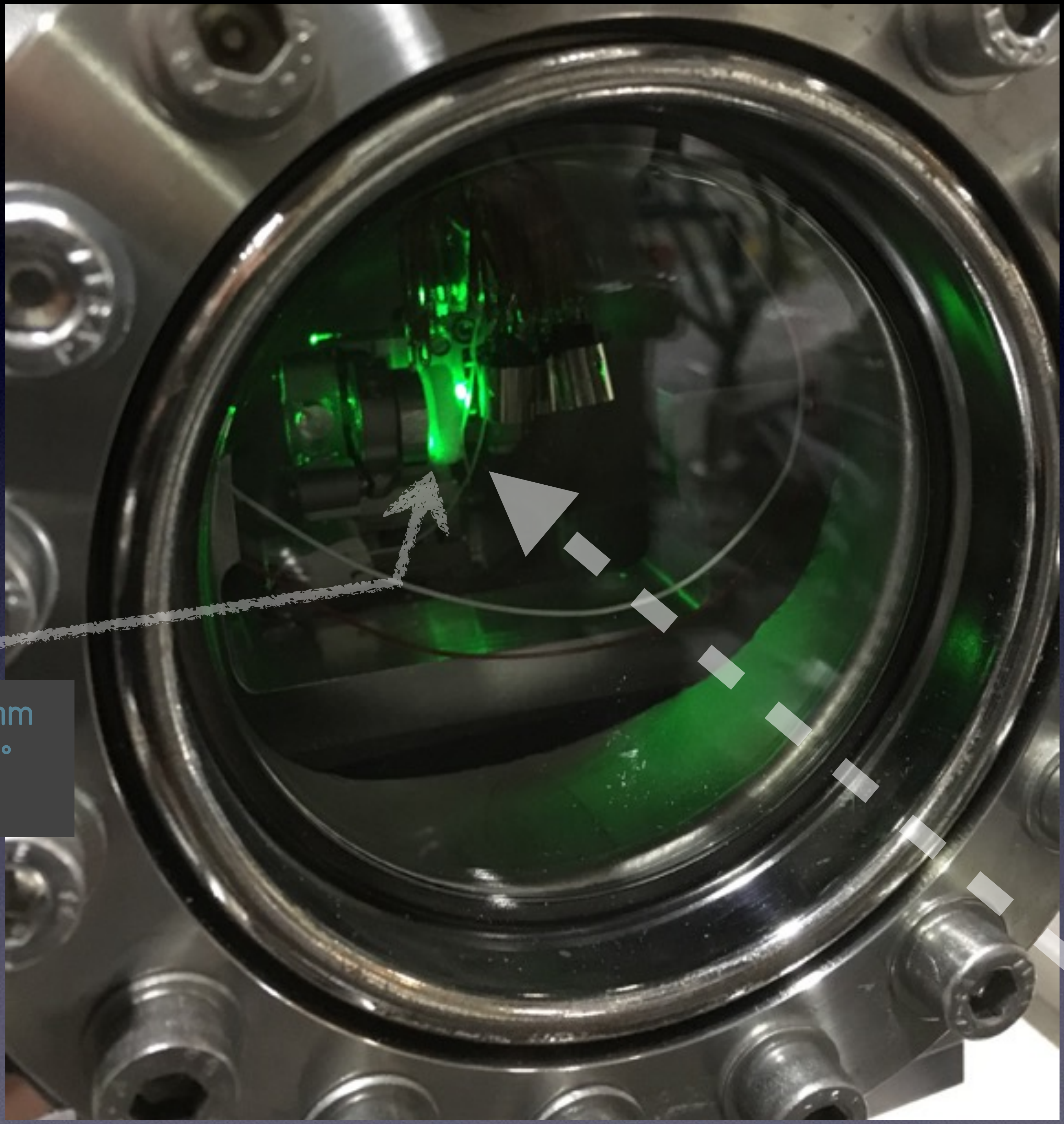
Chameleon chopper slow motion

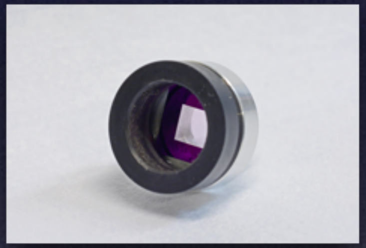


KWISP gallery I

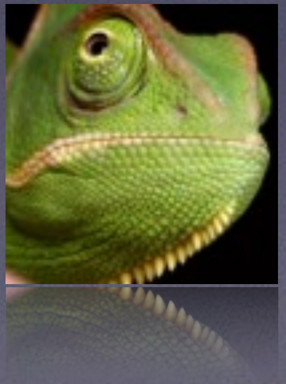


KWISP seen by Chameleons …



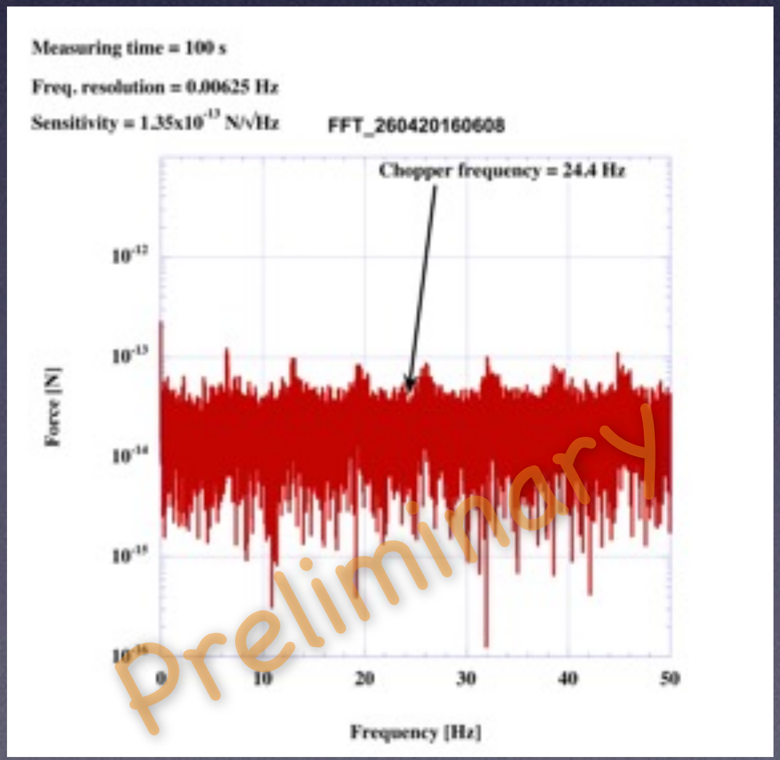


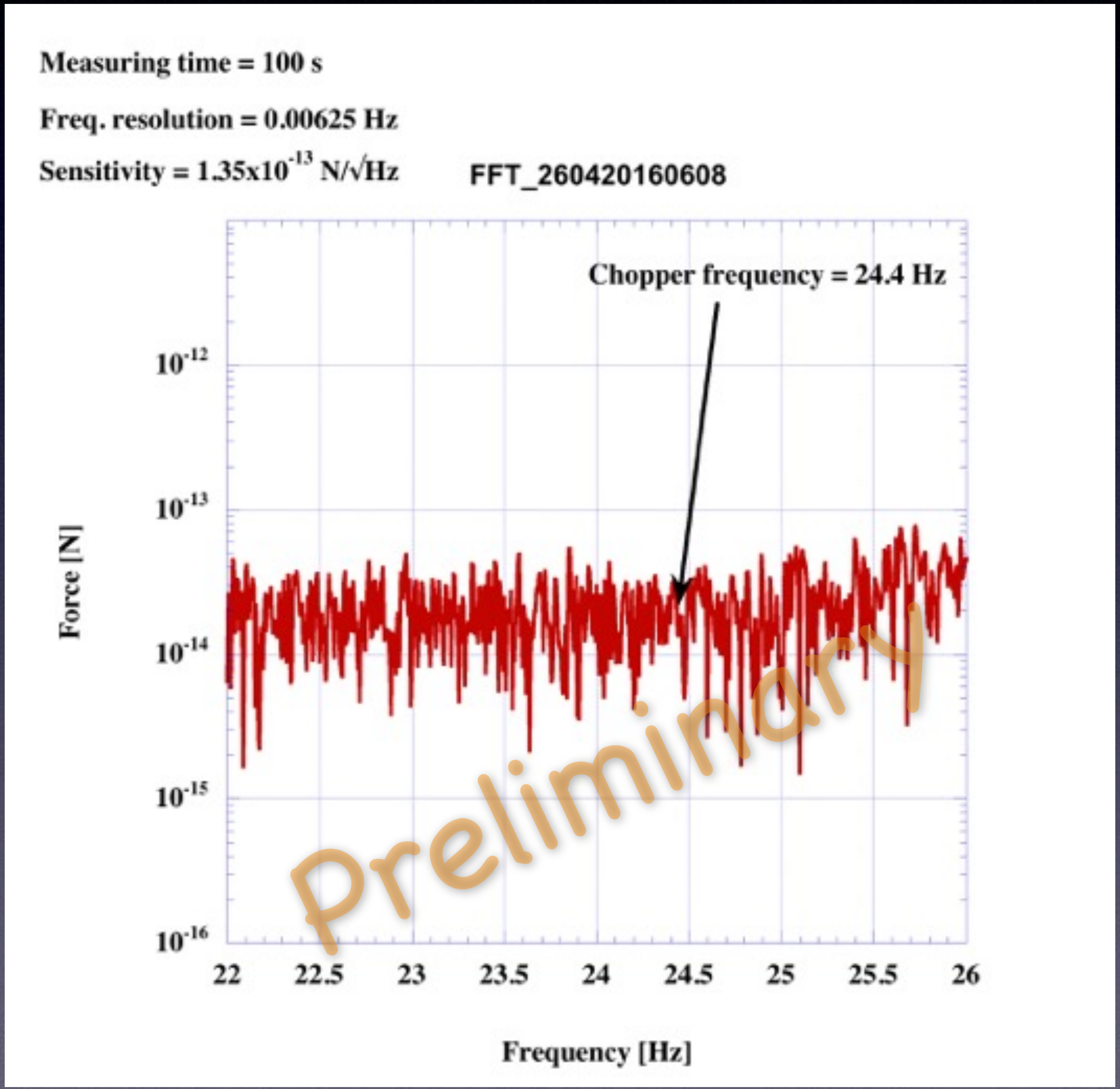
5x5 mm^2 Si_3N_4, 100 nm thick membrane at 5° incidence angle



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





April 2016 KWISP solar run at CAST

- **First data run ever with a force sensor looking for solar Chameleons**
- Bad news
  - preliminary run done with reduced sensitivity Michelson setup
  - chopper version 1.0 runs at few Hz chopping frequency
- Good news
  - good physics can be extacted from the data
  - expect first bounds in Chameleon parameter space
  - many lessons learned for the next full-sensitivity run at end of 2016
- 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)

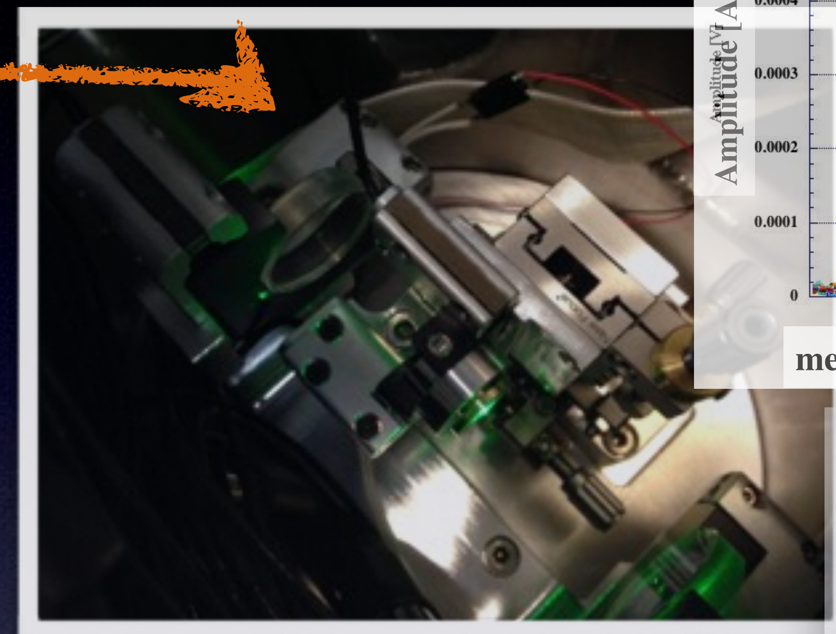
advanced-KWISP

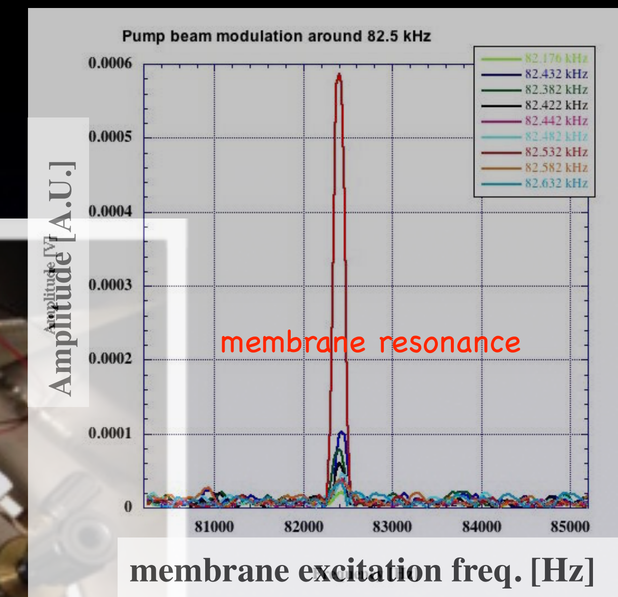
*a*KWISP - *advanced* KWISP

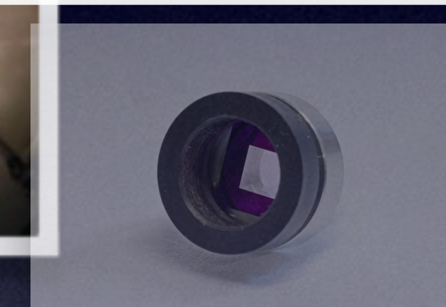
Investigating short range interactions at distance scales below 1 micron

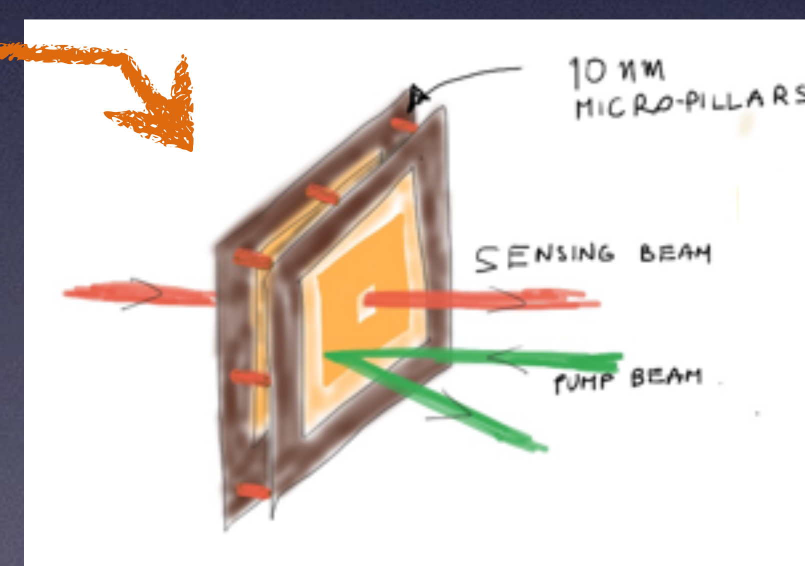
Univ. and INFN Trieste, Univ. of Camerino and INFN Perugia
Univ. of Freiburg, TU Darmstadt, CAPP-IBS (Korea), CERN , Univ. of Patras

- Start from the KWISP (*) force sensor core apparatus
  - membrane-based optomechanical force sensor
  - sensitivity enhanced by the combined quality factors of a mechanical and an optical reosnator
  - sensitive to extremely tiny forces and sub-nuclear size displacements
- Implement advanced technologies to achieve the ultimate sensitivity
  - homodyne detection
  - membrane optimisation
  - cryogenic and laser cooling
- Introduce the **double-membrane concept**
  - two membranes separated by nm-size micropilars acting as **sensing** and **source** masses
  - diffents Q' and resonante frequency
- Attack frontier physics themes
  - extra dimensions
  - scalar Dark Matter (moduli, …)
  - short range interactions: exchange of light elementary particles between pairs of atoms belonging to two macroscopic bodies
  - dilatons
  - …









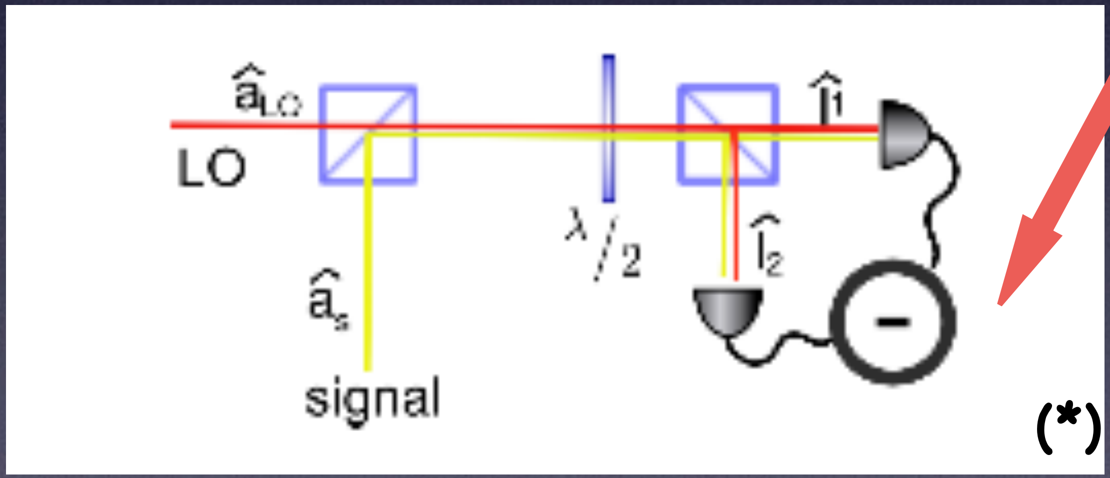
(*) M. Karuza, G. Cantatore, A. Gardikiotis, D.H.H. Hoffmann, Y.K. Semertzidis, K. Zioutas, Physics of the Dark Universe, 12 (2016) 100-104

Direct homodyne detection

- The laser beam is split into two beams:
  - a local oscillator beam
  - sensing beam passing through the FP cavity 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

balanced photodetetctor

local oscllator (LO) directly from the laser

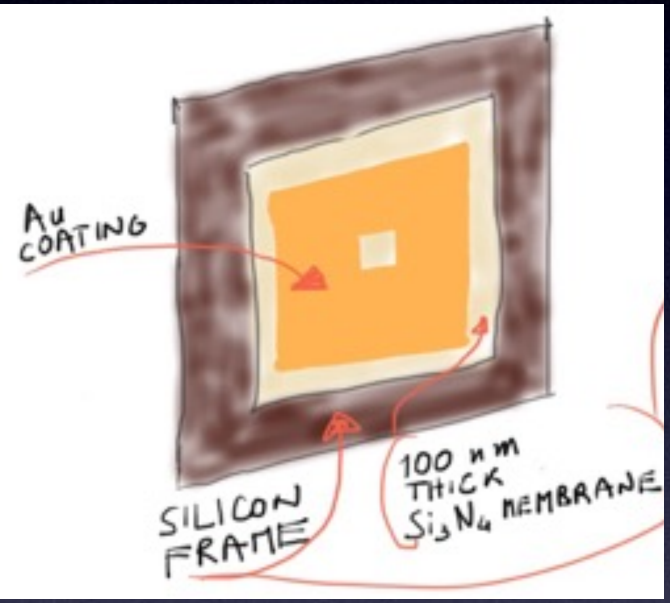


"signal" - beam exiting the FP cavity and carrying the information on membrane displacements

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

Membrane customisation

- Membrane design is flexible and can be highly customised during the production stage at a relatively low cost
- Key membrane parameters
  - resonant frequency
  - mechanical quality factor “Q”
  - equivalent spring constant
- Desirable customisations
  - density
  - spatial distributon of reflectivity
- Already working with
  - Norcada Inc., the company producing the membranes,to design
  - a CERN group specialized 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)

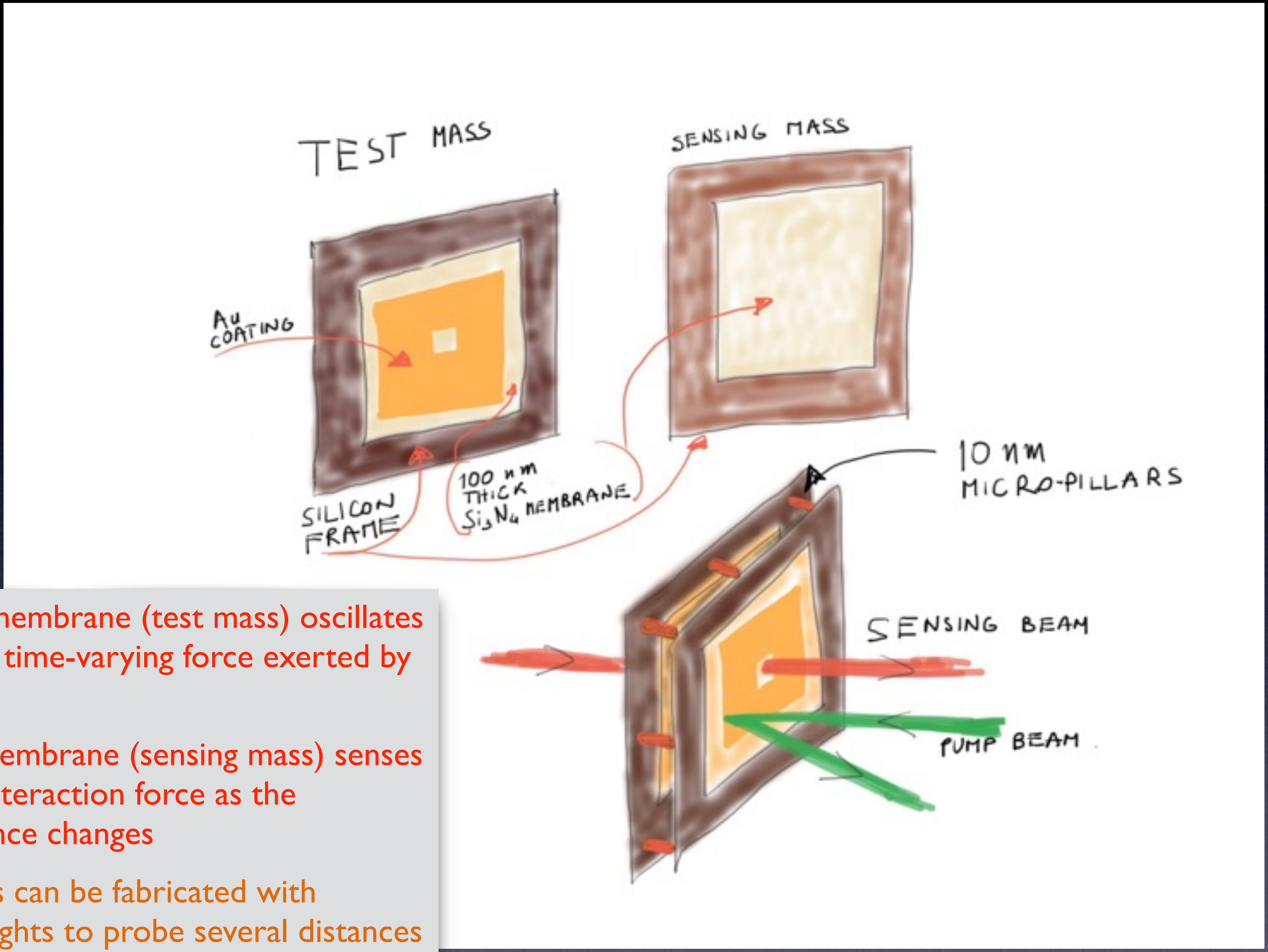
*a*KWISP physics themes

- Many extensions of the standard model predict corrections of Yukawa-type to Newton's gravitational law. These corrections can be caused by the exchange of light elementary particles between pairs of atoms belonging to two macroscopic bodies (**"short range interactions"** or "fifth force")
    - scala dark matter (moduli…)
    - dilatons…
- Multi-dimensional compactification schemes, where extra dimensions are compactified at relatively low energy of the order of 1TeV, also generate Yukawa-type corrections to Newton's law (**"extra dimensions"**)
- Quantum gravity?

Basic experimental technique:

- set a "test" (or "source") mass as close as possible to a second "sensing" mass
- change the separation distance in a controlled way and search for the presence of deviations from the standard $1/r^2$ gravitational interaction force

aKWISP double-membrane sensor concept



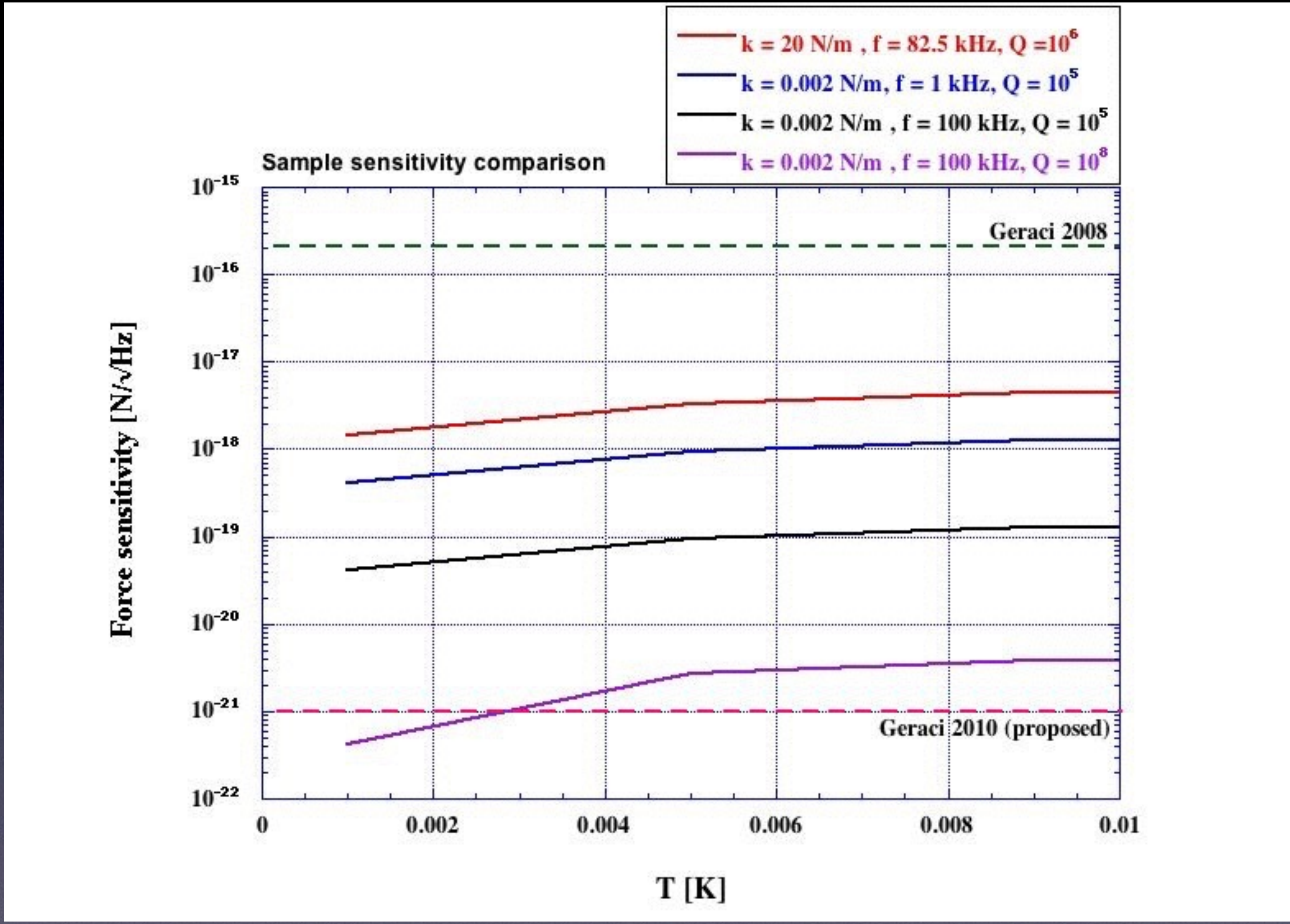
- The Au coated membrane (test mass) oscillates in response to a time-varying force exerted by the pump beam
- The uncoated membrane (sensing mass) senses a time-varying interaction force as the separation distance changes
  - micro-pillars can be fabricated with different heights to probe several distances
  - Au coating thickness can be modulated to adjust the magnitude of the test mass

aKWISP Physics potential

- Recent experimental efforts(*) exploit force sensitivities of $2 \cdot 10^{-16}$ N/√Hz to explore distances below 10 microns
- Some proposed upgrades(*) envision sensitivities down to 10^{-21} N/√Hz at 1 micron distances
- *a*KWISP can reach atto- or even zepto-N sensitivities and probe interaction distances at the nm scale, gaining access to unexplored regions in the parameters space of the Yukawa-type short-range interaction force models

(*) see for instance A. Geraci et al., Physical Review D, D78(2), 022002 (2008), and Physical Review Letters, 105(10), 101101 (2010)

Sub-K sensitivity



Geraci 2008 - A. Geraci et al., Physical Review D, D78(2), 022002 (2008)
Geraci 2010 - A. Geraci et al., Physical Review Letters, 105(10), 101101 (2010)

*a*KWISP discovery potential

- The ATLAS experiment at LHC was able to explore short distance scales stopping at 10 microns
- Some recent experiments (*) achieve force sensitivities of $2 \cdot 10^{-16}$ N/√Hz and reach distance scales a little below 10 microns
- A few proposed upgrades (*) project force sensitivities of 10^{-21} N/√Hz at distance scales of 1 micron
- *a*KWISP could reach atto- or even zepto-N sensitivities and probe distance scales of a few nm, thus entering unexplored regions in the parameter space of Yukawa-type interactions and gaining access to the physics of
  - extra dimensions
  - dilatons
  - scalar dark matter (moduli,…)
  - …

esempio di potenzialità di scoperta di *a*KWISP

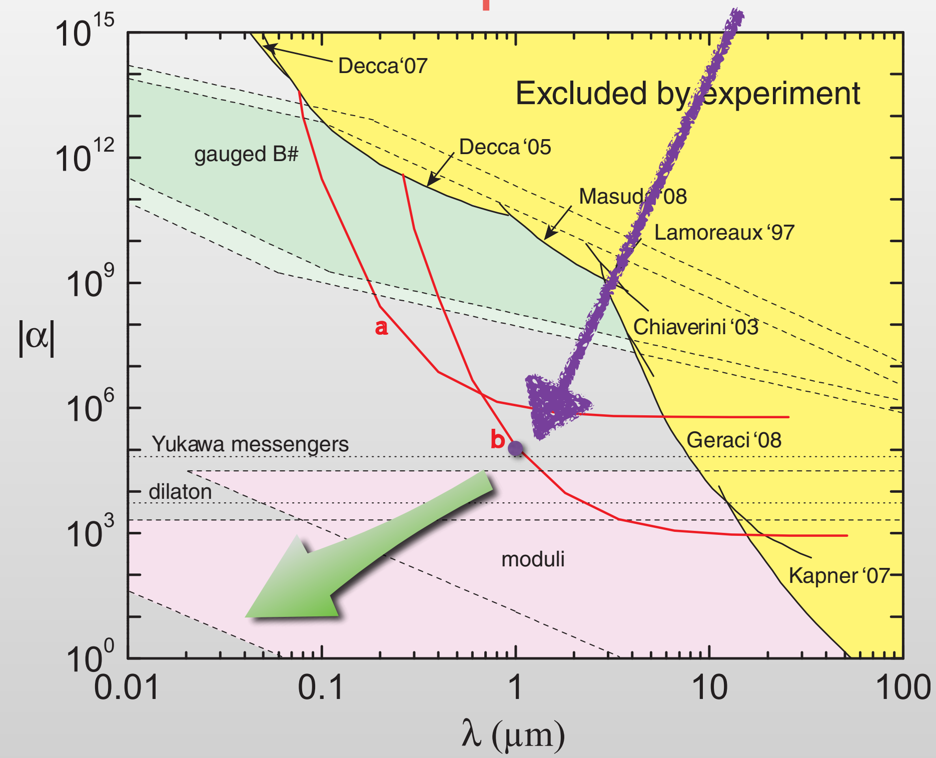


FIG. 3 (color online). Experimental constraints [23–29] and theoretical predictions [30] for short-range forces due to an interaction potential of Yukawa form $V = -\frac{G_N m_1 m_2}{r} \times [1 + \alpha e^{-r/\lambda}]$. Lines ($a$) and ($b$) denote the projected improved search reach for microspheres of radius $a = 150$ nm and $a = 1500$ nm, respectively.

da A. Geraci et al., Physical Review Letters, 105(10), 101101 (2010)

(*) A. Geraci et al., Physical Review D, D78(2), 022002 (2008), and Physical Review Letters, 105(10), 101101 (2010)

*a*KWISP projected timeline

- Approximate timescale : 2-3 years
- 4 R&D phases

1. Preliminary installation phase (~6 months)
   - preparation of the experimental area
   - infrastructure installation (optical bench, vacuum system, instrumentation)
   - optics setup and initial alignment
   - beam and cavity characterisation

2. Room temperature commissioning phase (~4 months)
   - membrane studies at room temperature
   - absolute sensitivity measurements with pump beam technique
   - preliminary data taking

3. Low temperature preliminary phase (~12 months)
   - design and construction of membrane cooling cryostat
   - setup of laser cooling optics
   - cooling tests
   - integration of laser and cryogenic cooling
   - preliminary sensitivity tests

4. Low temperature commissioning phase (~8 months)
   - insertion of double membrane assembly or of piezo actuated test mass
   - preliminary pumping and sensitivity tests
   - final commissioning
   - data taking

Conclusions

- The **KWISP** super-sensitive opto-mechanical force sensor is running in Trieste and is now in use at **CAST (CERN)** to search for solar Chameleons and perhaps gain a first glimpse at the Dark Energy sector
- The key KWISP technologies can be pushed to achieve the limiting sensitivity for this type of sensor ⇒ ***advanced*-KWISP**
- *a*KWISP, with the "double membrane concept", presents an excellent opportunity to attack frontier physics themes in the field of short-distance interactions
  - access to interaction distances below 1 micron with atto- to zepto-N sensitivity
  - easy scalability of experimental parameters