



advanced-KWISP

Investigating Short Range Interactions at sub-micron scales

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Summary

- The *aKWISP* idea
- The force sensor and its key technologies
- The *aKWISP* project
 - the device
 - physics potential
- Conclusions

Idea and motivations

- **Short range interactions (SRI)** give access to

- extra dimensions
- chameleons
- scalar dark matter (moduli...)
- dilatons
- ...

Basic experimental technique in SRI:

- two masses: “source” mass and “sensing” mass
- excite the “source” \Rightarrow “sensing” mass gives signal $f(\text{separation distance})$

- **We present aKWISP, a device able to investigate SRI at $O(10 \text{ nm})$ separation distances**

- **start from a membrane-based opto-mechanical force sensor**

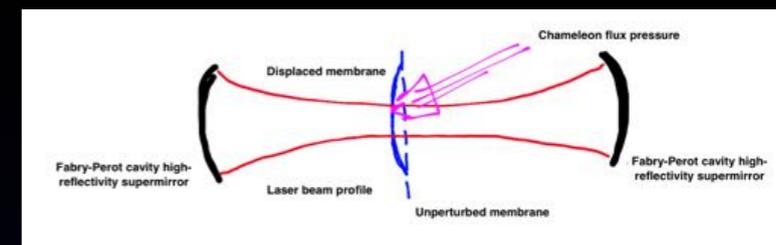
- KWISP: used at CAST to search for solar Chameleons via their “radiation pressure”
- extreme sensitivity comes from the combined quality factors of two resonators

- **go one step further for *advanced-KWISP* (aKWISP)**

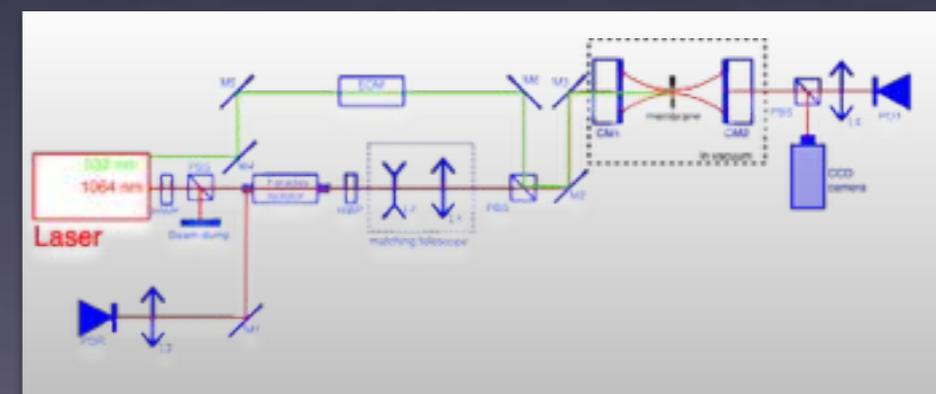
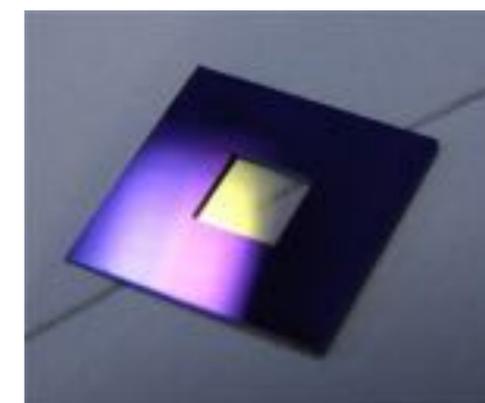
- two membranes in close proximity
- excite one with a pump laser, monitor the other with a sensing laser

Membrane force sensor

- Membrane-in-the-middle configuration
 - a thin and taut nano-membrane (~10's of nm thick Si_3N_4) is centred and aligned inside a Fabry-Perot resonant cavity
- Membrane displacements shift the cavity mode frequencies in response to an externally applied force
- A feedback loop frequency-locks a laser beam to the cavity: the error signal senses frequency shifts and gives the information on membrane displacements

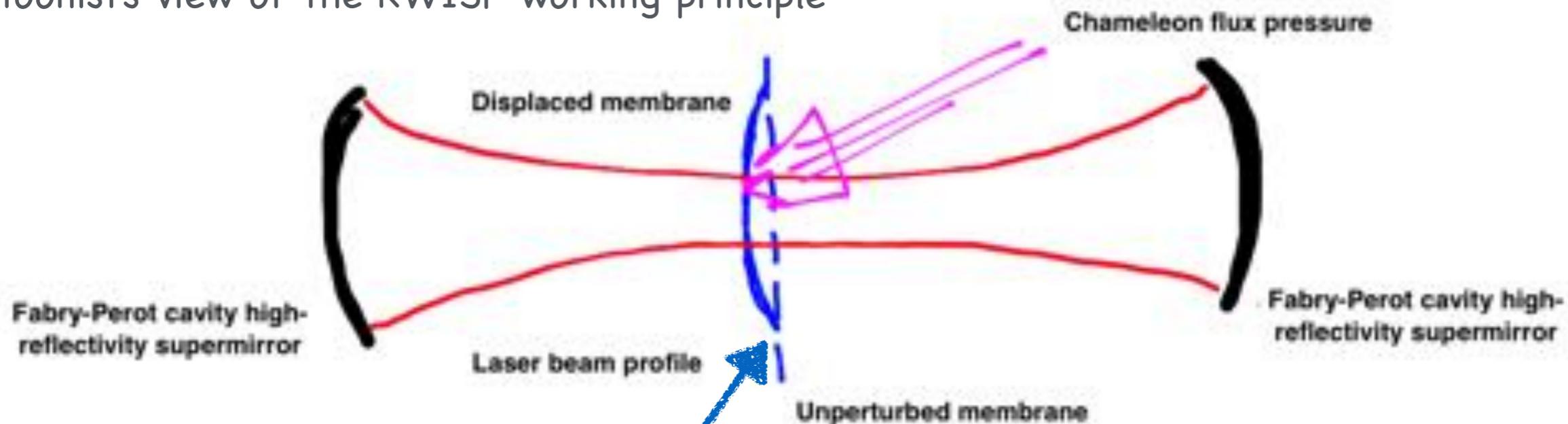


(1 mm)x(1 mm), 50 nm thick Si_3N_4 micromembrane mounted on a 200 μm thick Si substrate



KWISP @ CAST

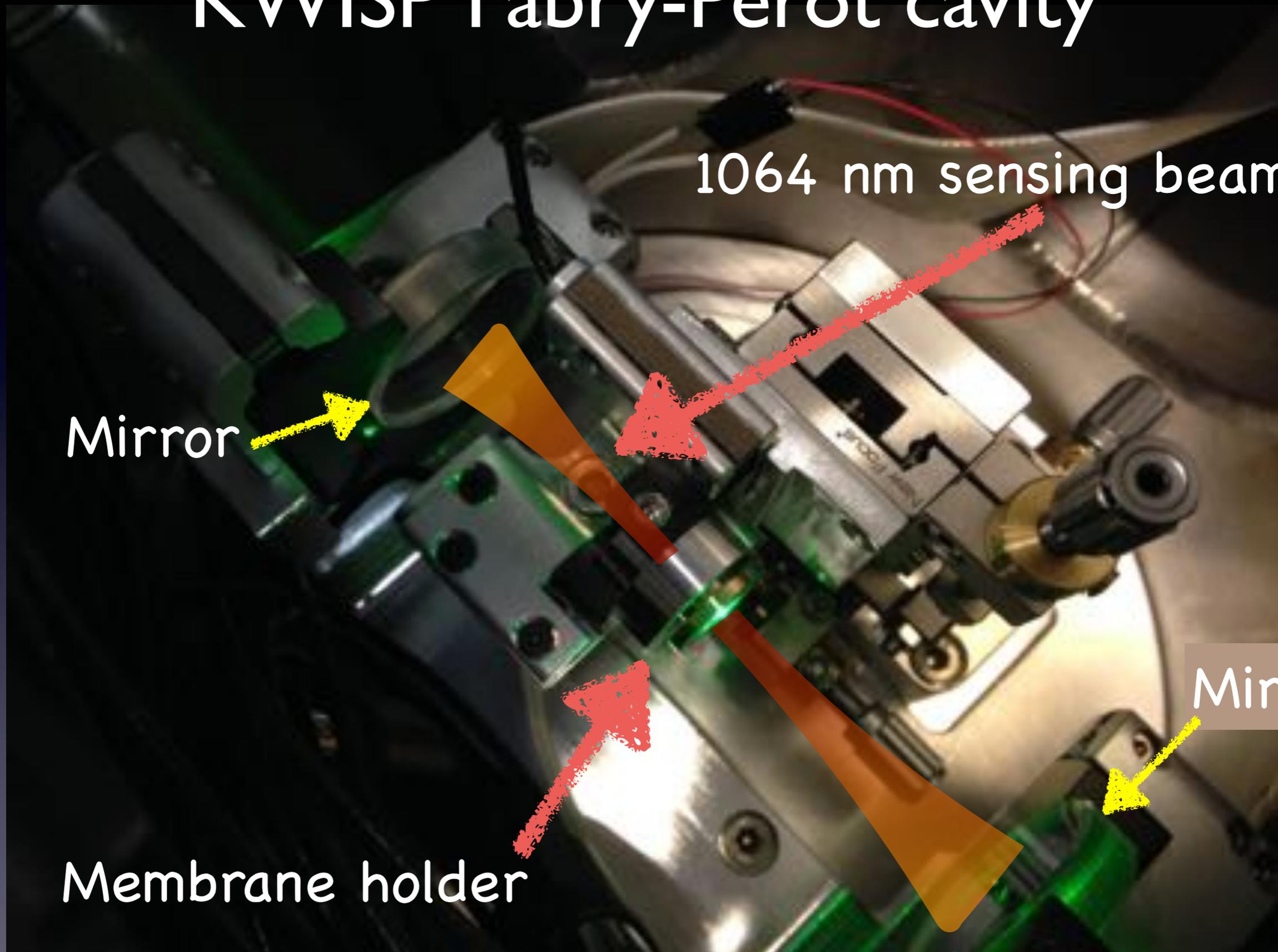
Cartoonist's view of the KWISP working principle



- The opto-mechanical sensor technology is already in use at CERN
- The CAST experiment is equipped with the KWISP detector looking for the direct coupling to matter of solar Chameleons

(see G. Cantatore, M. Karuza and K. Zioutas, Cern Courier, January-February 2016)

KWISP Fabry-Perot cavity



Mirror

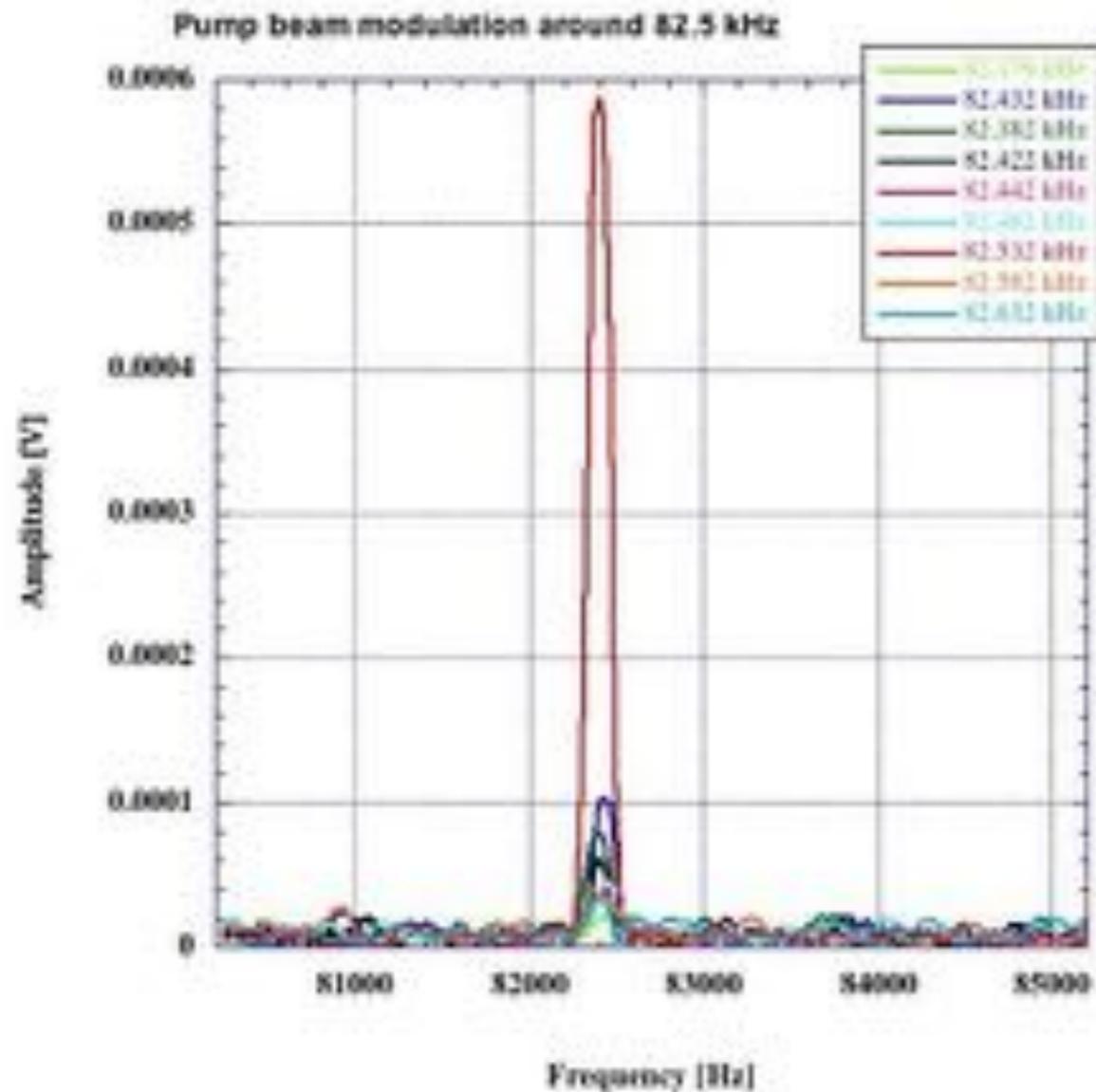
1064 nm sensing beam

Mirror

Membrane holder

Direct force calibration of the KWISP sensor

Equivalent force on membrane: $7.9 \cdot 10^{-14}$ N



T = 300 K

- A known radiation pressure from a “pump” beam at 532 nm (membrane reflects 25%) is amplitude modulated at the membrane mechanical resonance frequency (82.5 kHz in this case)
- The amplitude of the membrane displacement in response to the force is amplified by a factor Q (3000, up to 10^5)
- Room temperature sensitivity at resonance: $1.7 \cdot 10^{-17}$ N/ $\sqrt{\text{Hz}}$
- measurements carried out in the Trieste INFN lab

This procedure is fully equivalent to calibrating a particle detector with a radioactive source

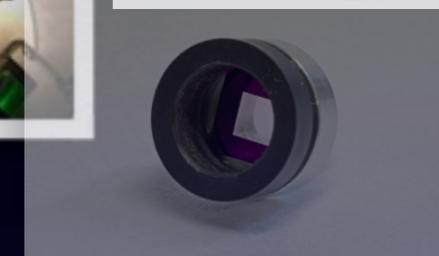
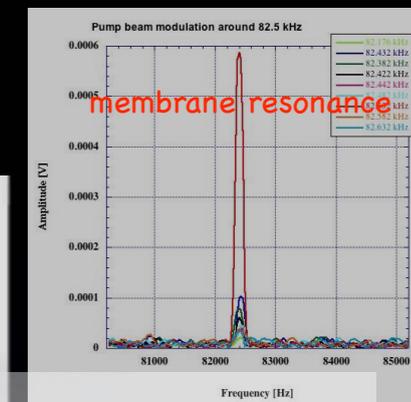
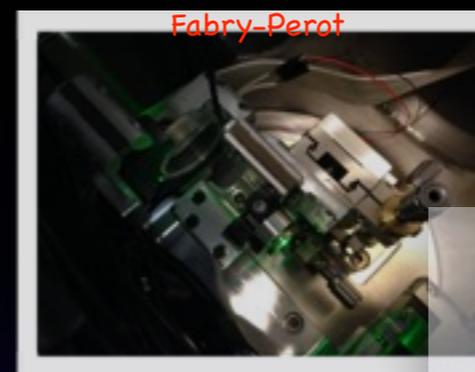


advanced-KWISP

aKWISP in a nutshell

- Build on the KWISP (*) force sensor core apparatus

- membrane-based optomechanical force sensor
- sensitivity enhanced by the combined quality factors of two resonators: mechanical (membrane) and optical (FP)
- sensitive to extremely tiny forces and sub-nuclear size displacements



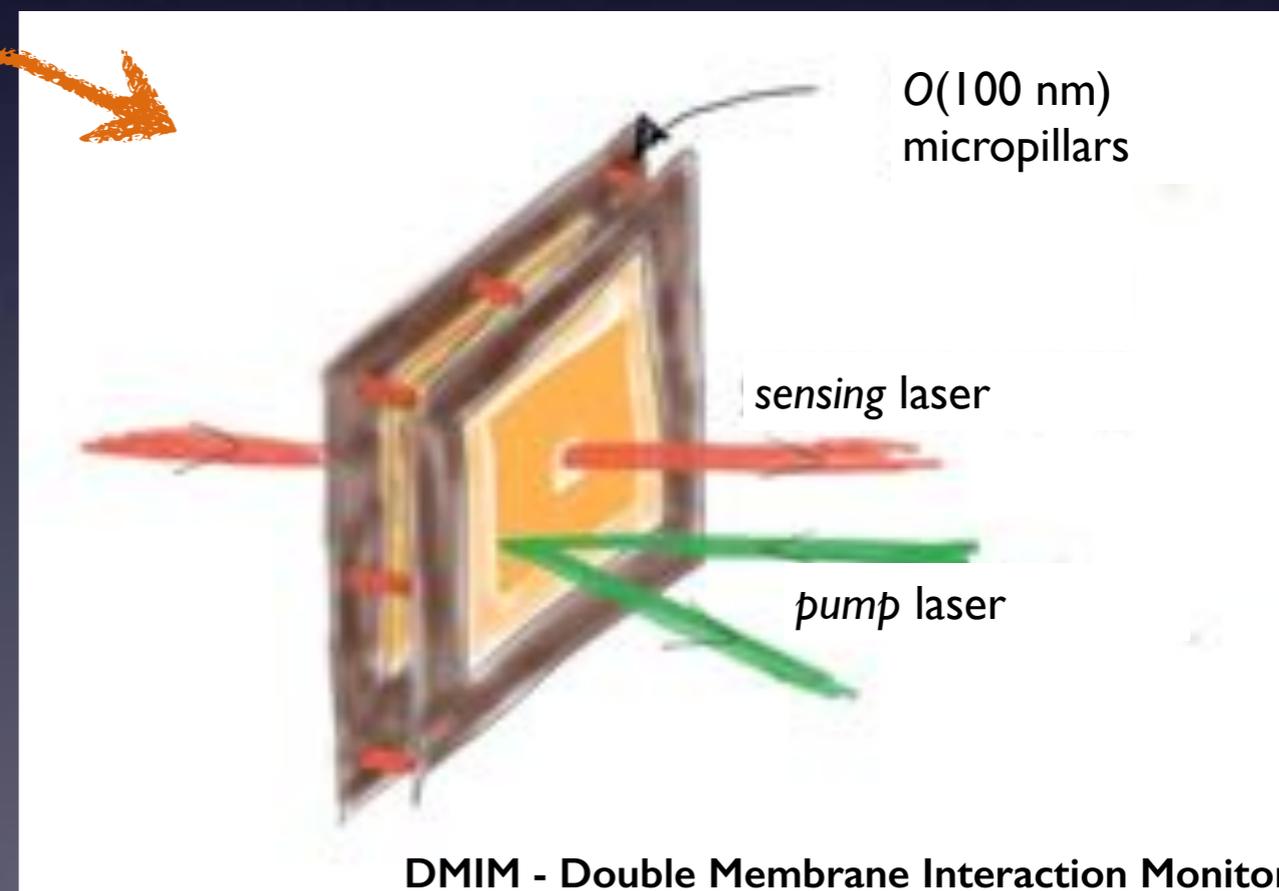
- Introduce the double-membrane device concept

- two membranes separated by $O(10\text{ nm})$ -size micropillars acting as sensing and source masses
- different Q's and resonant frequencies

- Implement advanced technologies to achieve the ultimate sensitivity

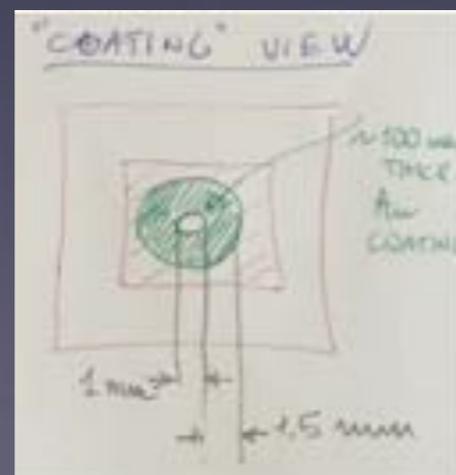
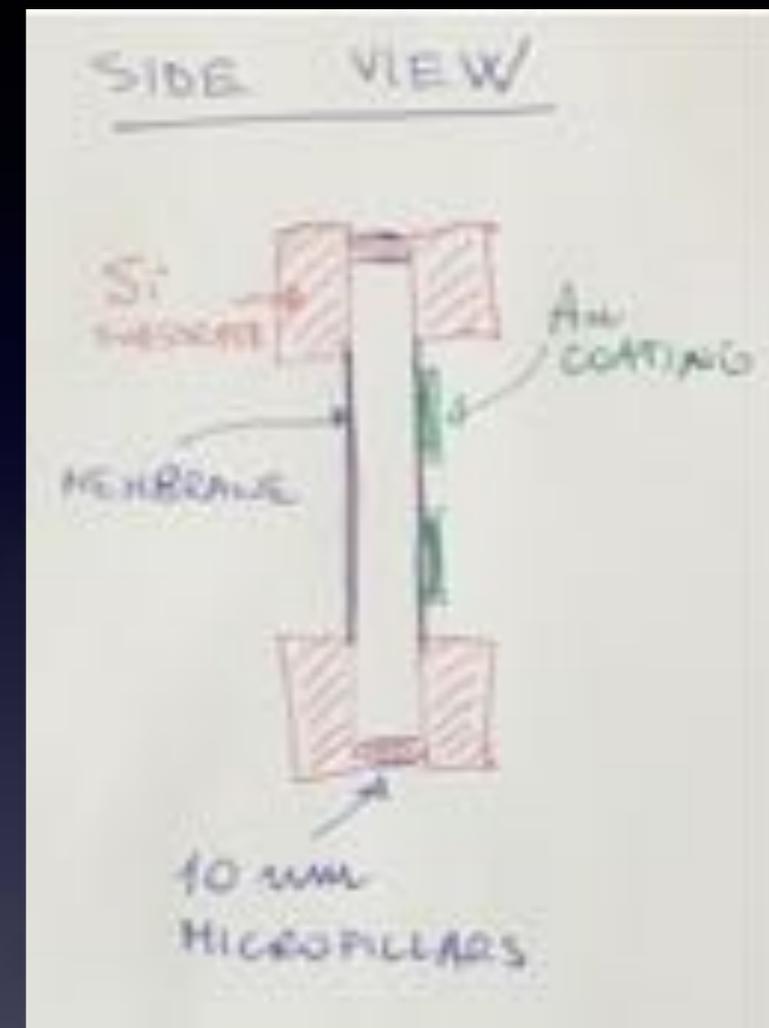
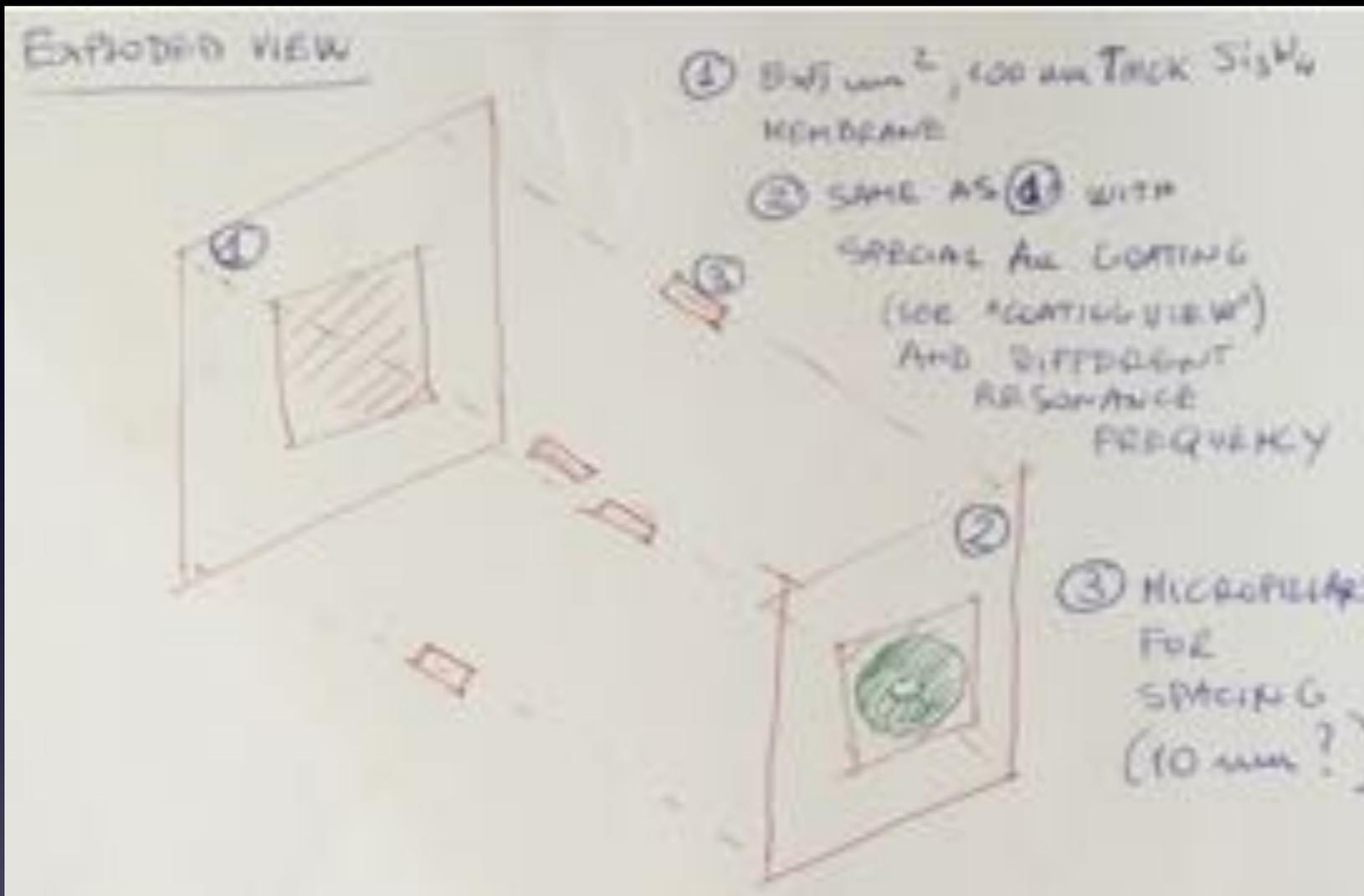
- homodyne detection
- membrane optimisation
- cryogenic cooling

- Study Short Range Interactions



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

aKWISP DMIM - Double Membrane Interaction Monitor



Key aKWISP technologies

- Fabry-Perot resonator
- **DMIM** (**D**ouble **M**embrane **I**nteraction **M**onitor)
- pump laser beam calibration
- homodyne detection
- cryogenic cooling
- membrane coating and customisation
- 3D printing and micromechanics

Why are SRI interesting for particle physics?

- The exchange of elementary particles:

- chameleons
- axions
- dilatons
- moduli (scalar DM)
- ...

$$V = -\frac{G_N m_1 m_2}{r} (1 + \alpha e^{-r/\lambda})$$

generates Yukawa-type potentials

- Extra dimensions

- Recently:

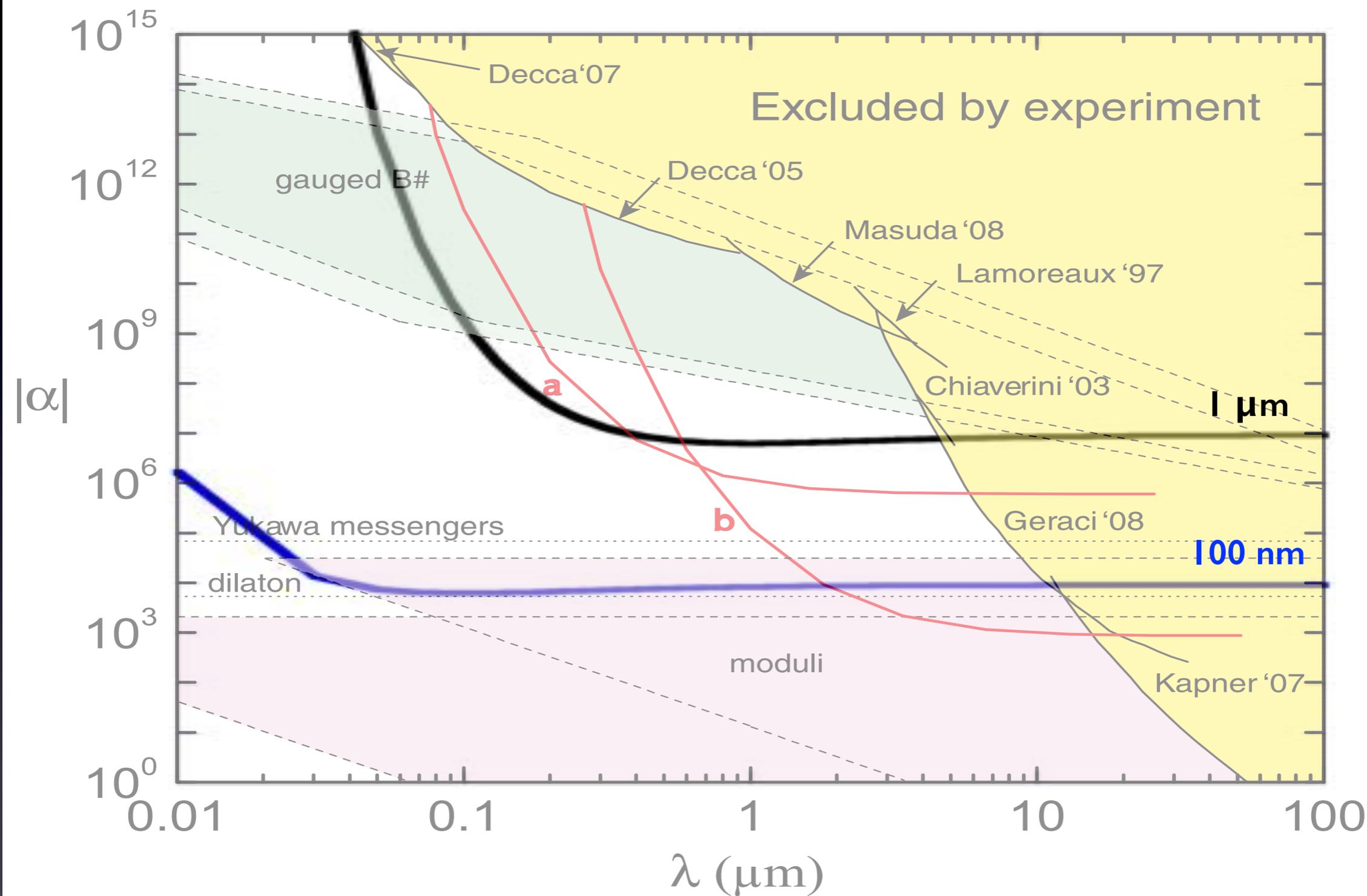
Casimir effect \iff gravity waves

experiment needs two superconducting mirrors

A scenario for *aKWISP*

- The **ATLAS** experiment at LHC was able to explore the compactification of extra dimensions at short distance scales stopping at **11 μm** (arXiv:1604.07773 and CERN thesis at <https://cds.cern.ch/record/2194414?ln=en>)
- Other experiments probe Yukawa-type forces down to **10 μm \Rightarrow 1 μm**
(for example A. Geraci et al., PRD, D78(2), 022002 (2008))
- ***aKWISP* could probe distance scales of $O(100 \text{ nm})$ reaching atto-N or even zepto-N sensitivities \Rightarrow unexplored regions in the parameter space of Yukawa-type interactions**

aKWISP physics reach for Yukawa-type interactions



Exclusion plot taken from;
 A. Geraci et al., Physical Review
 Letters, 105(10), 101101 (2010)

Projected aKWISP detection @ 3 mK with 10^5 s integration time = 10^{-20} N

- black curve: 1 micron separation distance
- blue curve: 100 nm separation distance

aKWISP projected timeline (2-3 years)

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
- cooling tests
- preliminary sensitivity tests

4. Low temperature commissioning phase (~8 months)

- insertion of double membrane assembly
- preliminary pumping and sensitivity tests
- final commissioning
- data taking

CERN has a key role in

- **cryogenics**
 - low temperature operation is essential
- **coating customisation**
 - standard membranes must be coated with different materials and patterns \Rightarrow R&D
- **advanced 3D printing**
 - design, modelling and 3D printing of special components
 - device customisation
- **superconductivity expertise**
 - materials
 - characterisation
 - control

Conclusions

- Building on our expertise on membrane force sensors, we present *aKWISP*: a novel device to investigate short range interactions at separation distances $O(100 \text{ nm})$
- *aKWISP* deeply ventures into uncharted territory
- *aKWISP* will achieve its best performance with the support of the unique CERN environment

Thank you!

We have great ideas !!

... but then we must work!

