Searching for Dark Matter and Dark Energy at CERN with CAST

G. Cantatore

Università and INFN Trieste

Summary

I. Open questions and the **Dark Side**

- **Dark Matter:** Axions and WISP's
- **Dark Energy:** Chameleons

II. **CAST** at CERN

- Solar Axions
- The CAST physics program: deeper in the Dark Side

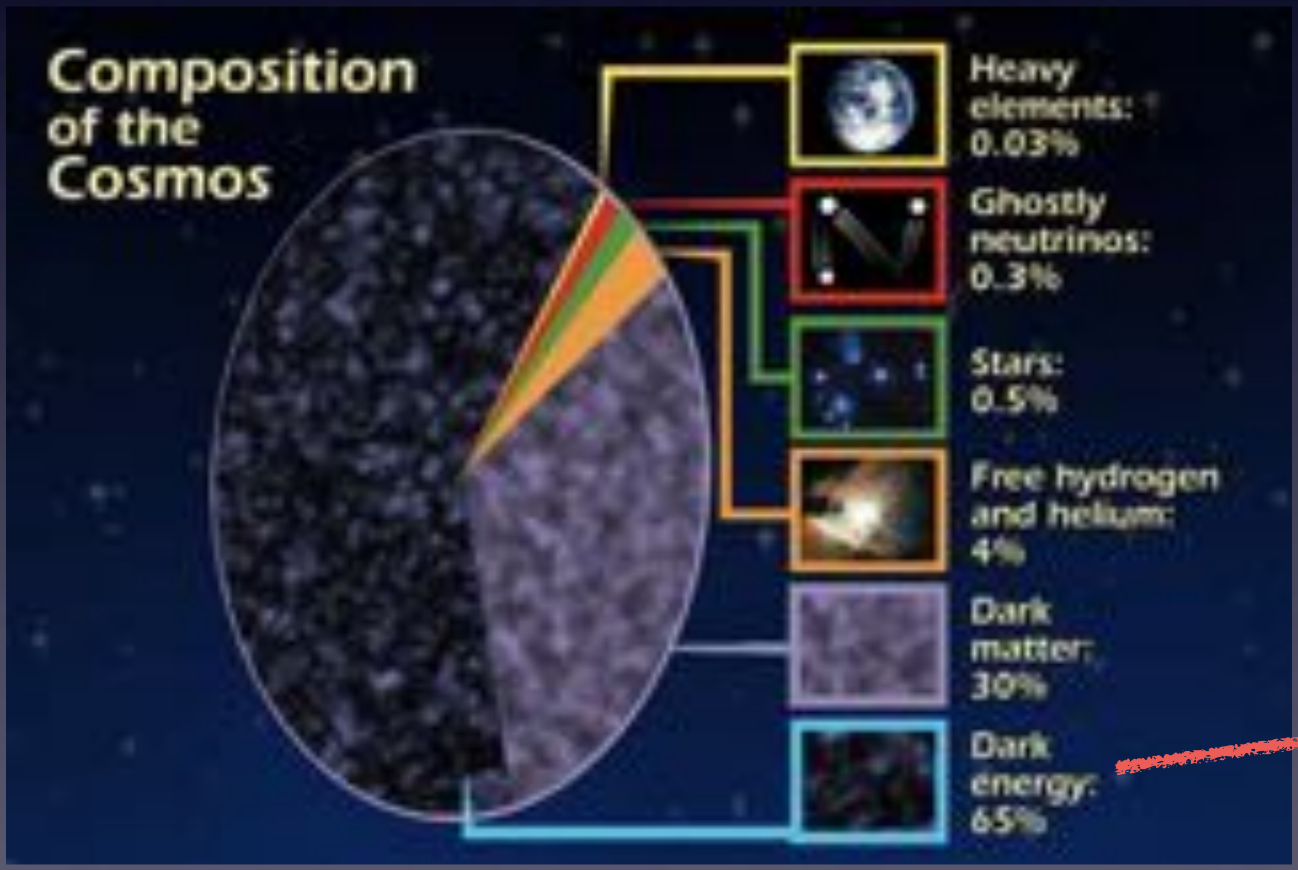
III. Dark Energy and **KWISP**

- The **KWISP** force sensor
- Searching for DE with **KWISP** at **CAST**

IV. Beyond: the ***advanced*-KWISP** project

Hints and puzzles from cosmology

- Matter-antimatter asymmetry
- Composition of the Universe
- (see your favourite cosmologist for more…)



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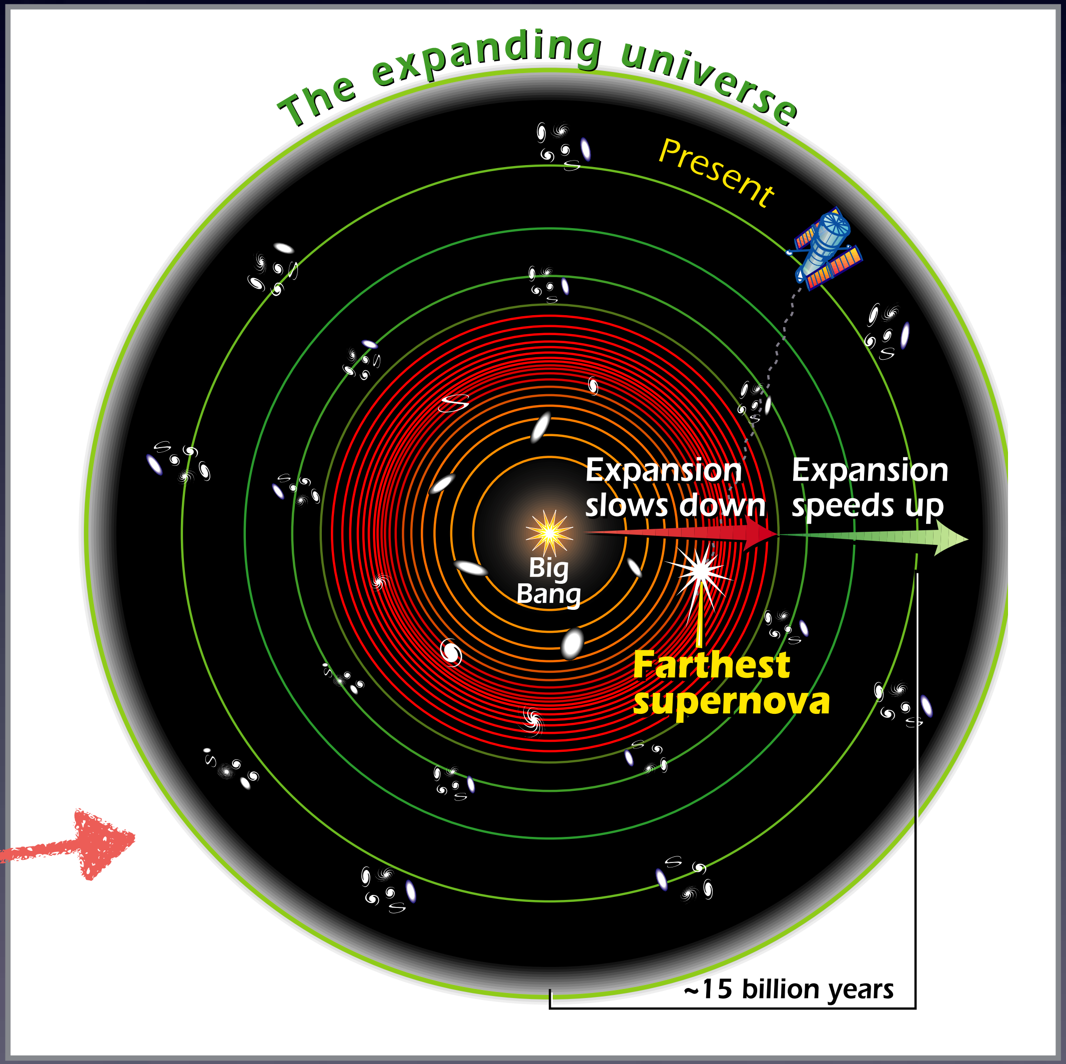

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Main puzzles in the Standard Model

- Large number of free parameters
- Does not include gravity
- $(g\text{-}2)_\mu$ deviates from SM prediction
- “Fine-tuning”
  - θ parameter (CP conserved in strong interactions ⇒ Axions!)
  - …
- (see your favourite theorist for more…)

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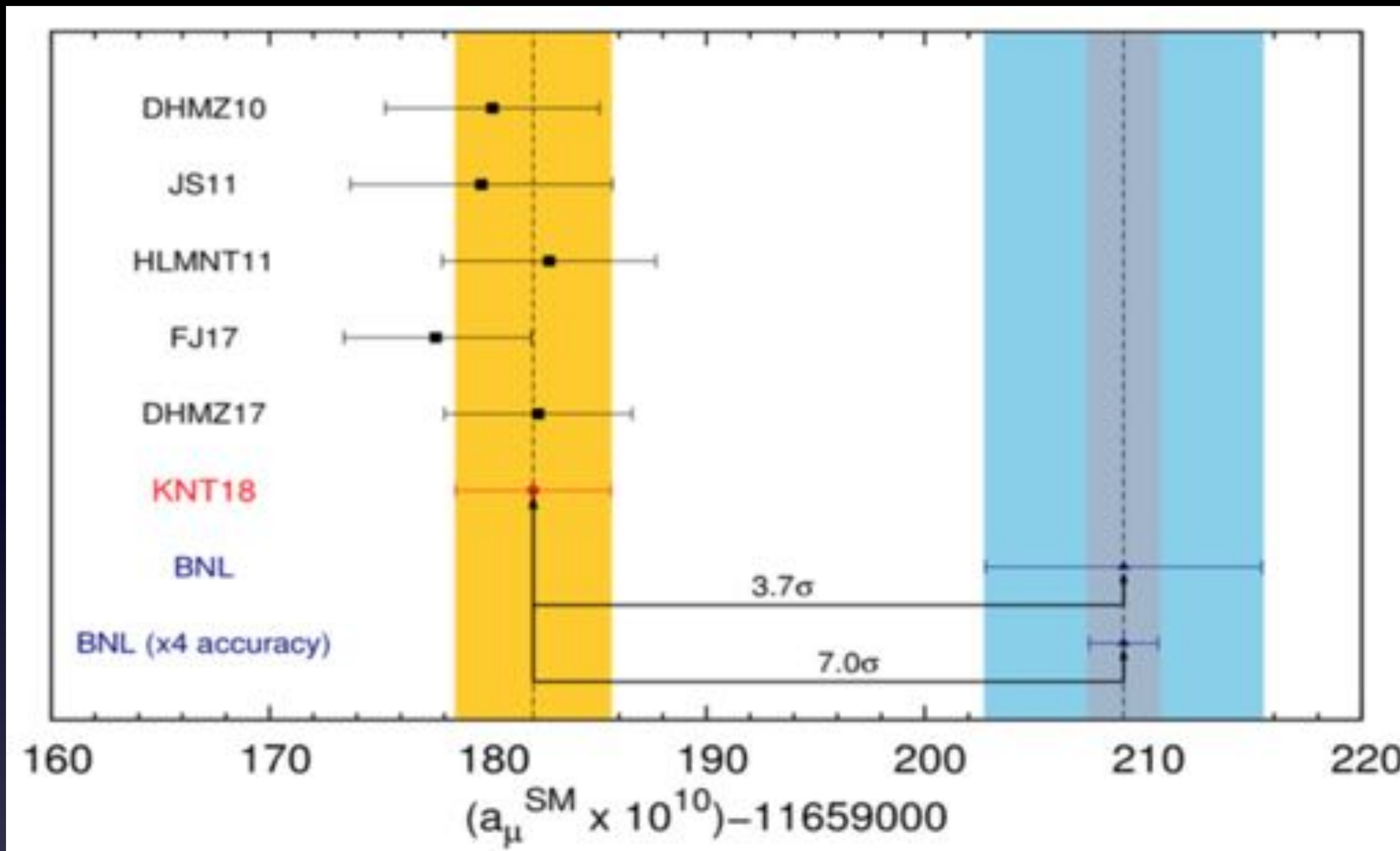

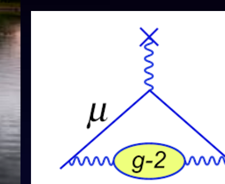

Axions.)

- …

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Light from the Dark Side!

Current view: the answers lie hidden in the Dark Side and its interactions with known physics (a.k.a. the SM)

The (astro-)particle physicist **Holy Grail**: identify candidate **particle components** of the Dark Side and **find them**!

- Dark Matter ⇒ WIMPs and Axions (maybe ν's and other WISP's)
- Dark Energy ⇒ Chameleons

Main DM & DE candidate constituents

- WIMPs - Weakly Interactive Massive Particles (mass > 50 GeV)
  - pros:
    - SUSY neutralinos fit the bill
  - cons:
    - experimental evidence against (no SUSY seen at LHC, WIMP searches have reached the "neutrino limit")
    - feeble hints in astrophysical observations
- Sterile neutrino (mass ~ 10^3 eV)
  - pros
    - could explain the small values of the neutrino masses and matter-antimatter asymmetry
  - cons
    - experimental evidence against (MINOS+ at Fermilab)
    - feeble hints in astrophysical observations
- Assioni e altre WISPs - Weakly Interacting Slim Particles (massa < 1 eV)
  - pros
    - explain CP conservation in strong interactions (Axions)
    - relic Axions are non-relativistic
    - hints in astrophysical observations
  - contro
    - no experimental evidence
- Chameleons as DE constituents
  - pros: have the necessary properties, unique candidate for the moment
  - cons: phenomenological mostly "ad hoc: theory, no experimental evidence

WISPs - Weakly Interacting Slim Particles

- Hypothetical particles with low mass (< eV), coupling weakly to baryons
  - WIMPs also couple weakly to ordinary matter, but masses > GeV
- WISPs
  - Could solve a few of the SM model puzzles
    - CP conservation in strong interactions ⇒ Axions
    - $(g\text{-}2)_\mu$ deviations from SM ⇒ Hidden Photons
  - DM or DE candidate constituents
    - Axions and Axion Like Particles (ALPs) ⇒ Dark Matter
    - Chameleons ⇒ Dark Energy
  - WISP search experiments probe extremely weak interactions (usually couplings < 10^{-10} GeV^{-1}), reaching energy scales not accessible at accelerators ⇒ complementarity
  - Possible mediators with "hidden sectors" predicted in string theory
    - Hidden Photons
    - Mini-Charged particles
    - …

WISP zoo…

- “standard” or QCD Axion
- Axion Like Particles (ALPs)
- Hidden Photons (HP)
- Mini-Charged Particles (MCPs)
- Chameleons
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Axion Primer

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- CP symmetry is found to be conserved in strong interactions

Axion Primer

CP-Violating Prameter
Effective QCD Lagrangian $\mathcal{L}_\theta \propto \overline{\theta}\frac{\alpha_s}{8\pi}G_b^{\mu\nu}\widetilde{G}_{b\mu\nu}$ $0 \le \overline{\theta} \le 2\pi$

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- In QCD the (nEDM) is proportional to θ, therefore CP conservation ⇒ θ = 0 ⇒ nEDM = 0

$$d_n \approx \theta \frac{e}{m_n} \frac{m^*}{\Lambda_{QCD}}$$

Λ_{QCD} QCD energy scale ≈ 1 GeV

$m^* = \frac{m_u m_d}{(m_u + m_d)}$ reduced mass of up and down quark

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- Peccei and Quinn give a solution in 1977: θ is a dynamical field with a <θ> = 0.

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- Wilczeck and Weinberg (1978) immediately realize that this scheme generates a new particle that they call “Axion”, after a detergent, since the Axion “washes away” the Strong CP Problem.

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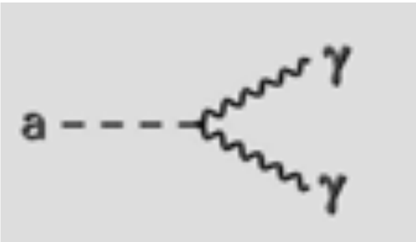
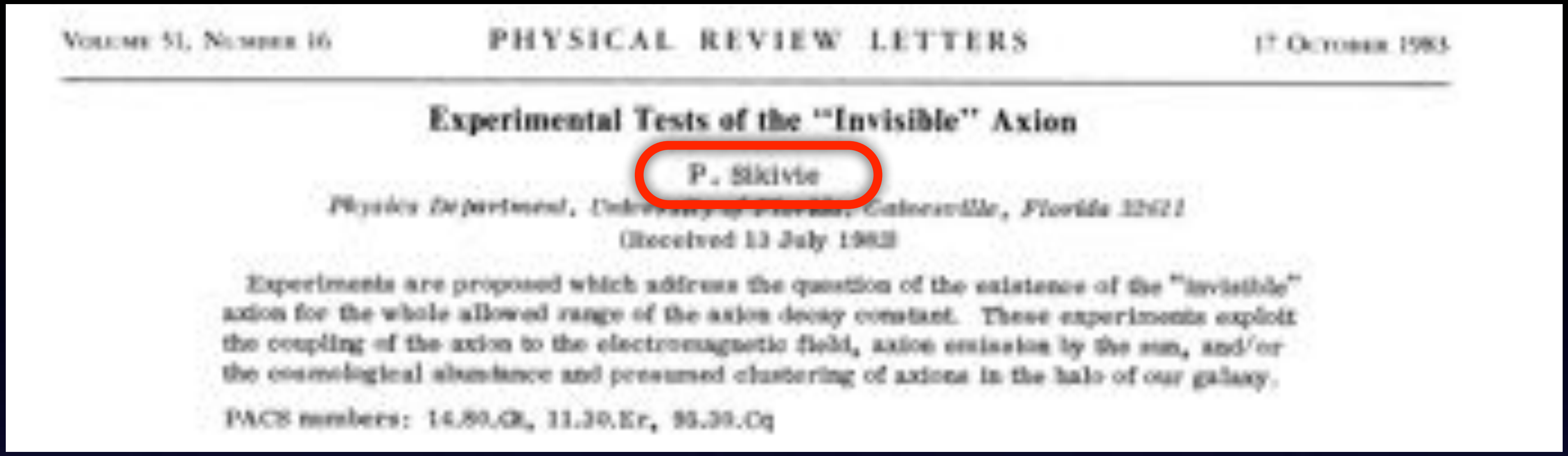
- Sikivie (1983) then describes the properties of the "invisible axion" (low mass and weak interactions) ⇒ a good DM candidate which can be seen exploiting it effective coupling to two photons ("Sikivie effect")

Photon Coupling

$\mathcal{L} = g_{a\gamma}\,\vec{E}\cdot\vec{B}\,a$



The “invisible” Axion


Volume 51, Number 16 PHYSICAL REVIEW LETTERS 17 October 1983

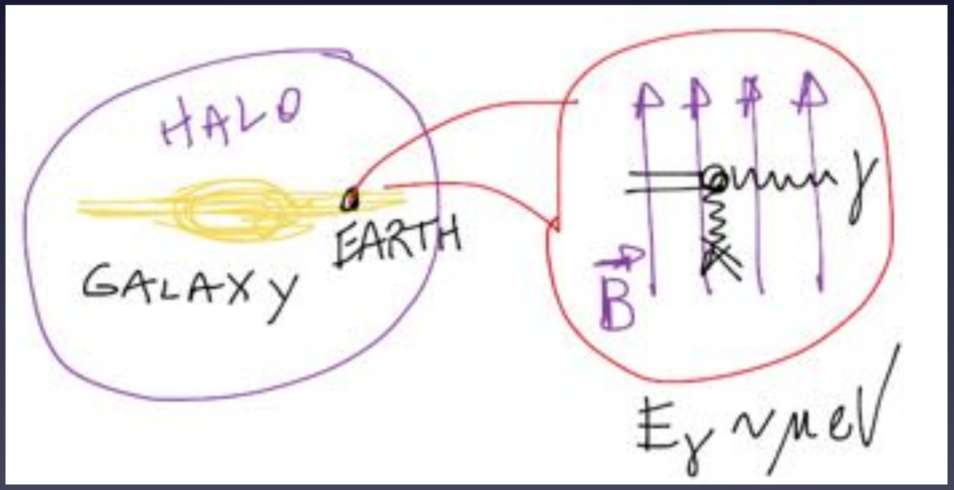
Experimental Tests of the "Invisible" Axion

P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611
(Received 13 July 1983)

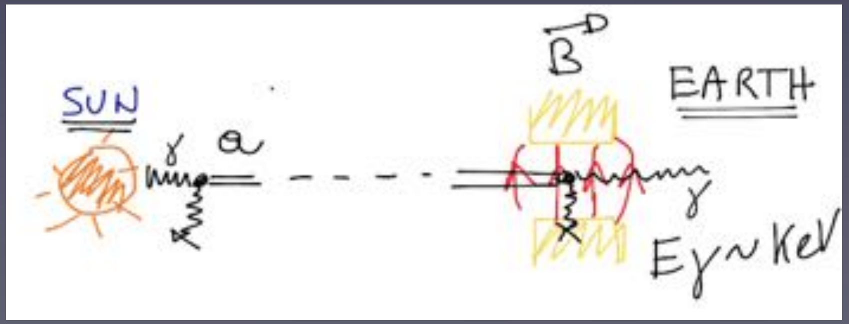
Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

PACS numbers: 14.80.Gt, 11.30.Er, 95.30.Cq

- Axion haloscope



- Axion helioscope



Chameleon primer

Chameleon primer

PHYSICAL REVIEW D **69**, 044026 (2004)

Chameleon cosmology

Justin Khoury and Amanda Weltman

Institute for Strings, Cosmology and Astroparticle Physics, Columbia University, New York, New York 10027, USA

(Received 15 September 2003; published 27 February 2004)

The evidence for the accelerated expansion of the Universe and the time dependence of the fine-structure constant suggests the existence of at least one scalar field with a mass of order H_0. If such a field exists, then it is generally assumed that its coupling to matter must be tuned to unnaturally small values in order to satisfy the tests of the equivalence principle (EP). In this paper, we present an alternative explanation which allows scalar fields to evolve cosmologically while having couplings to matter of order unity. In our scenario, the mass of the fields depends on the local matter density: the interaction range is typically of order 1 mm on Earth (where the density is high) and of order $10-10^4$ AU in the solar system (where the density is low). All current bounds from tests of general relativity are satisfied. Nevertheless, we predict that near-future experiments that will test gravity in space will measure an effective Newton's constant different by order unity from that on Earth, as well as EP violations stronger than currently allowed by laboratory experiments. Such outcomes would constitute a smoking gun for our scenario.

DOI: 10.1103/PhysRevD.69.044026 PACS number(s): 04.50.+h, 04.80.Cc, 98.80.−k

Chameleon primer

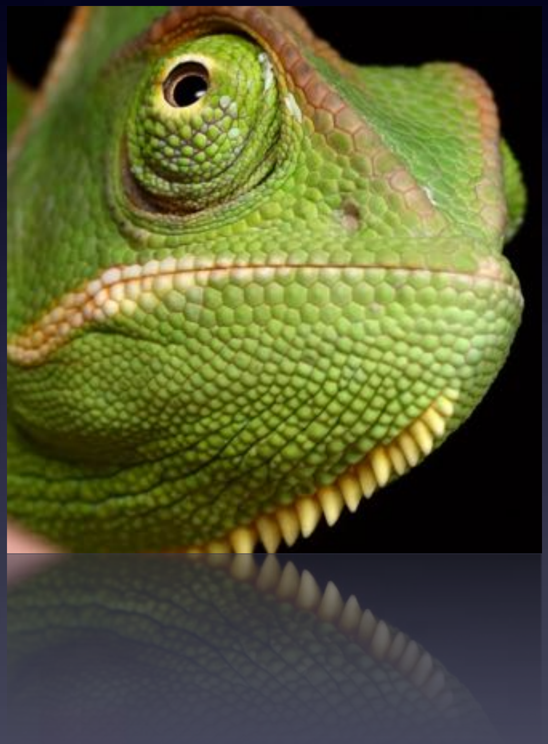
- Chameleons are a type of scalar WISPs having an effective mass depending on the local matter density

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



Chameleon primer

- Chameleons are a type of scalar WISPs having 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.

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Chameleon primer

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- 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 (Sikivie effect inside a magnetic field)
  - directly to matter (no magnetic field needed)

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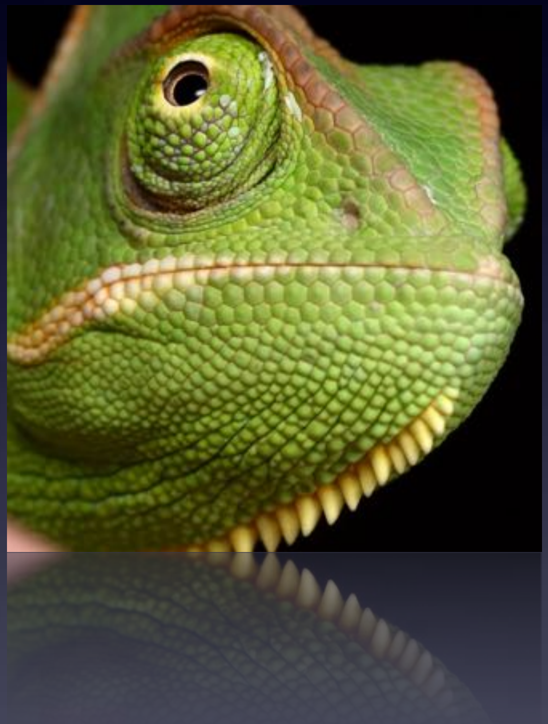
Effective mass



matter coupling

photon coupling

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

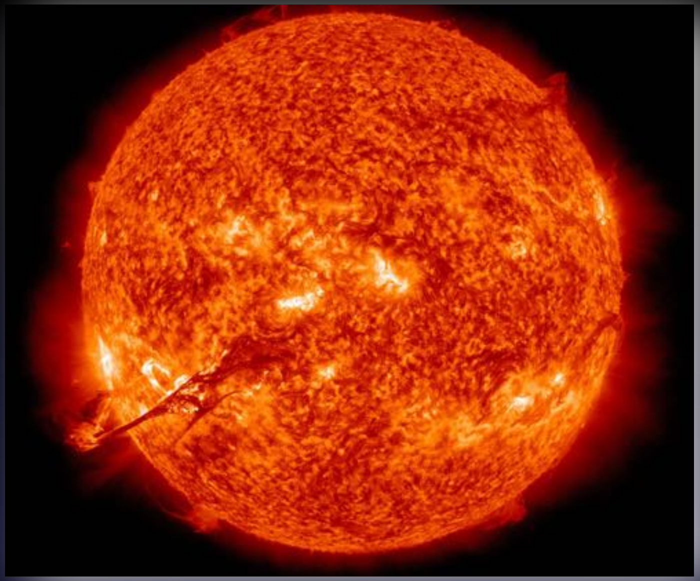
Effective potential

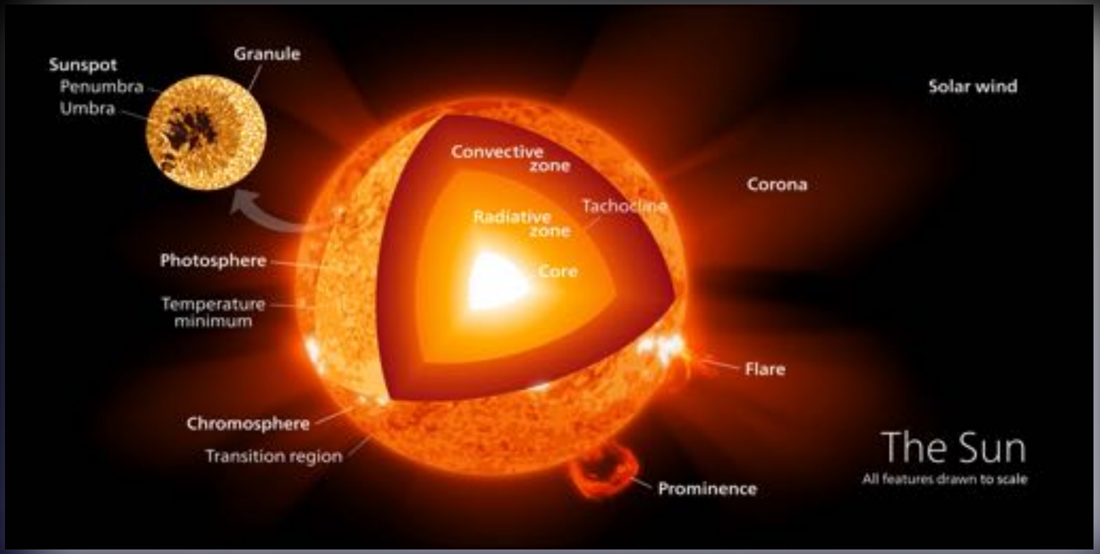
Where to find them…

- Look for photons interacting with a magnetic field
  - in the heavens
    - stars (sun) as sources
    - astrophysical processes producing or interacting with WISPs
  - in the lab
    - send a photon beam through a magnetic field
- Look for cosmological signatures
  - relic WISPs (mainly axions) interacting in a magnetic field
- Look for other interactions with dedicated sensors
  - Chameleons coupling to matter - force sensor

CAST: axions and more

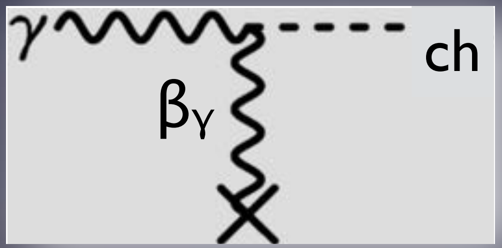
The Sun is our primary source





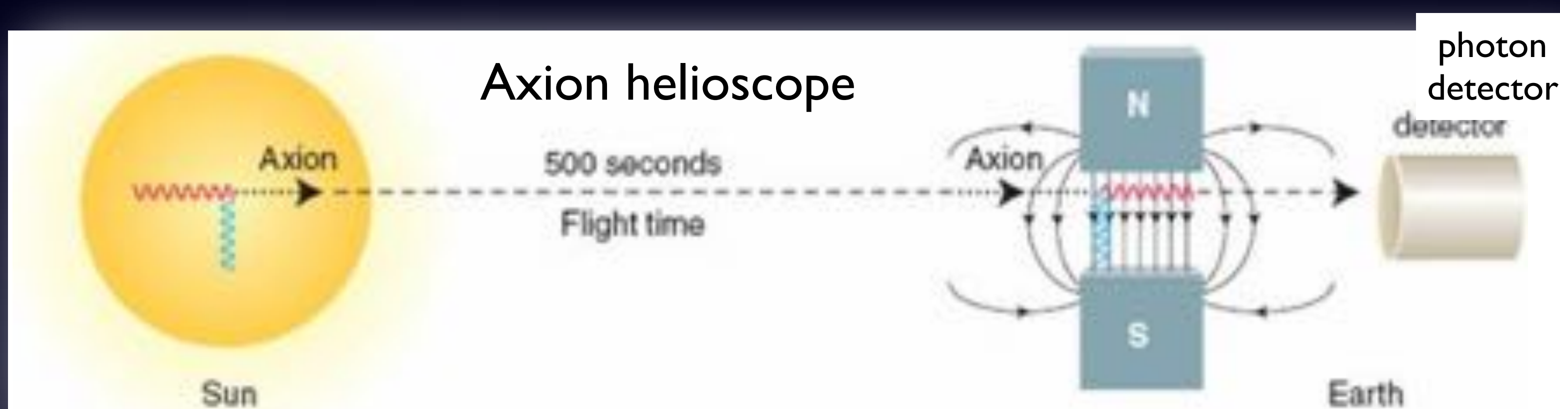
- Axions are produced by the Sikivie process in the magnetic fields of the hot solar core (coupling $g_{a\gamma\gamma}$) and stream out freely reaching the Earth

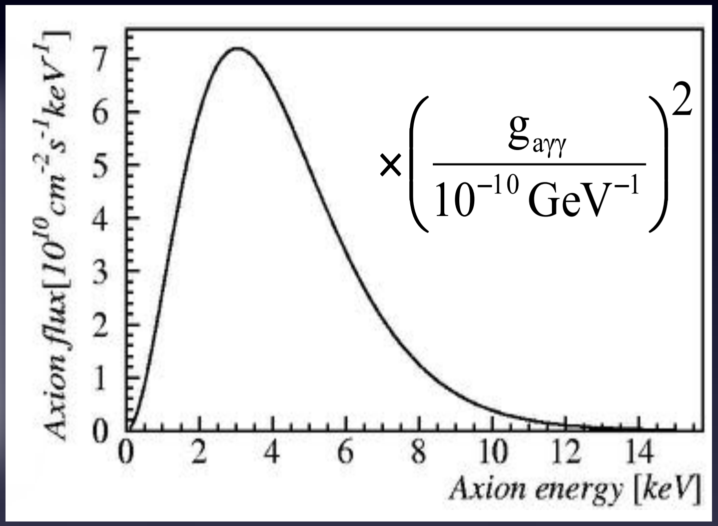
- Chameleons are produced in the thin solar tachocline region, with a 30 T magnetic field, from the Sikivie conversion of photons (coupling β_γ), then propagate unhindered to Earth

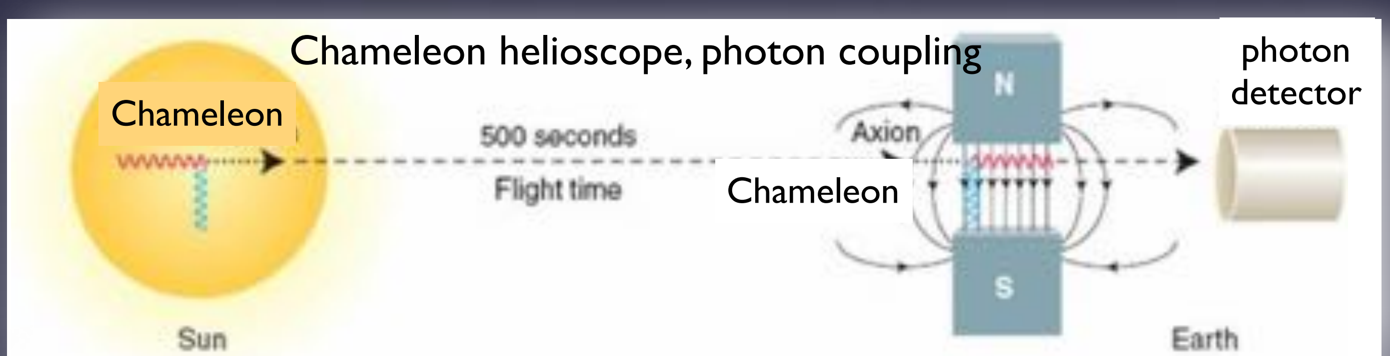


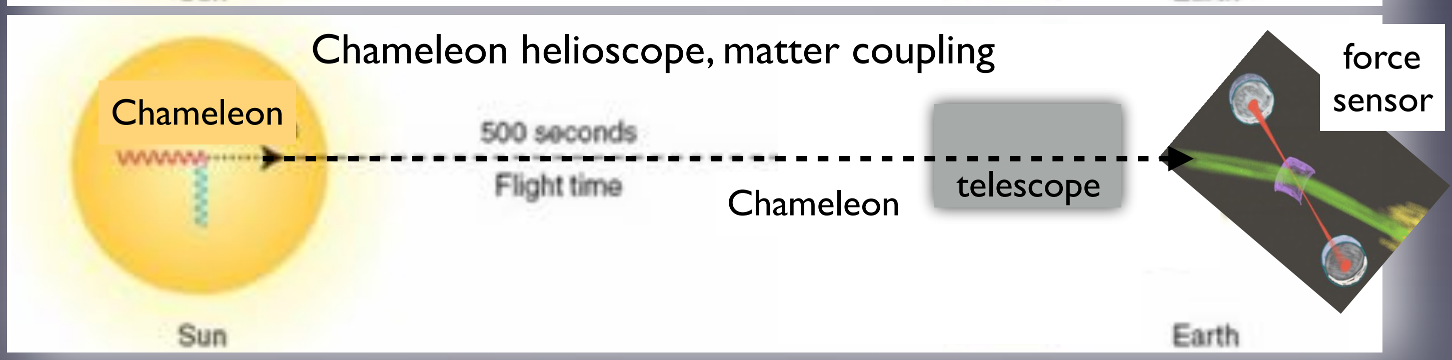
The Helioscope principle

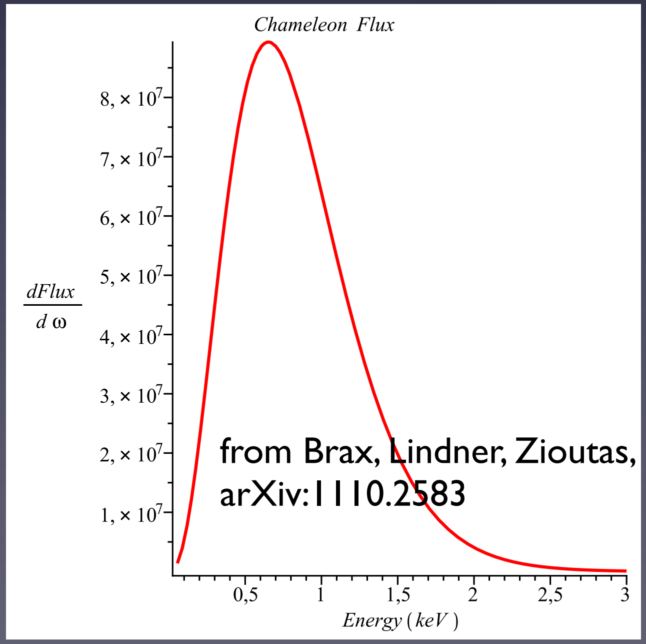
- Axions and Chameleons produced in the Sun stream to Earth
  - **Axions** convert back into photons inside a magnet: detect the regenerated photons
  - **Chameleons** have two possibilities
    - converting into photons inside a magnet: detect the regerated photons
    - interacting directly with matter: detect the equivalent pressure with a force sensor









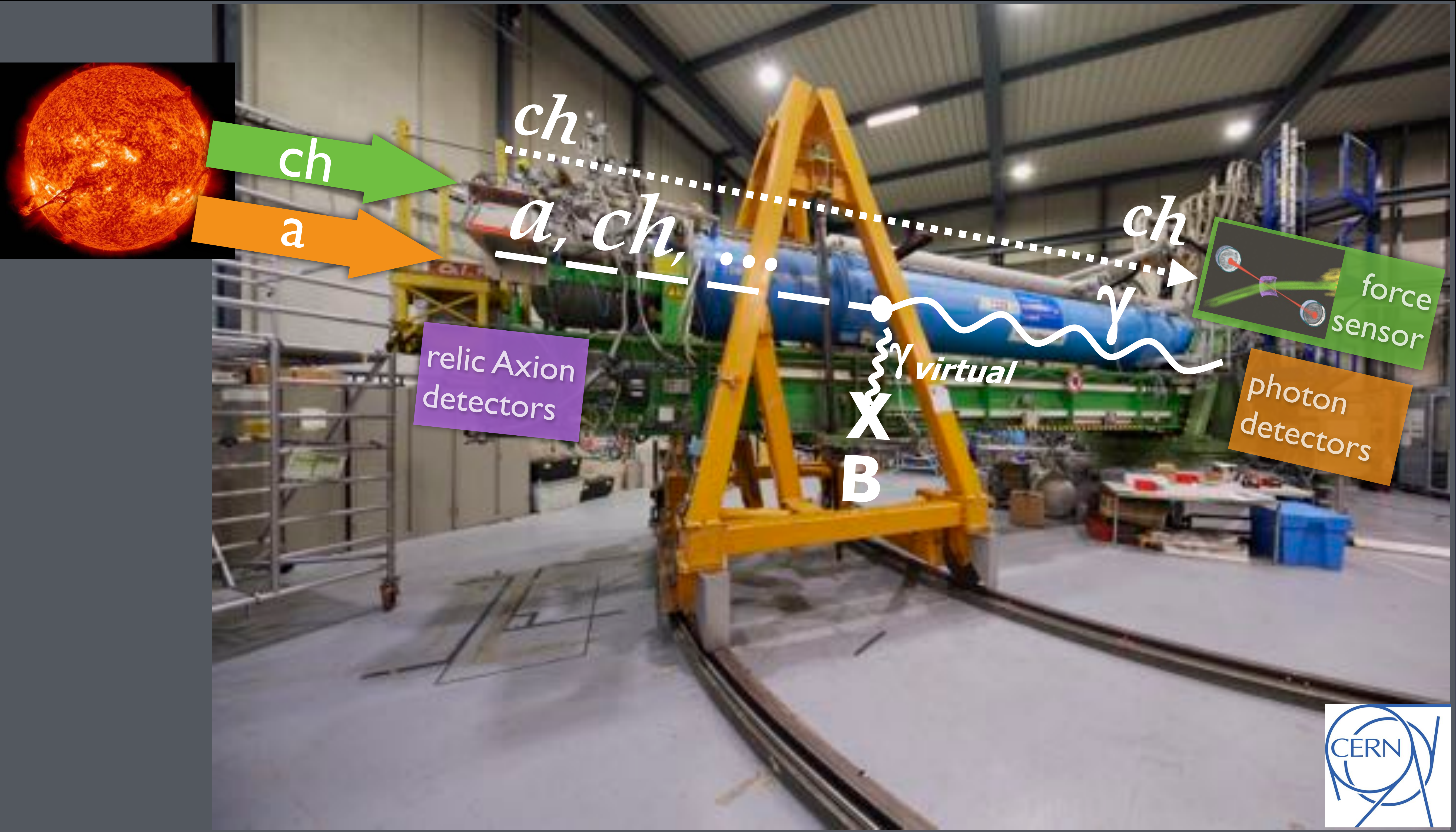


CERN Axion Solar Telescope

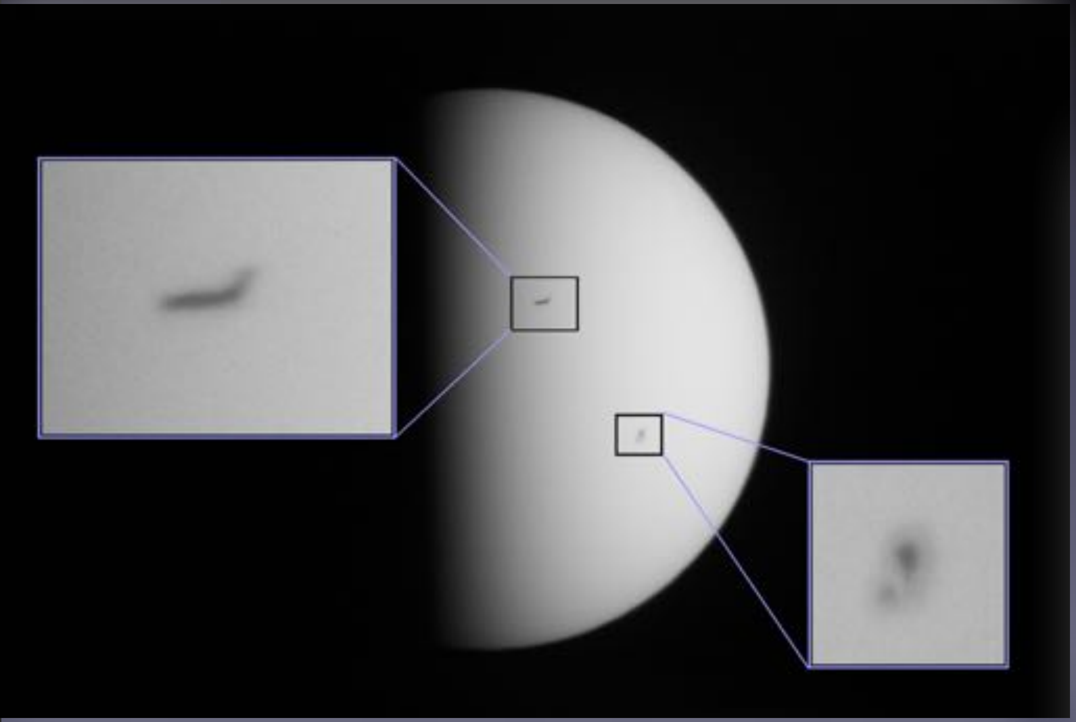
- 21 institutes, 48 authors, 12 countries…
- **Probing the mysteries of the Universe since 2003 !!!**

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

The CAST helioscope



Sun visuals



Still frame of the sun showing details of sunspots and of a passing airplane

Sun filming through a window

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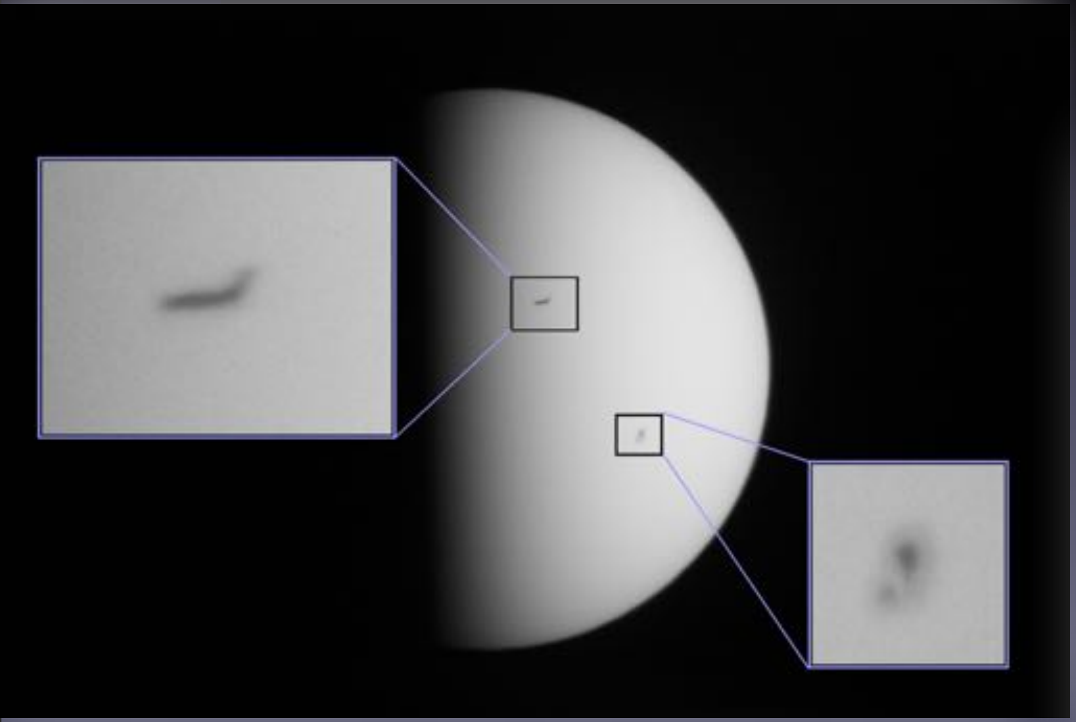

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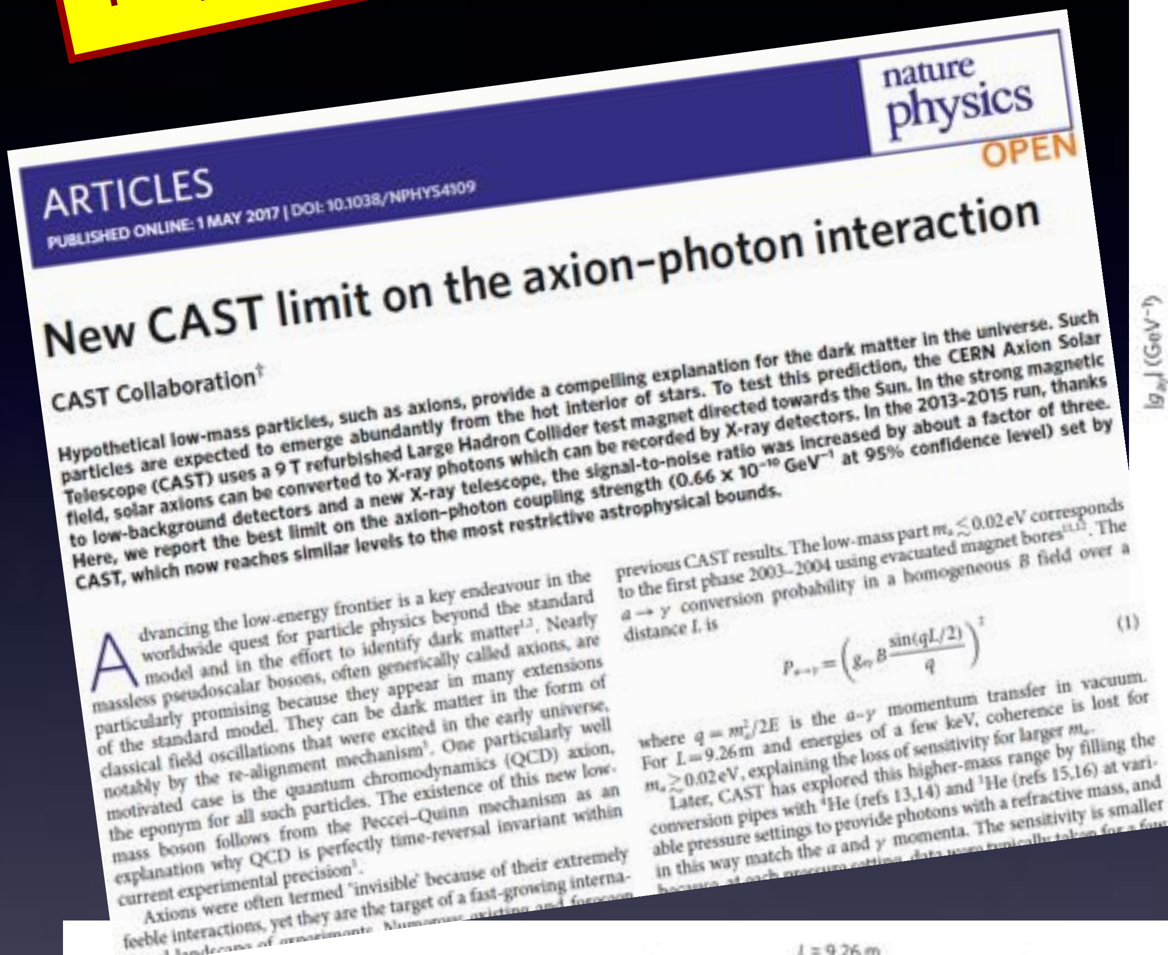
CAST as Axion Helioscope

May 1, 2017



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New CAST limit on the axion–photon interaction

CAST Collaboration†

Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are expected to emerge abundantly from the hot interior of stars. To test this prediction, the CERN Axion Solar Telescope (CAST) uses a 9 T refurbished Large Hadron Collider test magnet directed towards the Sun. In the strong magnetic field, solar axions can be converted to X-ray photons which can be recorded by X-ray detectors. In the 2013–2015 run, thanks to low-background detectors and a new X-ray telescope, the signal-to-noise ratio was increased by about a factor of three. Here, we report the best limit on the axion–photon coupling strength (0.66 × 10^{-10} GeV^{-1} at 95% confidence level) set by CAST, which now reaches similar levels to the most restrictive astrophysical bounds.

Advancing the low-energy frontier is a key endeavour in the worldwide quest for particle physics beyond the standard model and in the effort to identify dark matter[1,2]. Nearly massless pseudoscalar bosons, often generically called axions, are particularly promising because they appear in many extensions of the standard model. They can be dark matter in the form of classical field oscillations that were excited in the early universe, notably by the re-alignment mechanism[3]. One particularly well motivated case is the quantum chromodynamics (QCD) axion, the eponym for all such particles. The existence of this new low-mass boson follows from the Peccei–Quinn mechanism as an explanation why QCD is perfectly time-reversal invariant within current experimental precision[3].

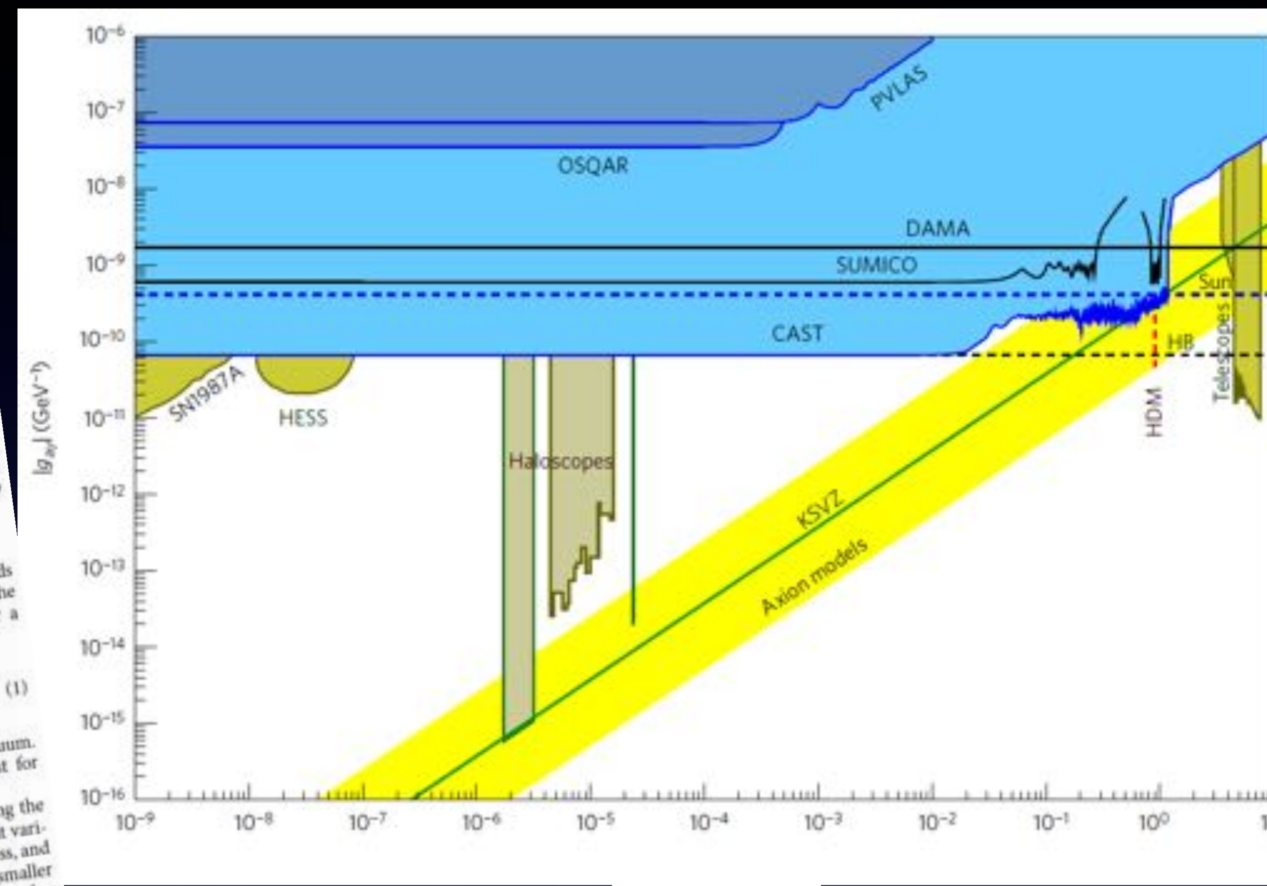
Axions were often termed 'invisible' because of their extremely feeble interactions, yet they are the target of a fast-growing interna-

previous CAST results. The low-mass part $m_a \lesssim 0.02$ eV corresponds to the first phase 2003–2004 using evacuated magnet bores[11,12]. The $a \to \gamma$ conversion probability in a homogeneous B field over a distance L is

$$P_{a\to\gamma} = \left(g_{a\gamma} B \frac{\sin(qL/2)}{q}\right)^2 \quad (1)$$

where $q = m_a^2/2E$ is the a–γ momentum transfer in vacuum. For $L = 9.26$ m and energies of a few keV, coherence is lost for $m_a \gtrsim 0.02$ eV, explaining the loss of sensitivity for larger m_a.

Later, CAST has explored this higher-mass range by filling the conversion pipes with ^4He (refs 13,14) and ^3He (refs 15,16) at variable pressure settings to provide photons with a refractive mass, and in this way match the a and γ momenta. The sensitivity is smaller



m_a [eV]

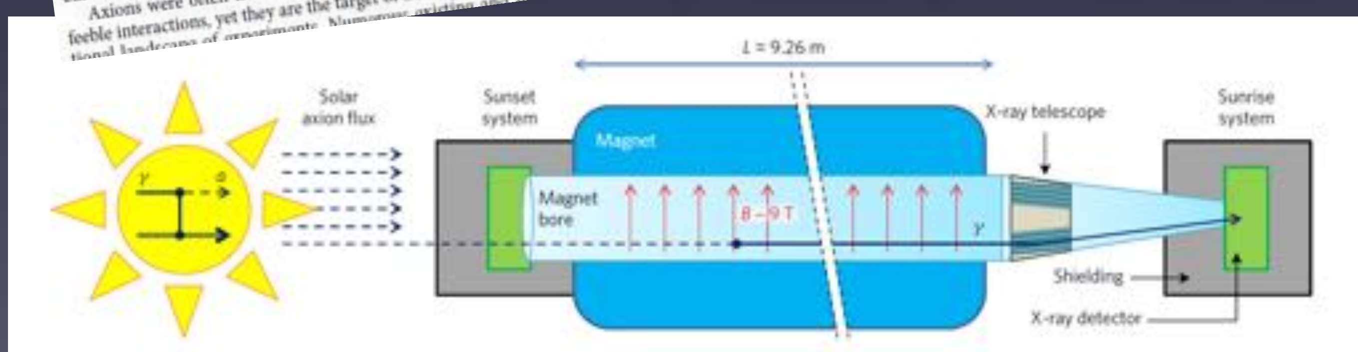


Figure 1 | Sketch of the CAST helioscope at CERN to search for solar axions. These hypothetical low-mass bosons are produced in the Sun by Primakoff scattering on charged particles and converted back to X-rays by the same process in the B-field of an LHC test magnet. The two straight conversion pipes have a cross-section of 14.5 cm^2 each. The magnet can move by ±8° vertically and ±40° horizontally, enough to follow the Sun for about 1.5 h at dawn and dusk with each end of the magnet, where separate detection systems can search for axions at sunrise and sunset, respectively. The sunrise system is equipped with an X-ray telescope (XRT) to focus the signal on a small detector area, strongly increasing signal to noise. Our new results were achieved thanks to an XRT specifically built for CAST and improved low-noise X-ray detectors.

- **Final result:**

$g_{a\gamma} = 0.66 \times 10^{-10}$ /GeV

(95% C.L.)

Slide courtesy of H. Fischer - CAST Collaboration

CAST as Axion Helioscope

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CAST Collaboration†

Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are expected to emerge abundantly from the hot interior of stars. To test this prediction, the CERN Axion Solar Telescope (CAST) uses a 9 T refurbished Large Hadron Collider test magnet directed towards the Sun. In the strong magnetic field, solar axions can be converted to X-ray photons which can be recorded by X-ray detectors. In the 2013–2015 run, thanks to low-background detectors and a new X-ray telescope, the signal-to-noise ratio was increased by about a factor of three. Here, we report the best limit on the axion–photon coupling strength (0.66 × 10^{-10} GeV^{-1} at 95% confidence level) set by CAST, which now reaches similar levels to the most restrictive astrophysical bounds.

Advancing the low-energy frontier is a key endeavour in the worldwide quest for particle physics beyond the standard model and in the effort to identify dark matter[1,2]. Nearly massless pseudoscalar bosons, often generically called axions, are particularly promising because they appear in many extensions of the standard model. They can be dark matter in the form of classical field oscillations that were excited in the early universe, notably by the re-alignment mechanism[3]. One particularly well motivated case is the quantum chromodynamics (QCD) axion, the eponym for all such particles. The existence of this new low-mass boson follows from the Peccei–Quinn mechanism as an explanation why QCD is perfectly time-reversal invariant within current experimental precision[3].

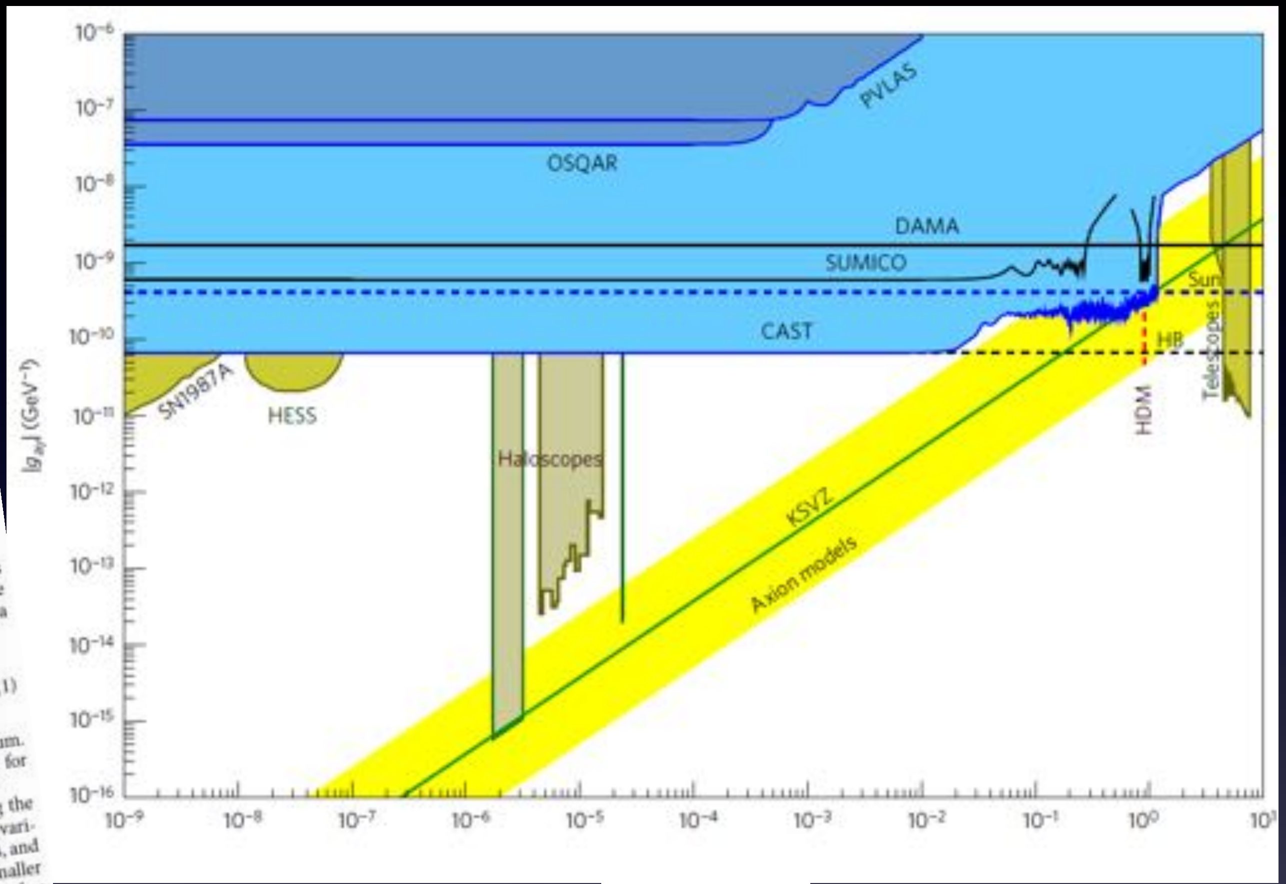
Axions were often termed 'invisible' because of their extremely feeble interactions, yet they are the target of a fast-growing interna-

previous CAST results. The low-mass part $m_a \lesssim 0.02$ eV corresponds to the first phase 2003–2004 using evacuated magnet bores[11,12]. The $a \rightarrow \gamma$ conversion probability in a homogeneous B field over a distance L is

$$P_{a\rightarrow\gamma} = \left(g_{a\gamma} B \frac{\sin(qL/2)}{q}\right)^2 \quad (1)$$

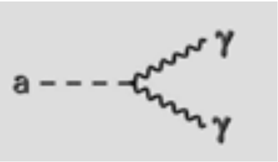
where $q = m_a^2/2E$ is the a–γ momentum transfer in vacuum. For $L = 9.26$ m and energies of a few keV, coherence is lost for $m_a \gtrsim 0.02$ eV, explaining the loss of sensitivity for larger m_a.

Later, CAST has explored this higher-mass range by filling the conversion pipes with ^4He (refs 13,14) and ^3He (refs 15,16) at variable pressure settings to provide photons with a refractive mass, and in this way match the a and γ momenta. The sensitivity is smaller



Photon Coupling

$$\mathcal{L} = g_{a\gamma}\, \vec{E} \cdot \vec{B}\, a$$



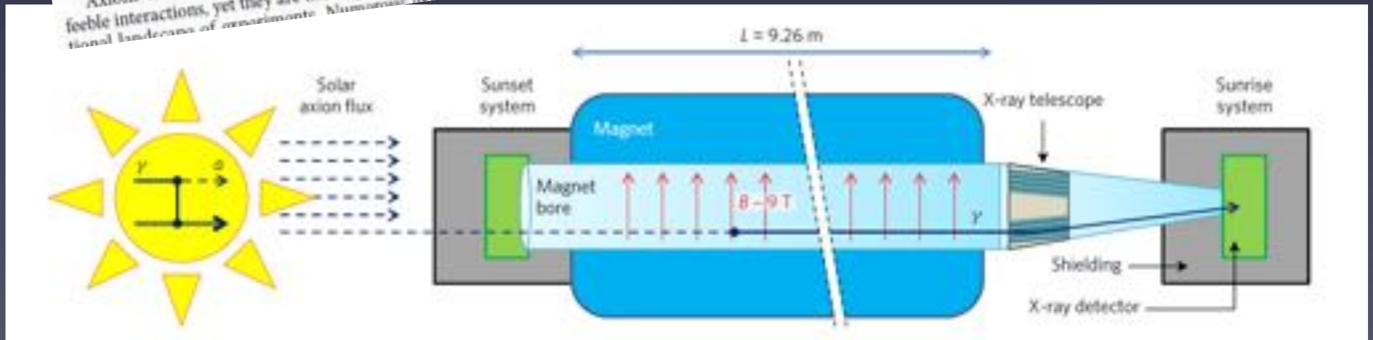


Figure 1 | Sketch of the CAST helioscope at CERN to search for solar axions. These hypothetical low-mass bosons are produced in the Sun by Primakoff scattering on charged particles and converted back to X-rays by the same process in the B-field of an LHC test magnet. The two straight conversion pipes have a cross-section of 14.5 cm² each. The magnet can move by ±8° vertically and ±40° horizontally, enough to follow the Sun for about 1.5 h at dawn and dusk with each end of the magnet, where separate detection systems can search for axions at sunrise and sunset, respectively. The sunrise system is equipped with an X-ray telescope (XRT) to focus the signal on a small detector area, strongly increasing signal to noise. Our new results were achieved thanks to an XRT specifically built for CAST and improved low-noise X-ray detectors.

- **Final result:**

$g_{a\gamma} = 0.66 \times 10^{-10}$ /GeV

(95% C.L.)

Slide courtesy of H. Fischer - CAST Collaboration

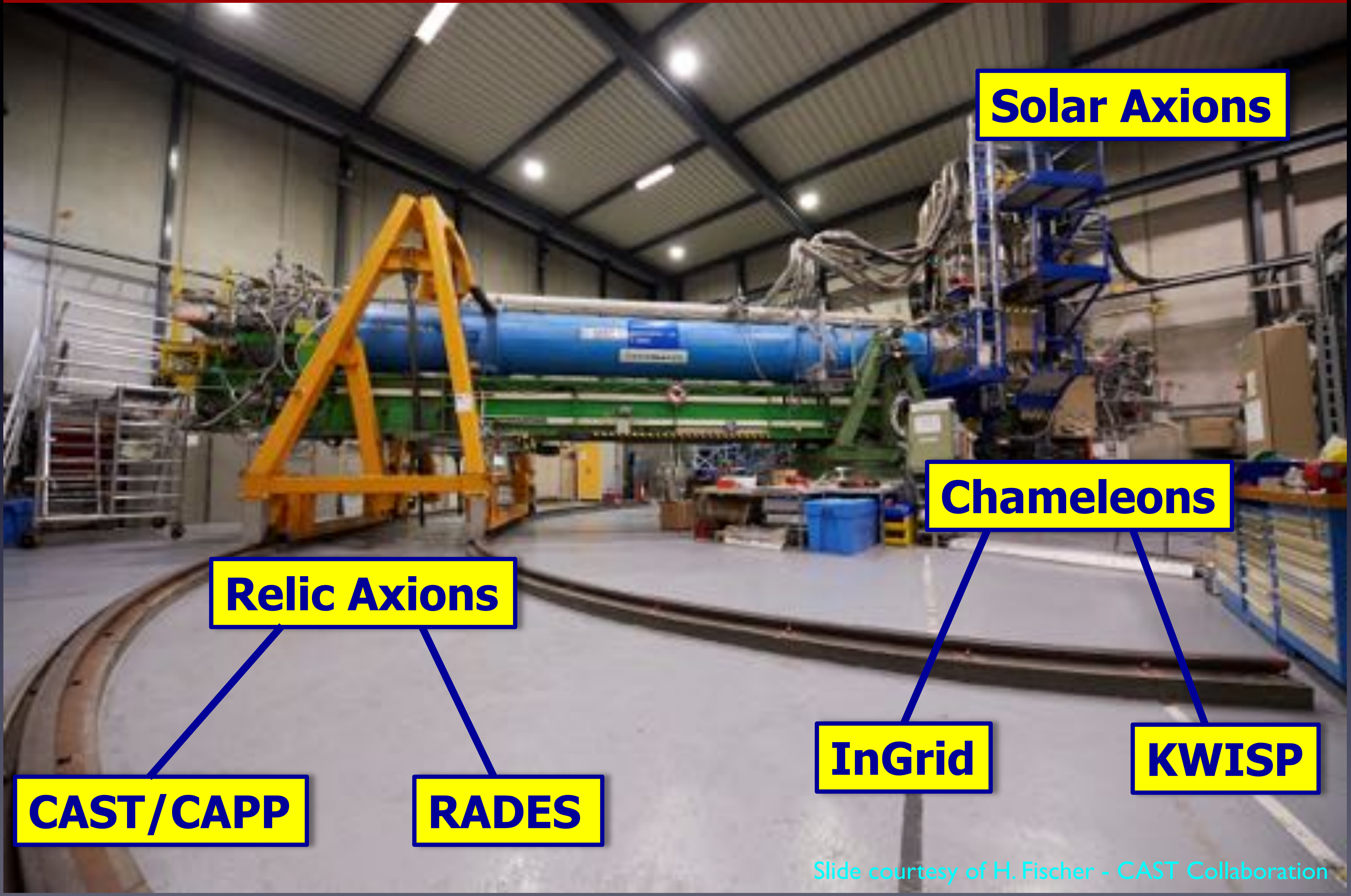
Deeper in the Dark Side

The CAST physics programme

- CAST has completed its original mission searching for evidence of solar axions
  - "Axion helioscope" configuration with MicroMegas x-ray photon detectors
  - Results published in Nature Physics: **CAST is still the benchmark reference for axion searches**
- With a **new physics program** (approved by CERN(*) in October 2015) CAST has expanded its horizons to Dark Matter and Dark Energy with three new research lines
  - detection of **relic** (or "Dark Matter") **Axions** with **μ-wave resonant cavities** (axion haloscope)
  - detection of **photon-coupled** solar **Chameleons** with the **InGrid** photon detector
  - detection of **matter-coupled** solar **Chameleons** with the **KWISP** force sensor

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

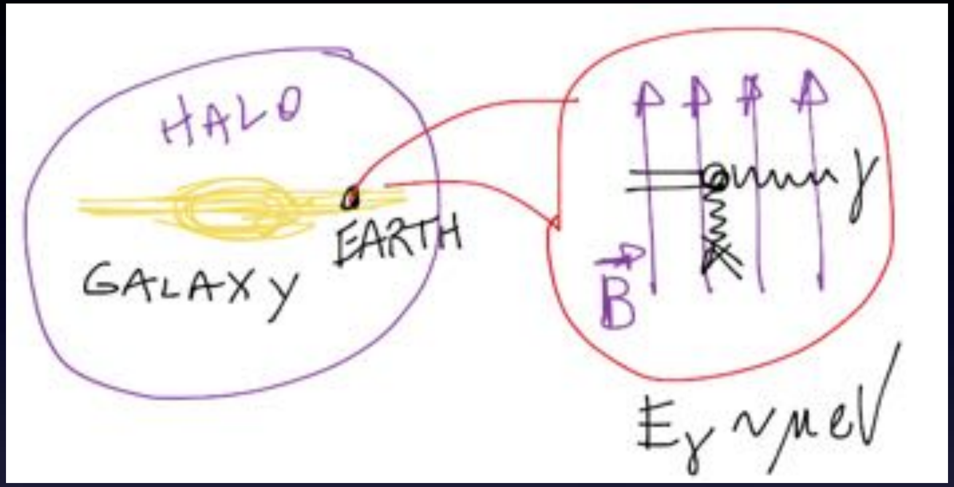
The CAST Physics Programme

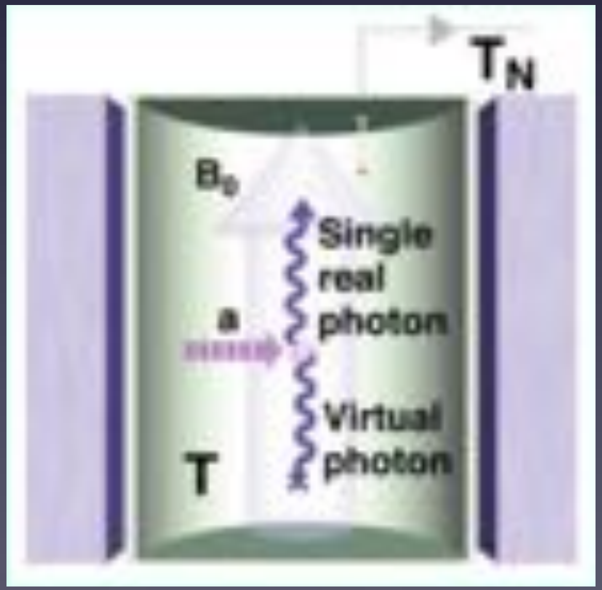


Dark Matter Axions

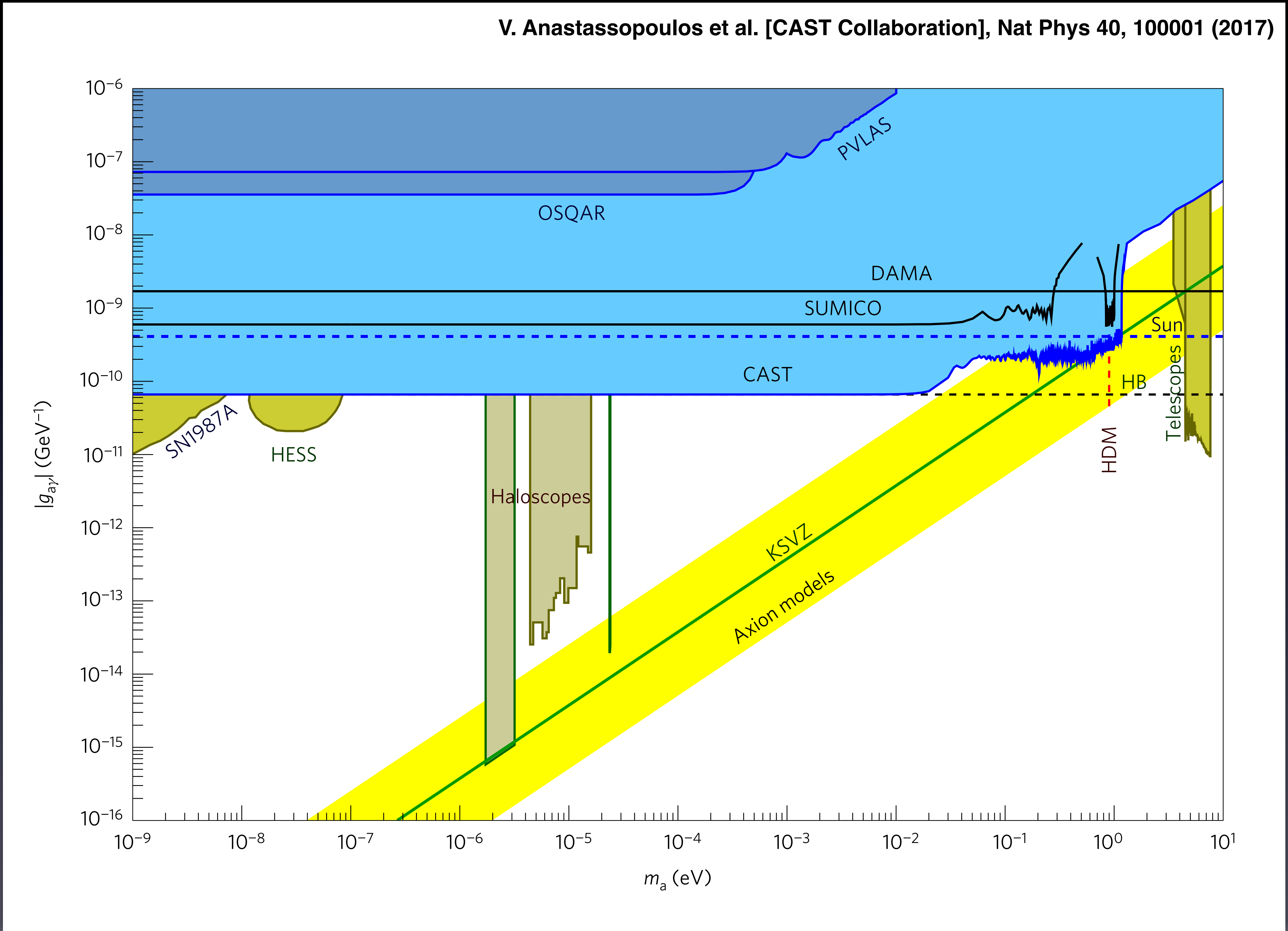
Haloscope search for DM Axions

- cold "relic" axions are believed to accrete gravitationally around the galactic halo resulting in a uniform density of particles in the vicinity of the Earth
- halo axions can convert into a (μ-wave) photon in the presence of a magnetic field, and a resonant cavity enhances the convcersion probability
- since the axion mass, and therefore the converted photon frequency, is not known, the cavity resonance must be tuned in search of a power excess over background
- haloscope searches can be very sensitive, but are extremely narrow band



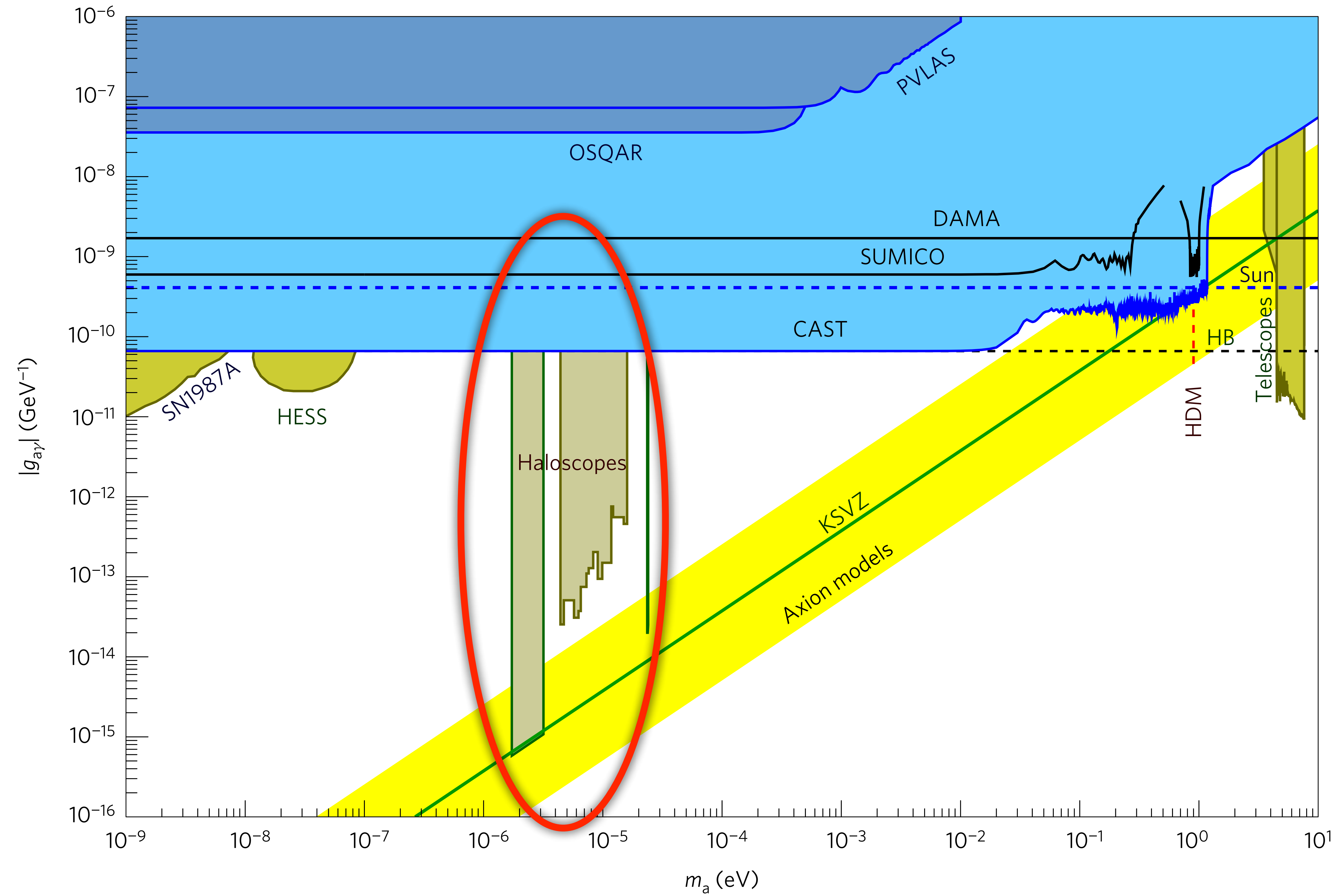


Axion haloscope searches mass bandwidth



Axion haloscope searches mass bandwidth

V. Anastassopoulos et al. [CAST Collaboration], Nat Phys 40, 100001 (2017)



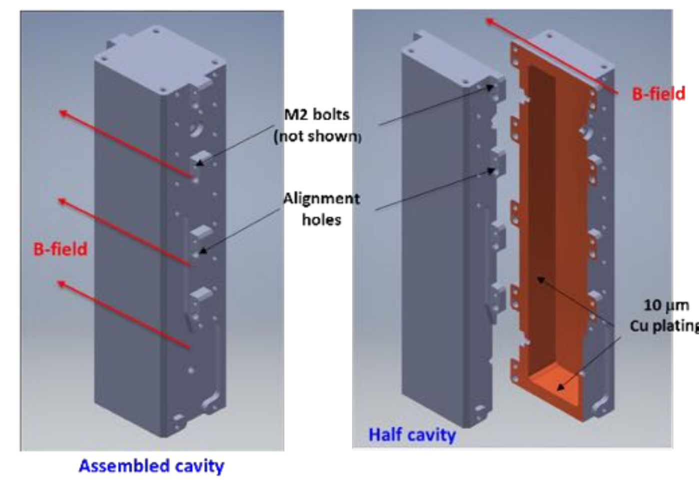
Today: CAST as Haloscope

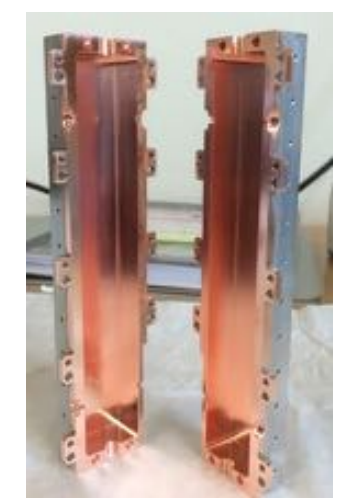
$$P \approx g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) \boldsymbol{B^2 \cdot Q \cdot V \cdot C}$$

$$Q = 2\pi f \frac{\text{Stored Energy}}{\text{Power Loss}}$$ Quality factor

$$C = \frac{1}{B_0^2 V} \frac{\left|\int \boldsymbol{B}\cdot\boldsymbol{E} d^3x\right|^2}{\int \boldsymbol{E}\cdot\boldsymbol{E} d^3x}$$ Geometry factor

- Measurement with cavities





- $$P = (g_{a\gamma\gamma})^2 \rho_a \frac{1}{\boldsymbol{m_a}} B^2 C V \, min[Q_c, Q_a]$$
$$= 1.6 \times 10^{-23}\text{W} \times (g_{a\gamma\gamma} 10^{14}\text{GeV})^2 \left(\frac{\rho_a}{300 \text{ MeV/cm}^3}\right)\left(\frac{2.4 \times 10^{-5} eV}{\boldsymbol{m_a}}\right) \times \left(\frac{B}{9 \text{ T}}\right)^2 \left(\frac{\boldsymbol{C}}{0.66}\right)\left(\frac{V}{5 \, l}\right)\left(\frac{Q}{5 \times 10^3}\right)$$

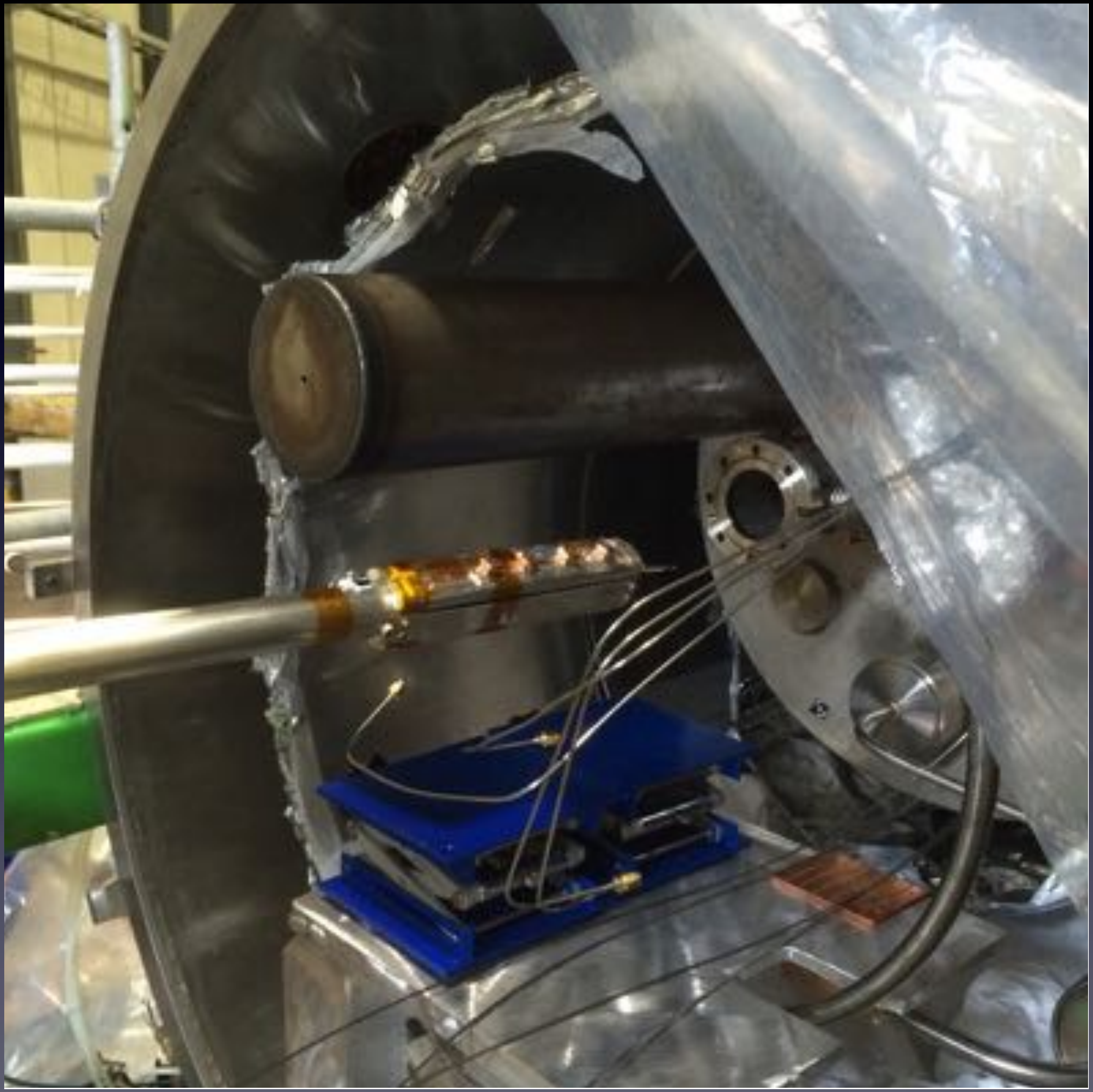
- m_a = 24 μeV (f = 5.8 GHz)
- B = 9 T , CAST magnet
- V = 5 liters
- Q = $min[Q_c,Q_a] = Q_0/2$ ~ 5,000; critical coupling
  - Q_c loaded quality factor
  - Q_0 cavity quality factor

- **Projected Sensitivity:**

~ 10 days, $g_{a\gamma\gamma} = 10^{-14}\text{GeV}^{-1}$

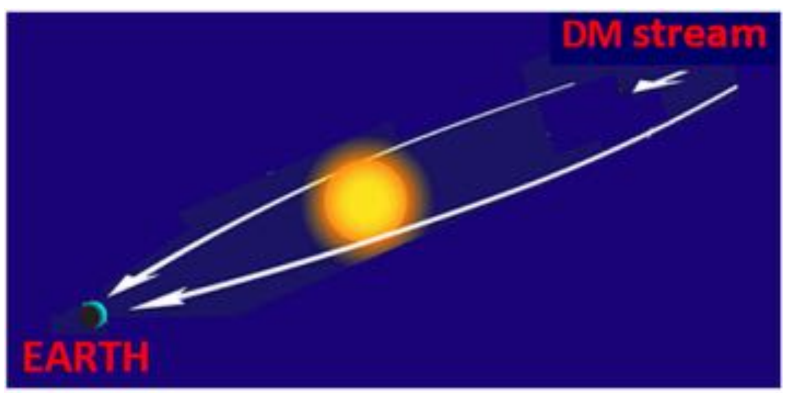
Slide courtesy of H. Fischer - CAST Collaboration

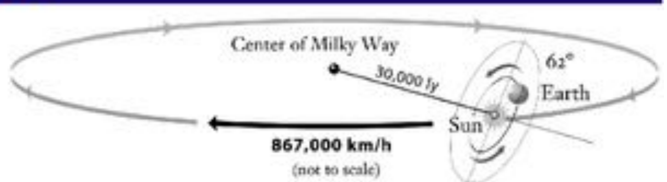
Cavity insertion in the CAST magnet



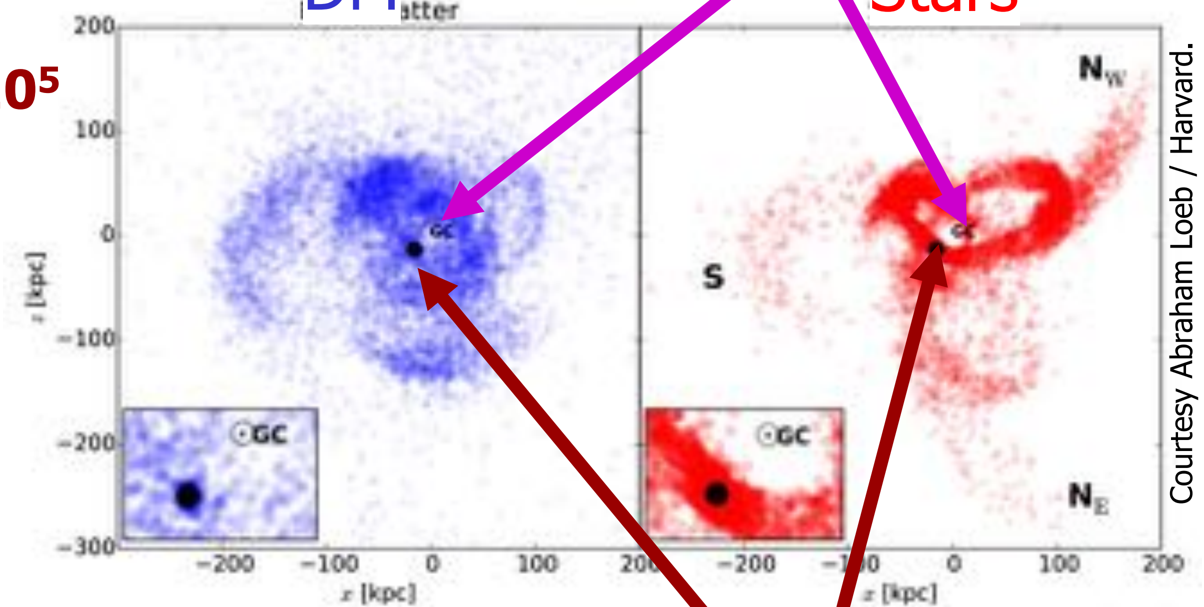
Streaming Dark Matter

- Distribution of DM in Galaxy not known
  - Believed to be homogeneous
- distribution following stars:
  - Local density increase by 10^5
  - **Sensitivity temporaly increased by 10^5**
  - Duty cycle O(1%) if crossing few days





Sagitarius Stream:



Strategy:

cf. https://arxiv.org/abs/1703.01436

- fast scanning for CAST-CAPP
- joint efforts of world wide cavity experiments

The Sagittarius Stream is a complex structure made of tidally stripped stars and dark matter from the Sagittarius Dwarf Galaxy due to the ongoing merging with our Galaxy the last ~5 Gyears.

Slide courtesy of H. Fischer - CAST Collaboration

Streaming Dark Matter

- Distribution of DM in Galaxy not known
  - B
- distr
  - L
  - S
  - D

arXiv:1803.08588v2 [astro-ph.IM] 26 Mar 2018

Search for streaming dark matter axions or other exotica

A. Gardikiotis[1], V. Anastassopoulos[1], S. Bertolucci[2], G. Cantatore[3], S. Cetin[4], H. Fischer[5], W. Funk[6], D.H.H. Hoffmann[7,8], S. Hofmann[9], M. Karuza[10], M. Maroudas[1], Y. Semertzidis[11], I. Tkachev[12], K. Zioutas[1,6]

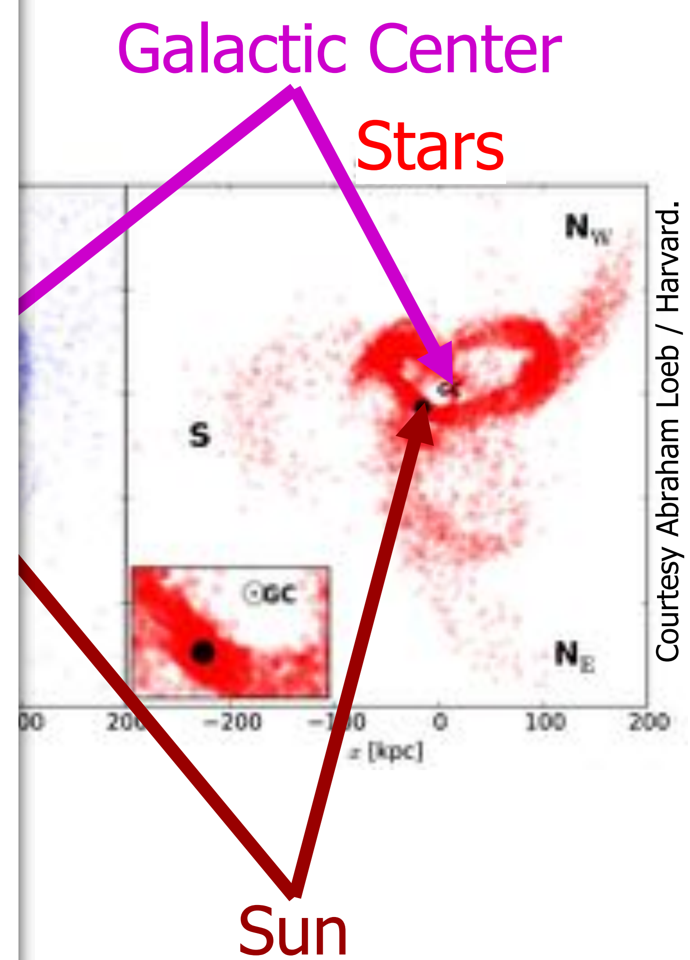
[1]University of Patras, Patras, Greece
[2]INFN, LNF, Bologna, Italy
[3]University and INFN Trieste, Italy
[4]Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Eyup, Istanbul, Turkeyi
[5]University of Freiburg, Germany
[6]CERN, Geneva, Switzerland
[7]Xi'An Jiaoton University, School of Science, Xi'An, China
[8]National Research Nuclear University MEPhI, Moscow, Russian Federation
[9]Munich, Germany
[10]Department of Physics, Center for micro, nano sciences and technologies, University of Rijeka, Croatia, and, INFN Trieste, Italy
[11]Department of physics, KAIST, and Center for Axion and Precision Physics Research, IBS, Daejeon, Republic of Korea
[12]INR, Moscow, Russia

DOI: will be assigned

We suggest a new approach to search for galactic axions or other similar exotica. Streaming dark matter (DM) could have a better discovery potential because of flux enhancement, due to gravitational lensing when the Sun and/or a planet are aligned with a DM stream [1]. Of interest are also axion miniclusters, in particular, if the solar system has trapped one during its formation. Wide-band axion antennae fit this concept, but also the proposed fast narrow band scanning. A network of detectors can provide full time coverage and a large axion mass acceptance. Other DM searches may profit from this proposal.

1 Introduction

...Stream:



...tarius Stream is a complex ... made of tidally stripped stars and dark matter from the Sagittarius Dwarf Galaxy due to the ongoing merging with our Galaxy the last ~5 Gyears.

Strate...

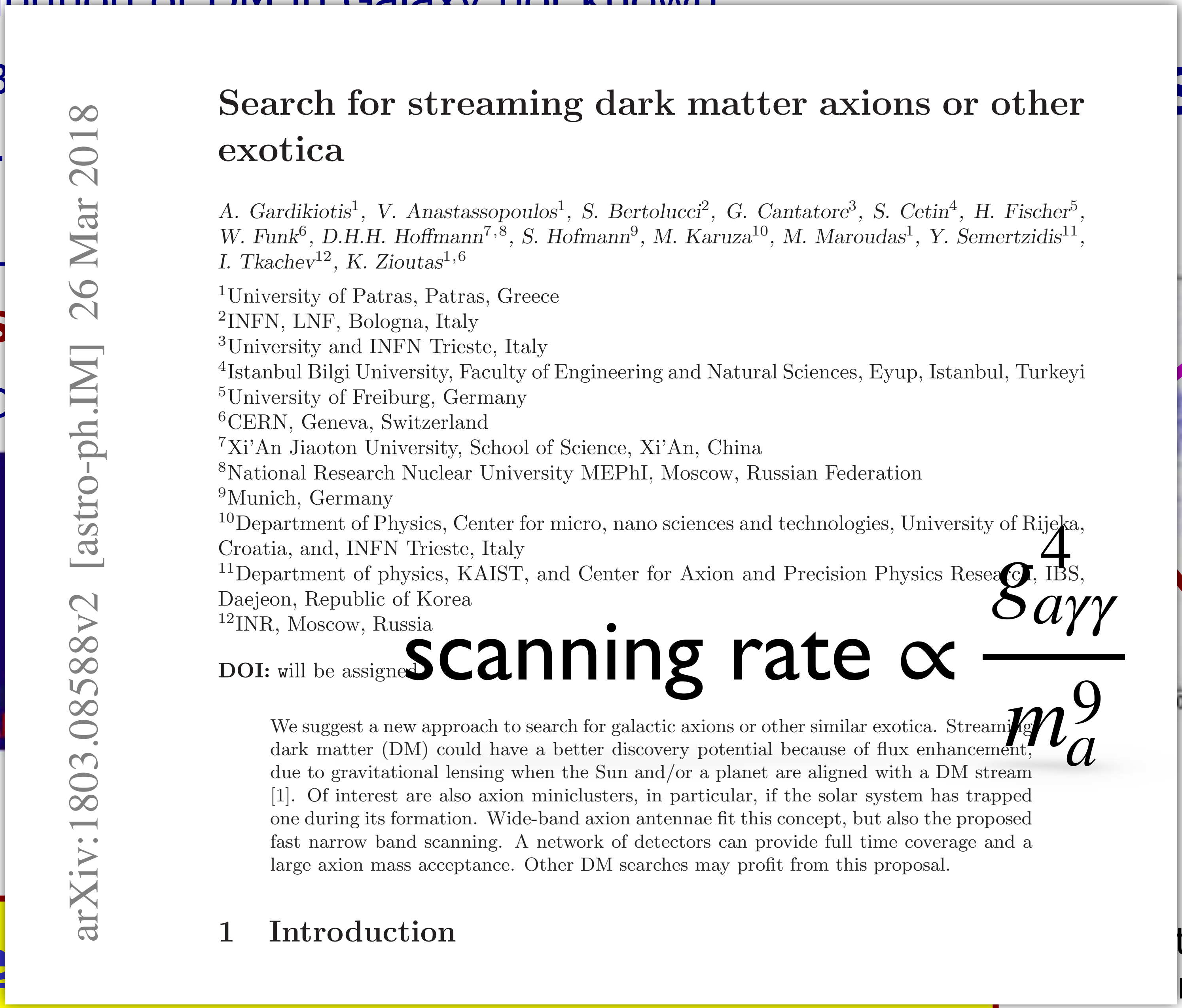
- fast scanning for CAST-CAPP
- joint efforts of world wide cavity experiments

Streaming Dark Matter

- Distribution of DM in Galaxy not known
  - B
- distr
  - L
  - S
  - D

EA

Strate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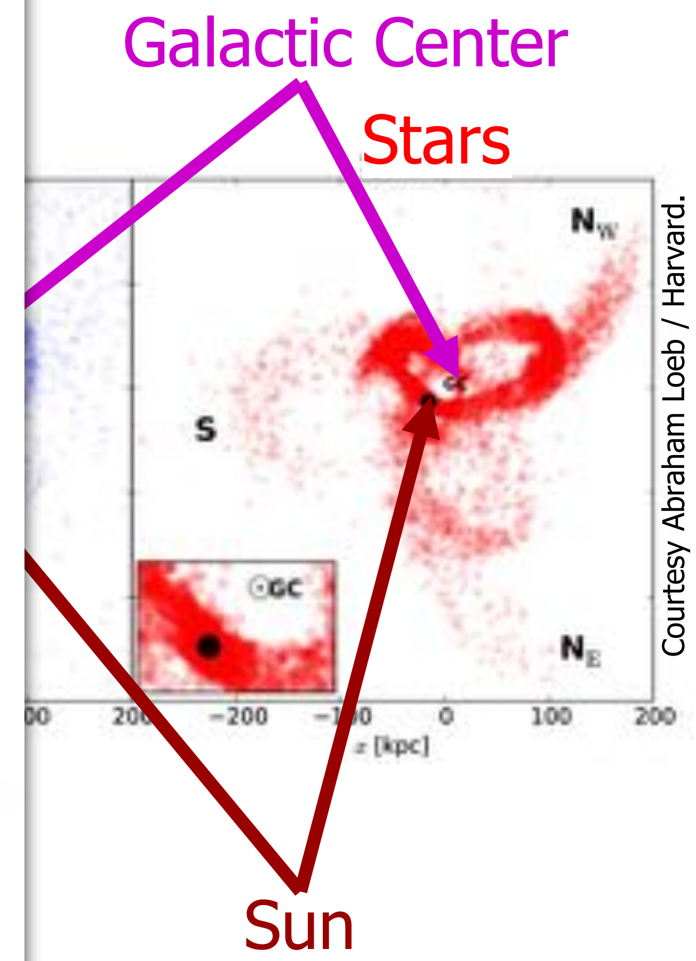
1 Introduction

arXiv:1803.08588v2 [astro-ph.IM] 26 Mar 2018

$$\text{scanning rate} \propto \frac{g_{a\gamma\gamma}^4}{m_a^9}$$

Stream:



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- fast scanning for CAST-CAPP
- joint efforts of world wide cavity experiments

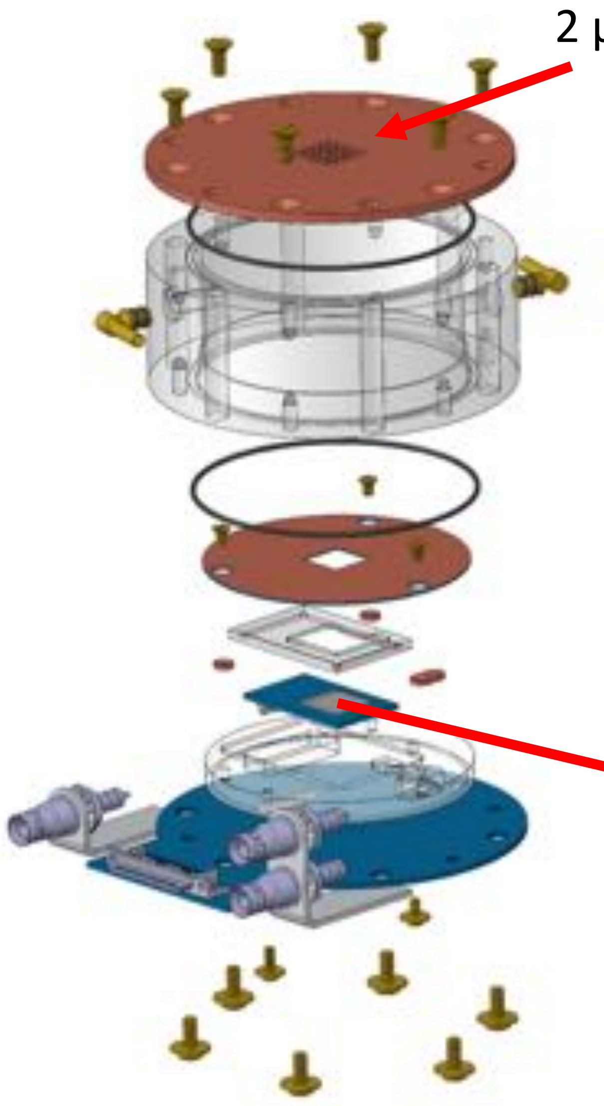
Slide courtesy of H. Fischer - CAST Collaboration

Chameleons

Chameleon to photon: the InGrid/GridPix detector

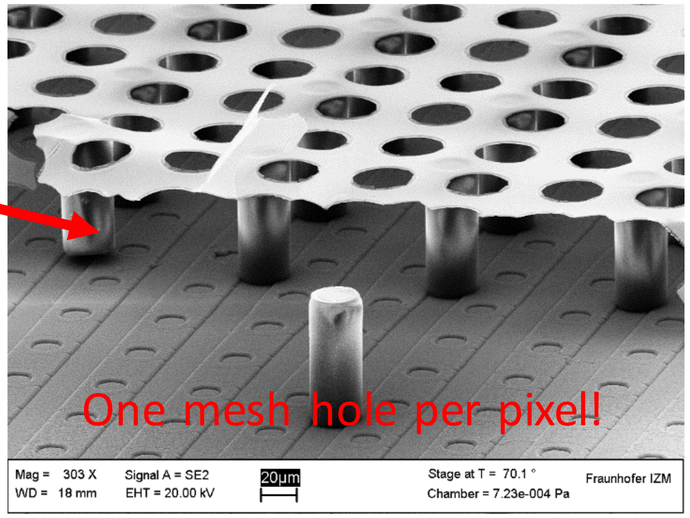
The InGrid based X-ray detector

2 µm Mylar entrance window

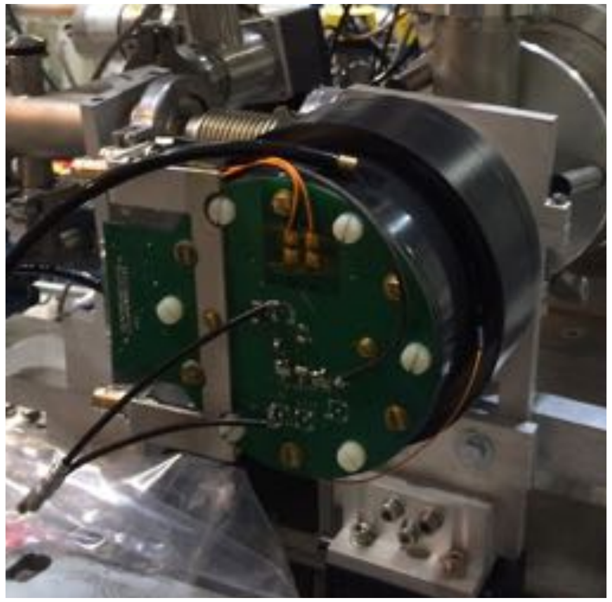


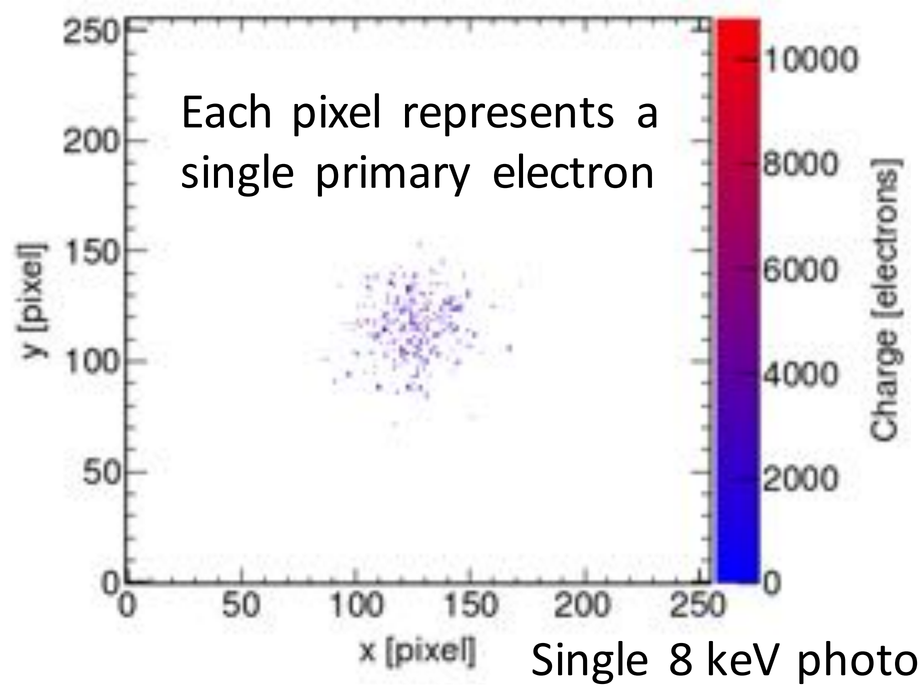
Detection of photons down to 277 eV (Carbon K_{α} line) possible

Timepix ASIC combined with integrated Micromegas stage (InGrid)



InGrid based X-ray detector

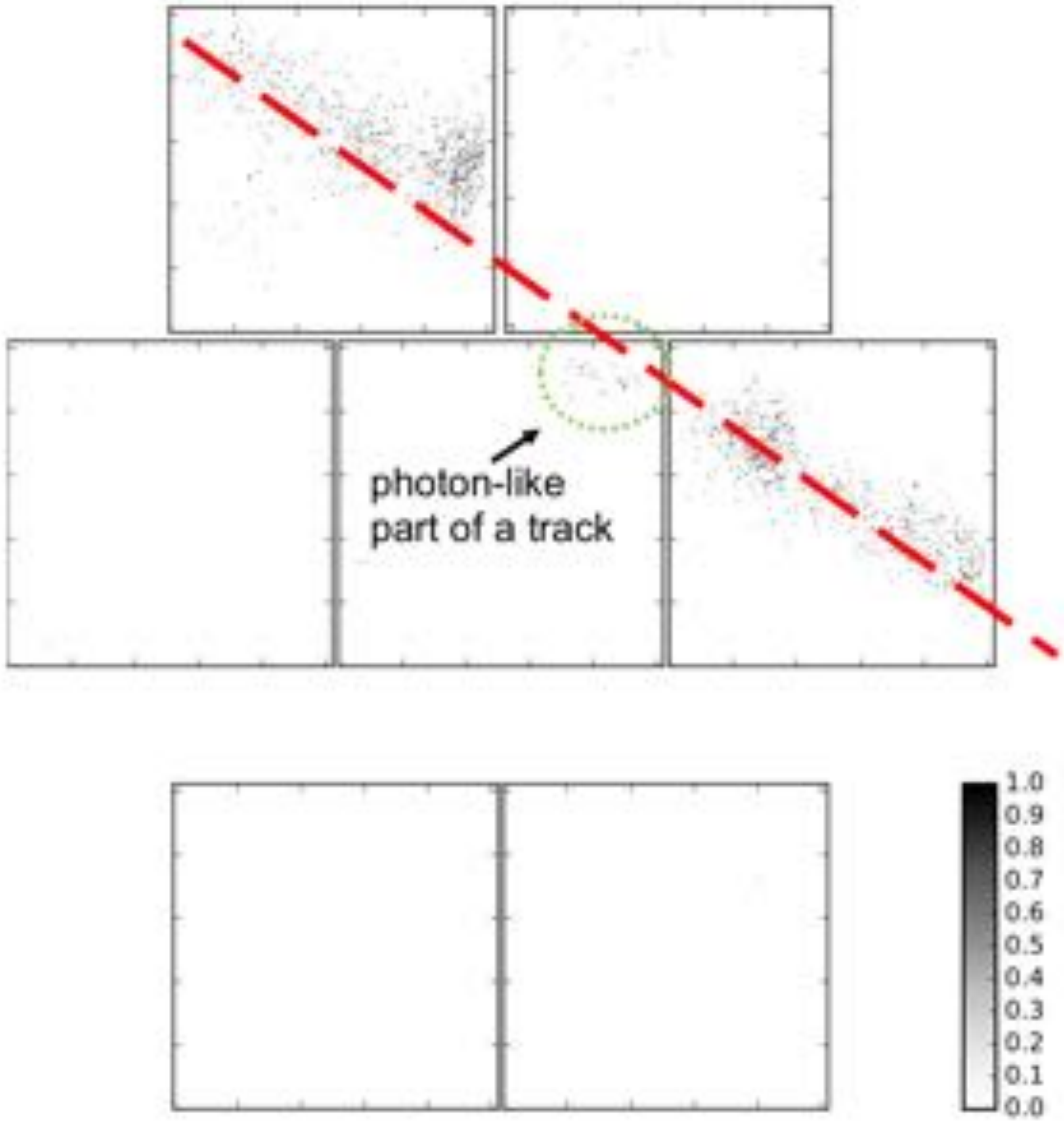




Single 8 keV photon

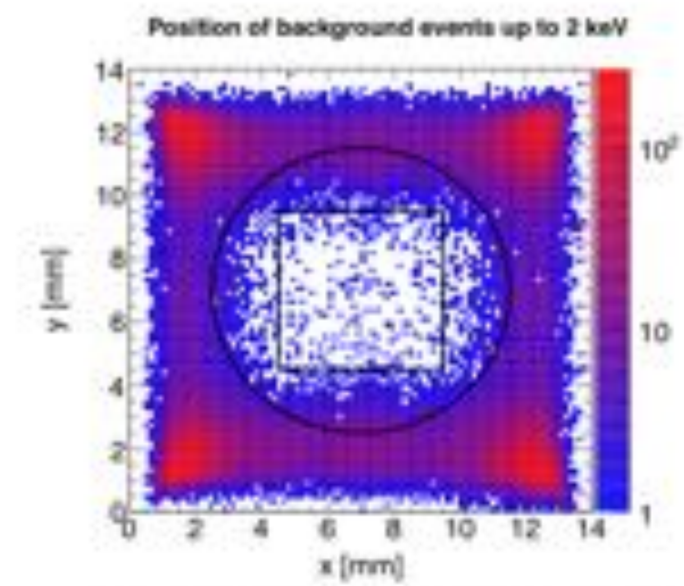
Slide courtesy of K. Desch - CAST Collaboration

7 InGrids at work



photon-like signature on central InGrid can now be easily vetoed by the surrounding chips

→ should reduce remaining background significantly



Background distribution on single InGrid chip in 2015

Slide courtesy of K. Desch - CAST Collaboration

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Improved search for solar chameleons with a GridPix detector at CAST

The CAST collaboration

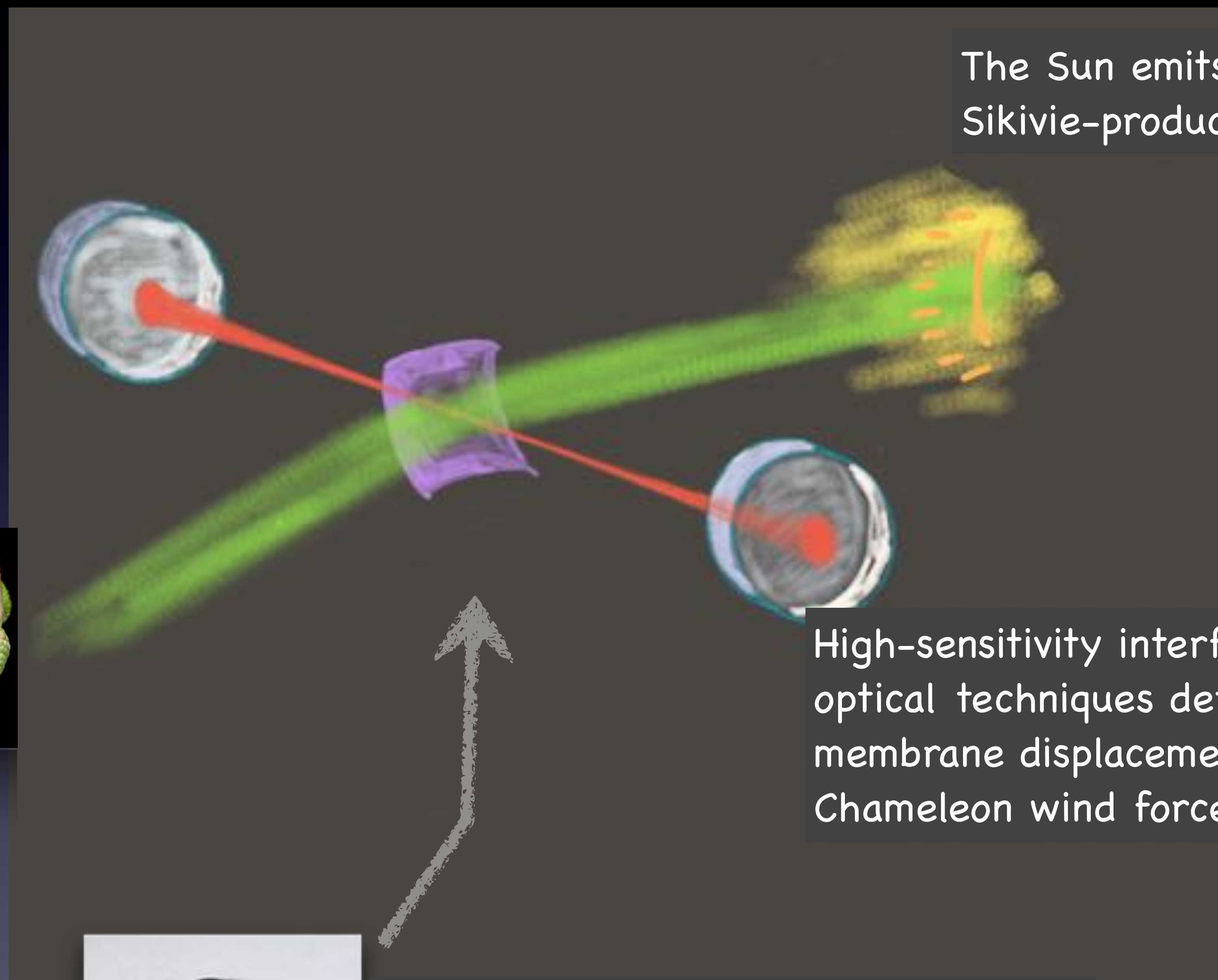
V. Anastassopoulos,[a] S. Aune,[b] K. Barth,[c] A. Belov,[d]
H. Bräuninger,[e] G. Cantatore,[f,g] J.M. Carmona,[h] J.F. Castel,[h]
S.A. Cetin,[i] F. Christensen,[j] T. Dafni,[h] M. Davenport,[c]
A. Dermenev,[d] K. Desch,[k] B. Döbrich,[c] C. Eleftheriadis,[l]
G. Fanourakis,[m] E. Ferrer-Ribas,[b] H. Fischer,[n] W. Funk,[c]
J.A. García,[h,1] A. Gardikiotis,[a] J.G. Garza,[h] E.N. Gazis,[o]
T. Geralis,[m] I. Giomataris,[b] S. Gninenko,[d] C.J. Hailey,[p]
M.D. Hasinoff,[q] D.H.H. Hoffmann,[r] F.J. Iguaz,[h] I.G. Irastorza,[h]
A. Jakobsen,[j] J. Jacoby,[s] K. Jakovčić,[t] J. Kaminski,[k] M. Karuza,[u]
S. Kostoglou,[c] N. Kralj,[u,2] M. Krčmar,[t] C. Krieger,[k,*,3] B. Lakić,[t]
J. M. Laurent,[c] A. Liolios,[l] A. Ljubičić,[t] G. Luzón,[h] M. Maroudas,[a]
L. Miceli,[v] S. Neff,[w] I. Ortega,[h,c] T. Papaevangelou,[b]
K. Paraschou,[l] M.J. Pivovaroff,[x] G. Raffelt,[y] M. Rosu,[w,4] J. Ruz,[x]
E. Ruiz Chóliz,[h] I. Savvidis,[l] S. Schmidt,[k] Y.K. Semertzidis,[v,z]
S.K. Solanki,[aa,5] L. Stewart,[c] T. Vafeiadis,[c] J.K. Vogel,[x]
M. Vretenar,[u] W. Wuensch,[c] S.C. Yildiz,[i,6] K. Zioutas[a,c]

and P. Brax[ab]

JCAP01(2019)032

Chameleon on matter: the KWISP detector

The Kinetic WISP detection principle



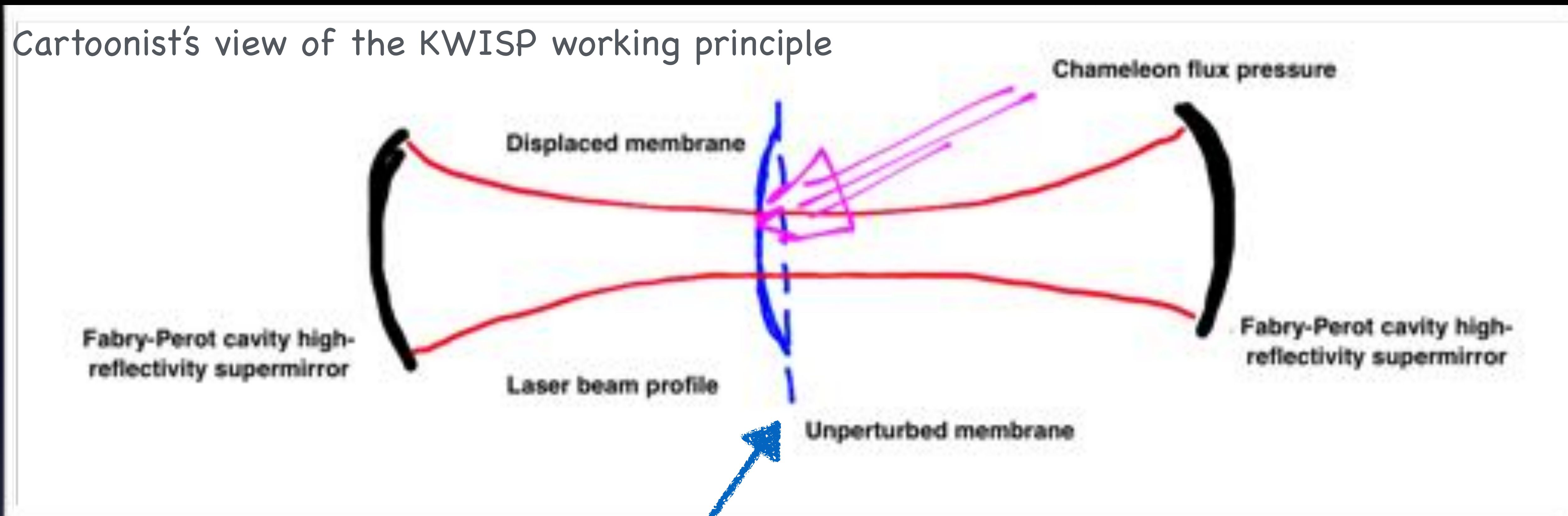
The Sun emits a stream of Sikivie-produced Chameleons

High-sensitivity interferometric 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

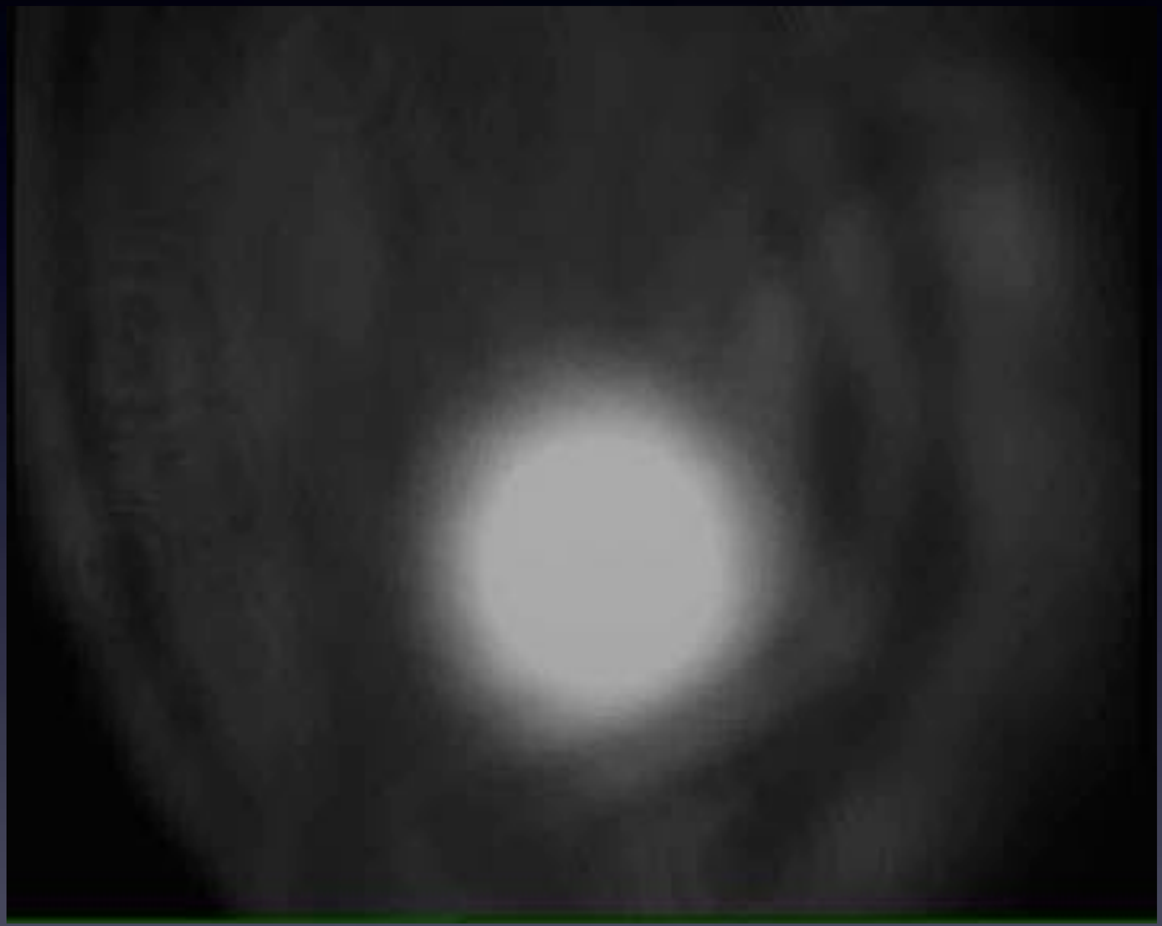
KWISP principle II



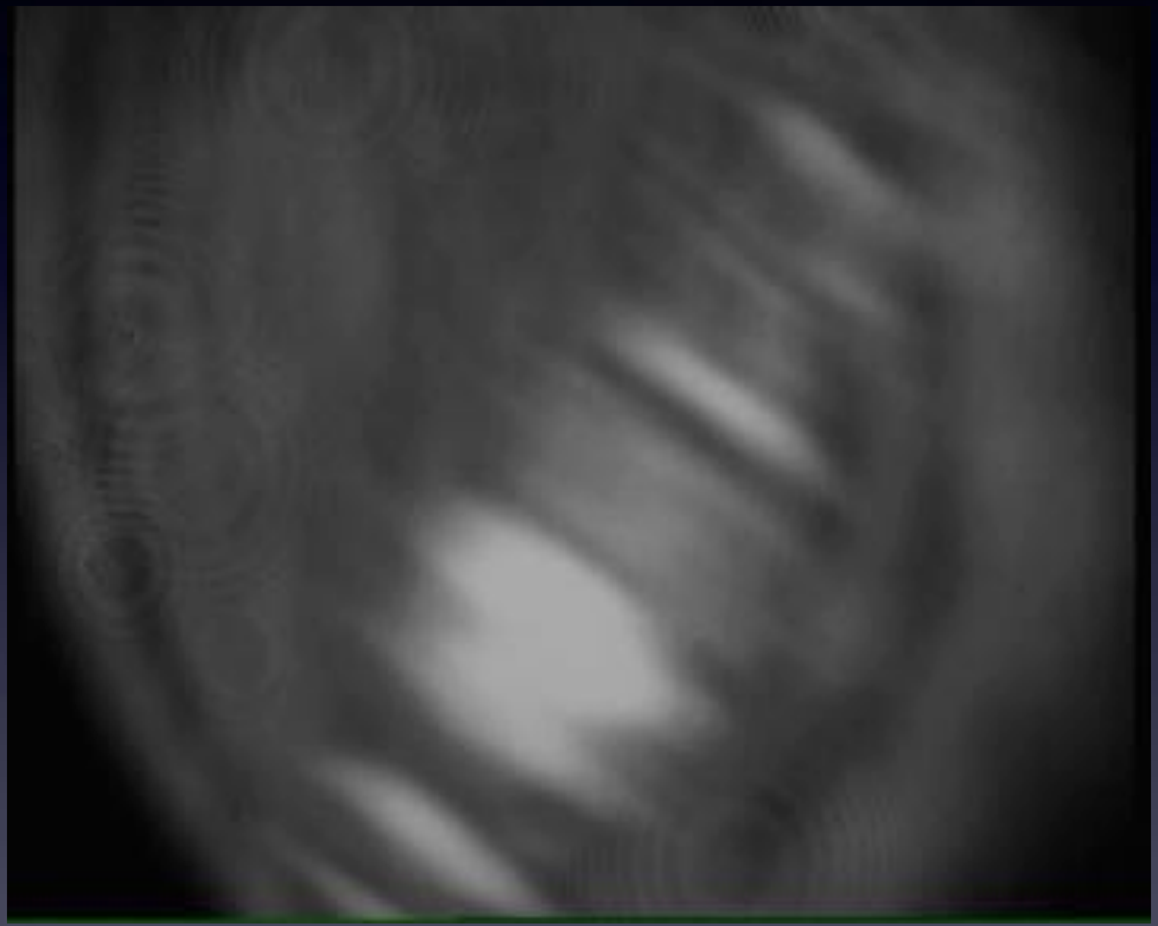

5x5 mm^2 Si_3N_4 membrane

- The opto-mechanical force-sensor technology at the heart of KWISP has been developed and tested preliminarily in the INFN Trieste laboratory (see M. Karuza, G. Cantatore, A. Gardikiotis, D.H.H. Hoffmann, Y.K. Semertzidis, K. Zioutas, Physics of the Dark Universe, 12 (2016) 100-104)
- The CAST experiment is now equipped with the latest version of 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 cavity lock

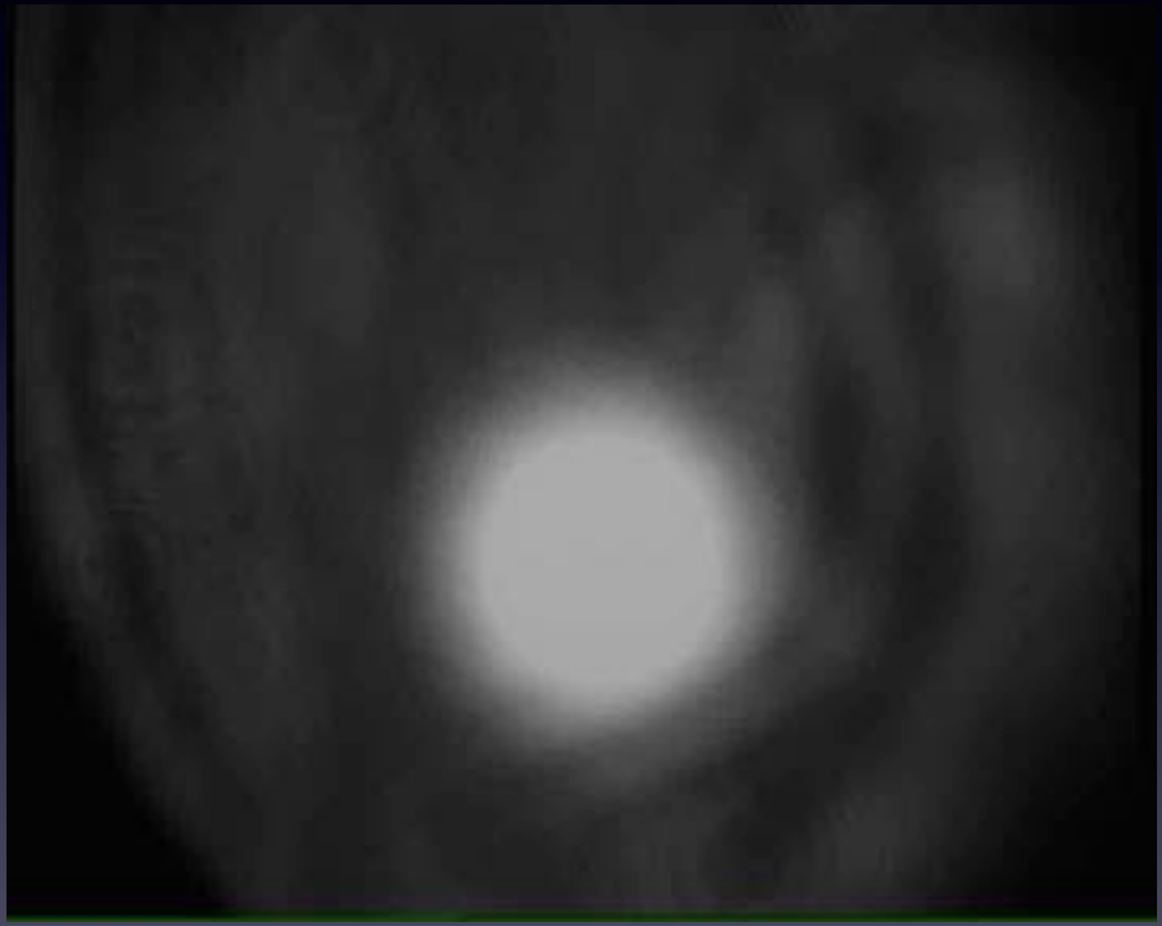


TEM00 mode, no membrane

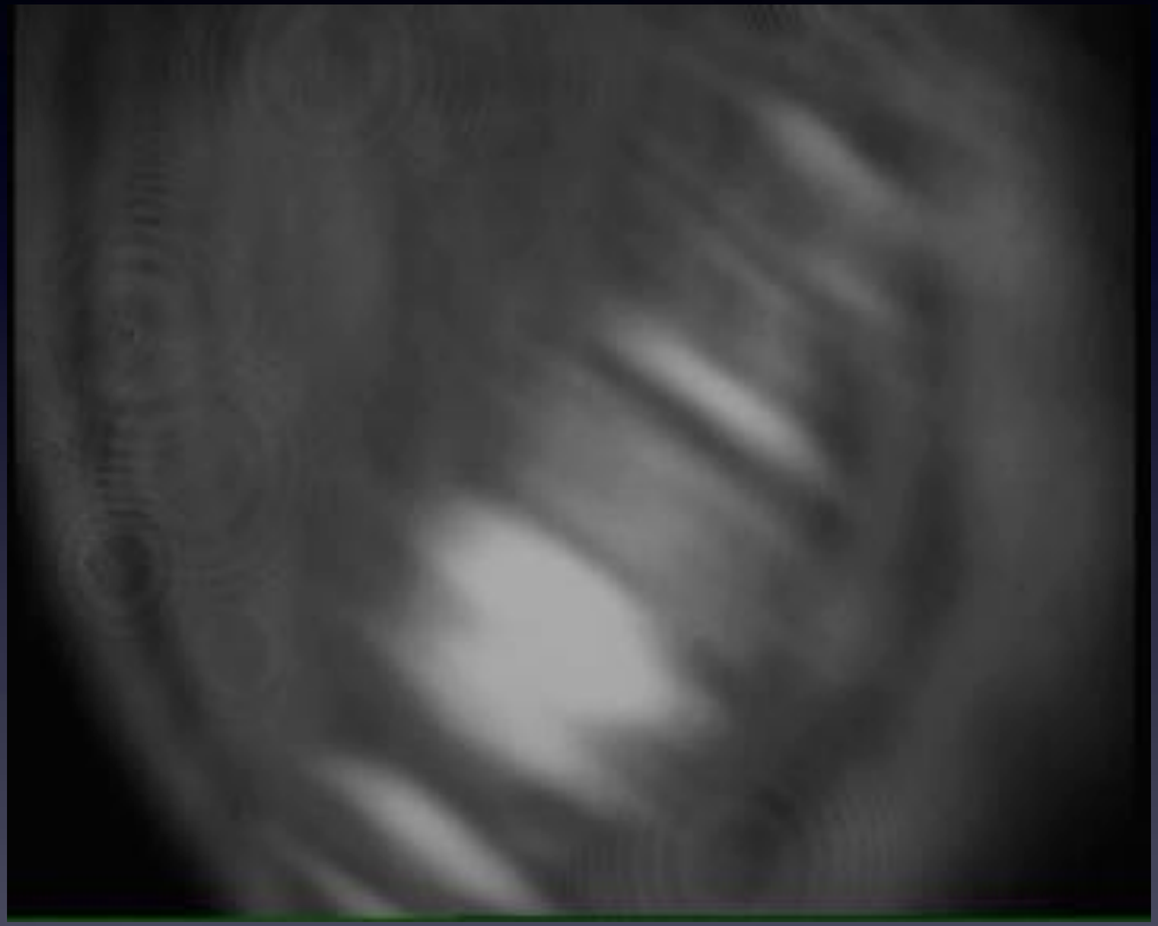


Mode mixture with membrane (TEM00 + h.o.m.)

KWISP cavity lock

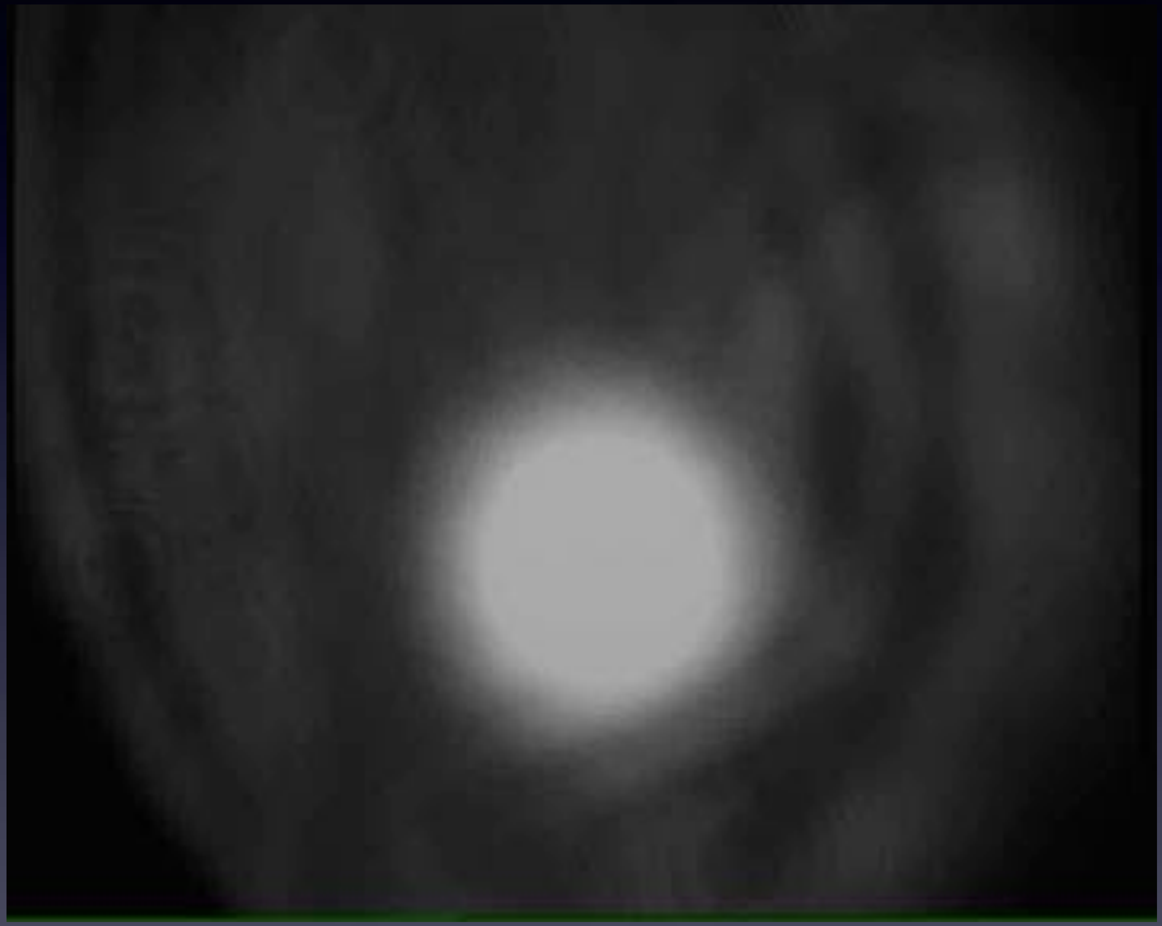


TEM00 mode, no membrane

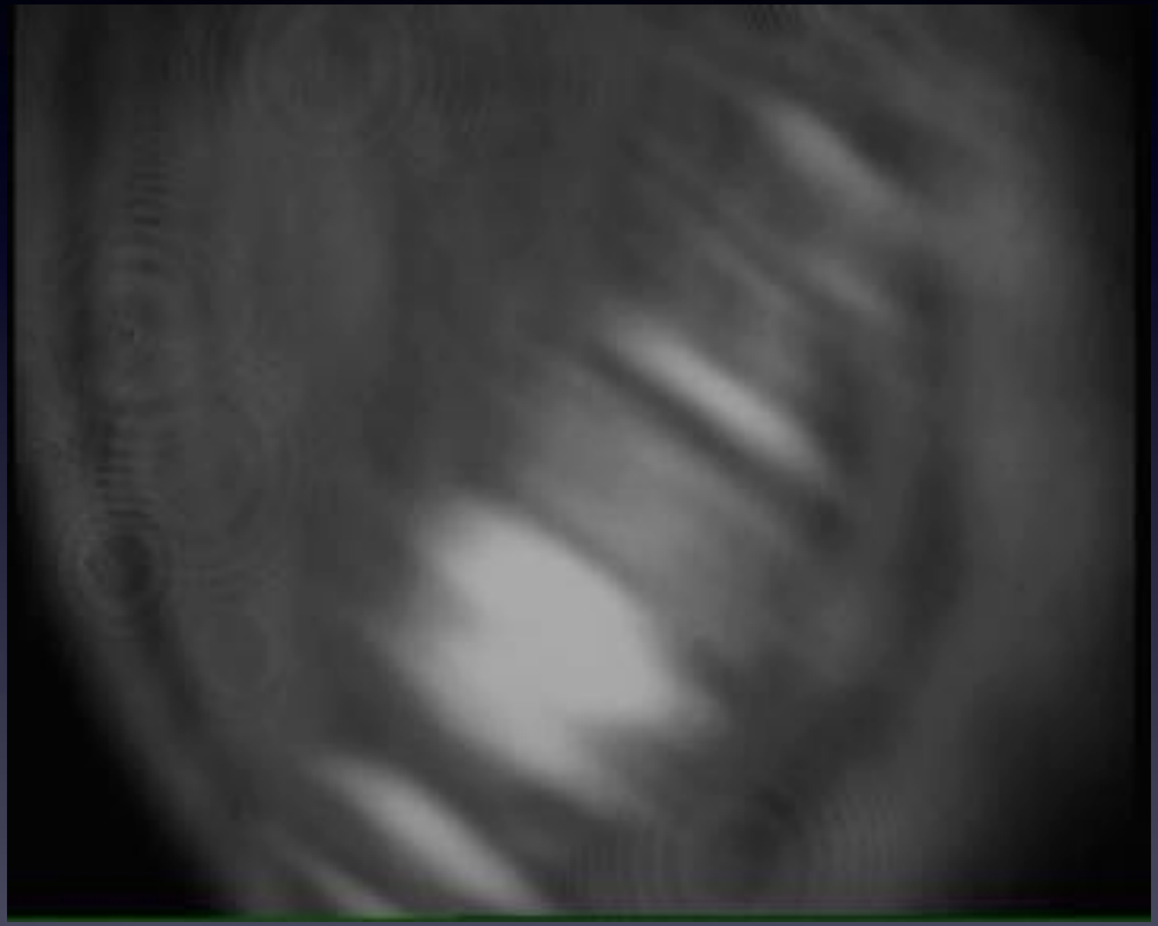


Mode mixture with membrane (TEM00 + h.o.m.)

KWISP cavity lock



TEM00 mode, no membrane



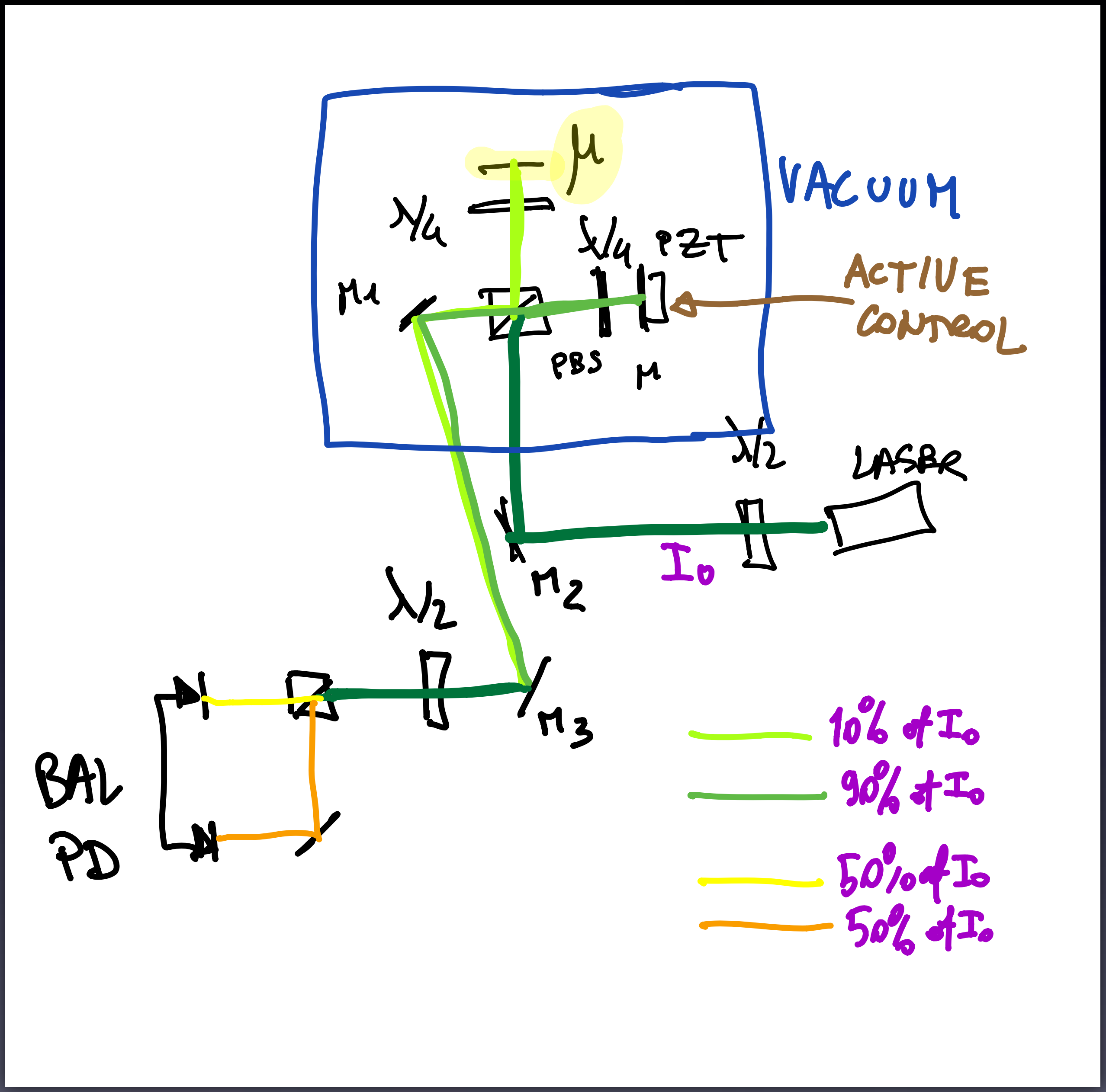
Mode mixture with membrane (TEM00 + h.o.m.)

The KWISP force sensor

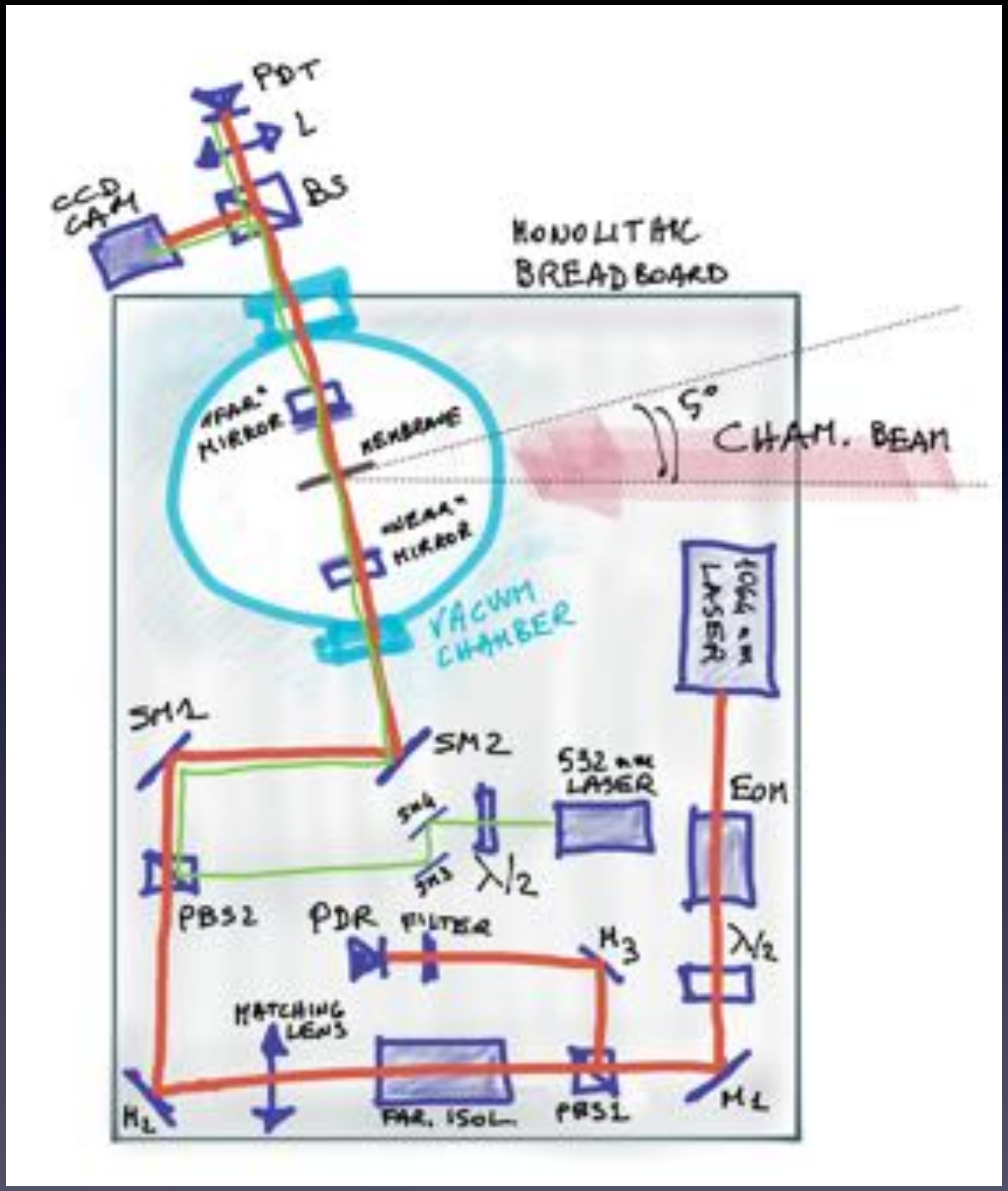
KWISP @ CAST

- Exploits
  - sun-tracking capability
  - presence of flux-enhancing XRT
- KWISP versions
  - KWISP 1.5 - Michelson interferometry
  - KWISP 2.0-3.0 - Fabry-Perot interferometry

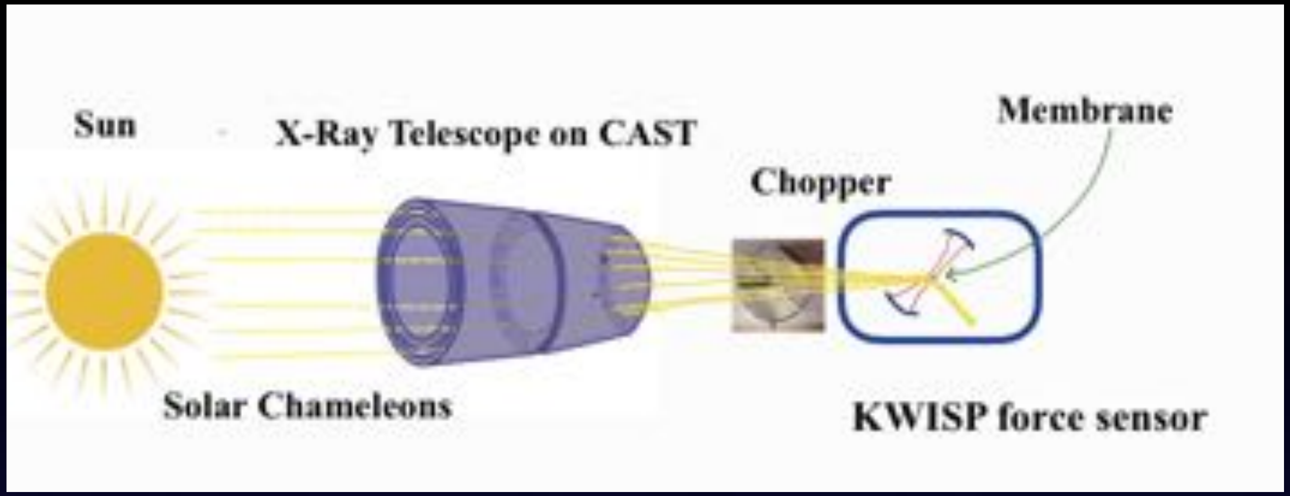
KWISP 1.5



KWISP 2.0 and above

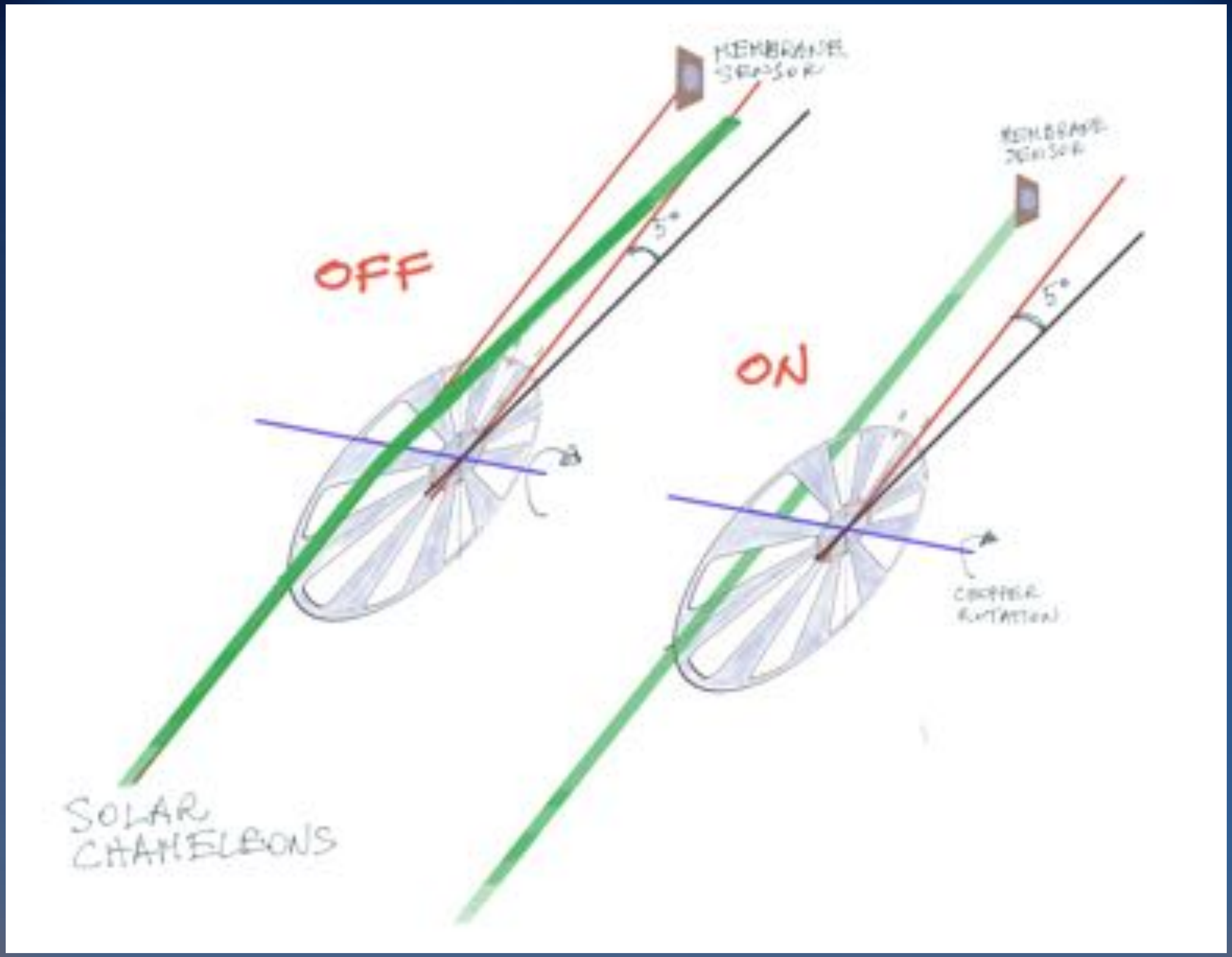


Precursor: KWISP 1.5 at CAST



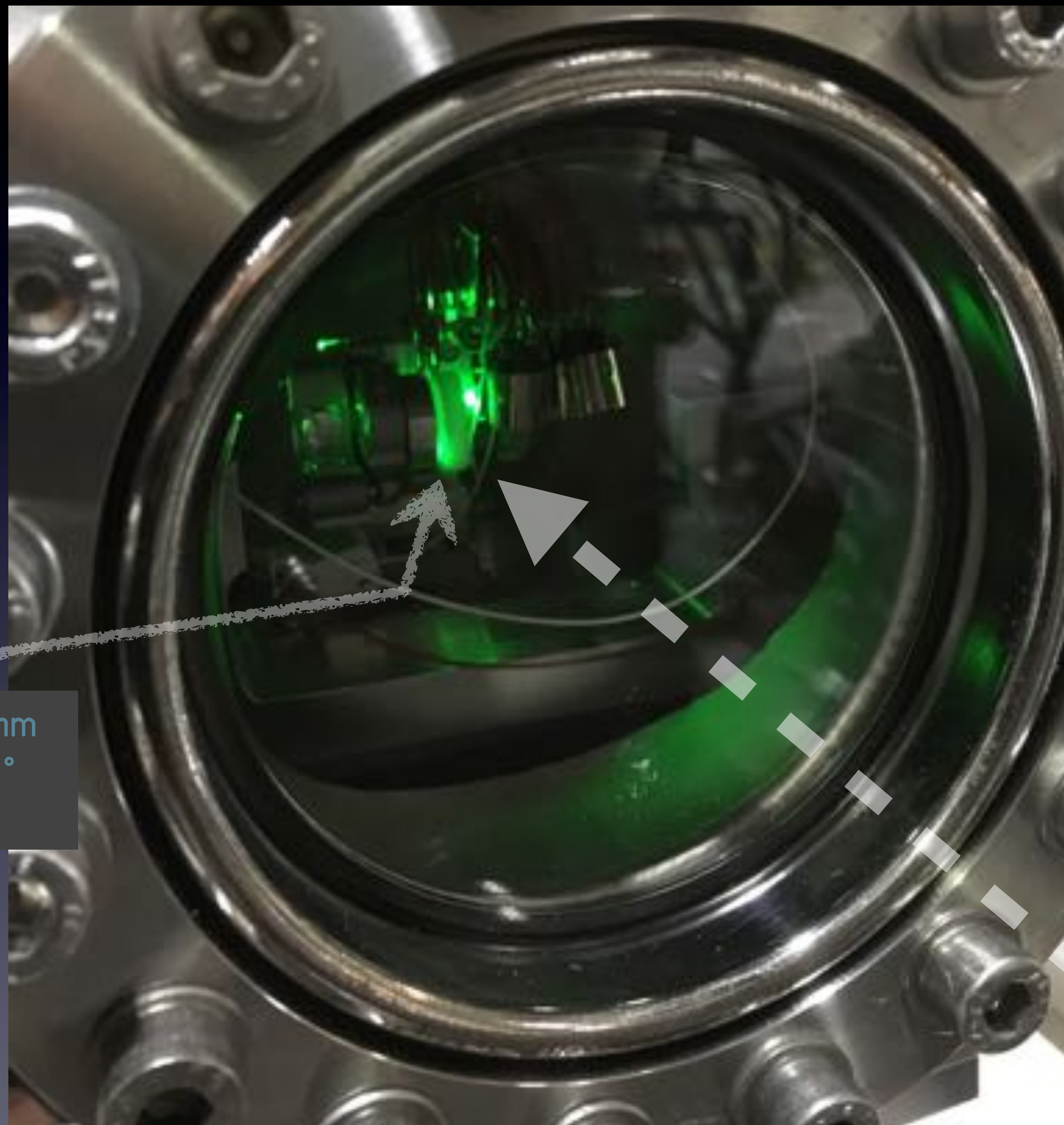
The Chameleon chopper

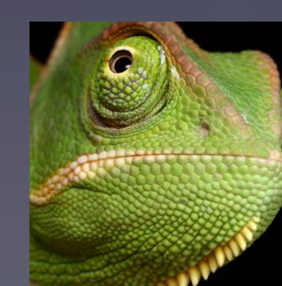
- Why does one need a chopper?
  - the sensor detects *relative* displacements, thus a *static* displacement is not seen
  - a time dependence must then be introduced in the membrane excitation
- Modulating the amplitude of something you cannot even see… the Chamelon chopper!
  - rests on the principle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



KWISP 1.5 seen by Chameleons …

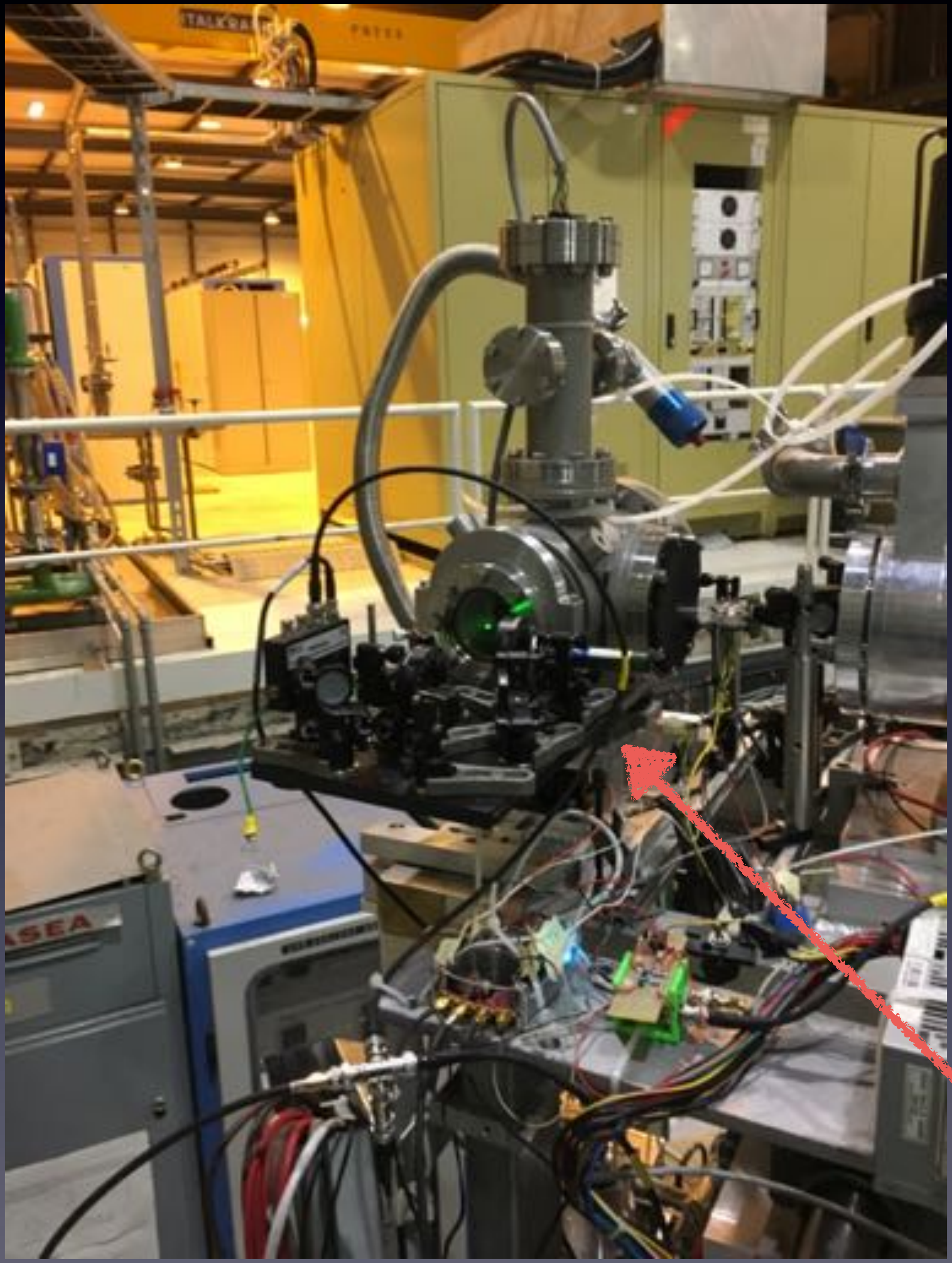
5x5 mm² Si_3N_4, 100 nm thick membrane at 5° incidence angle

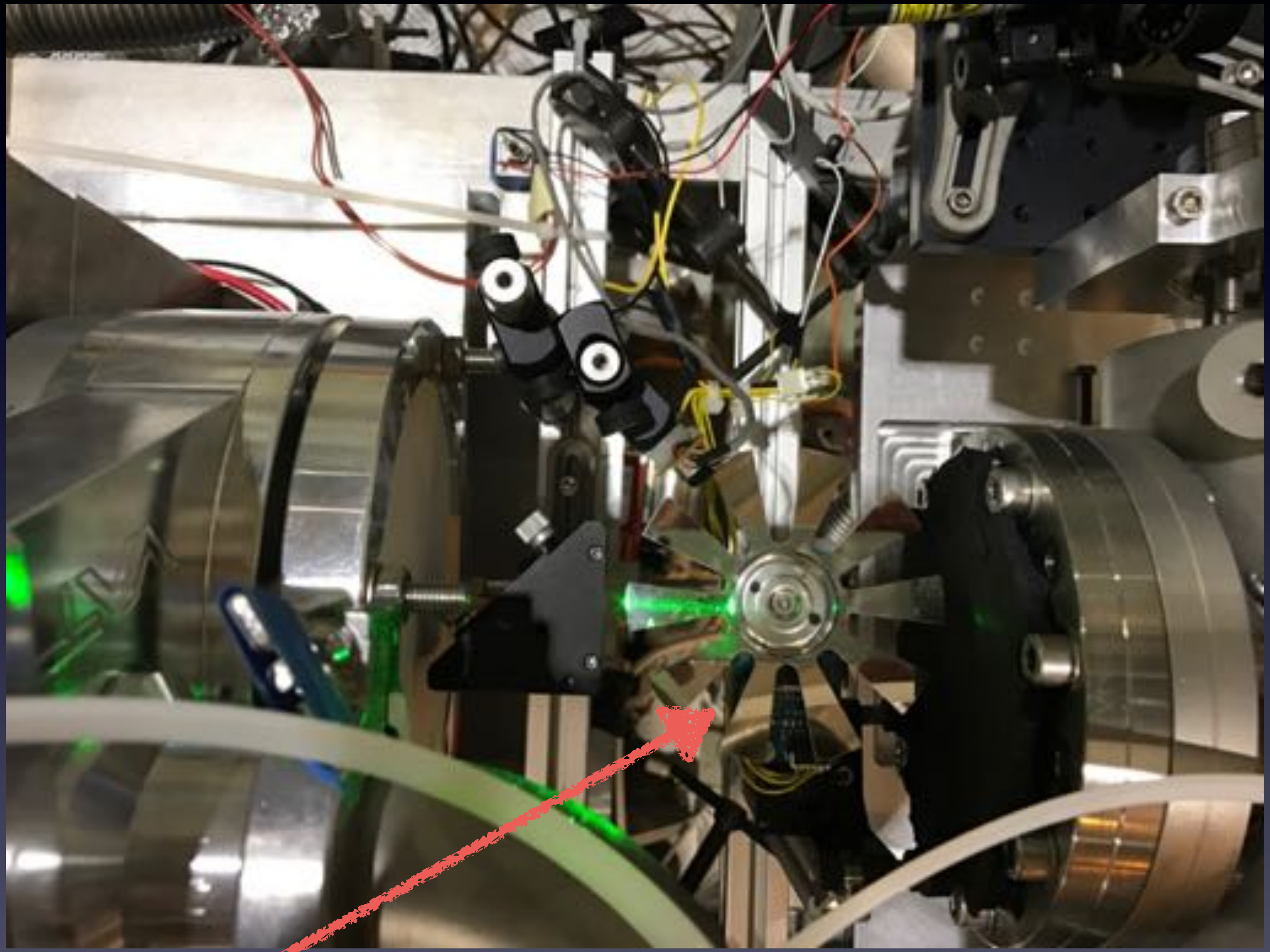




February 2017 solar tracking

- **The February 2017 solar tracking run was done at CAST with the KWISP 1.5 detector and the chameleon chopper in horizontal geometry for frequency stability**





Chameleon chopper (top view)

KWISP 1.5 on beam (side view)

KWISP 2.5 setup

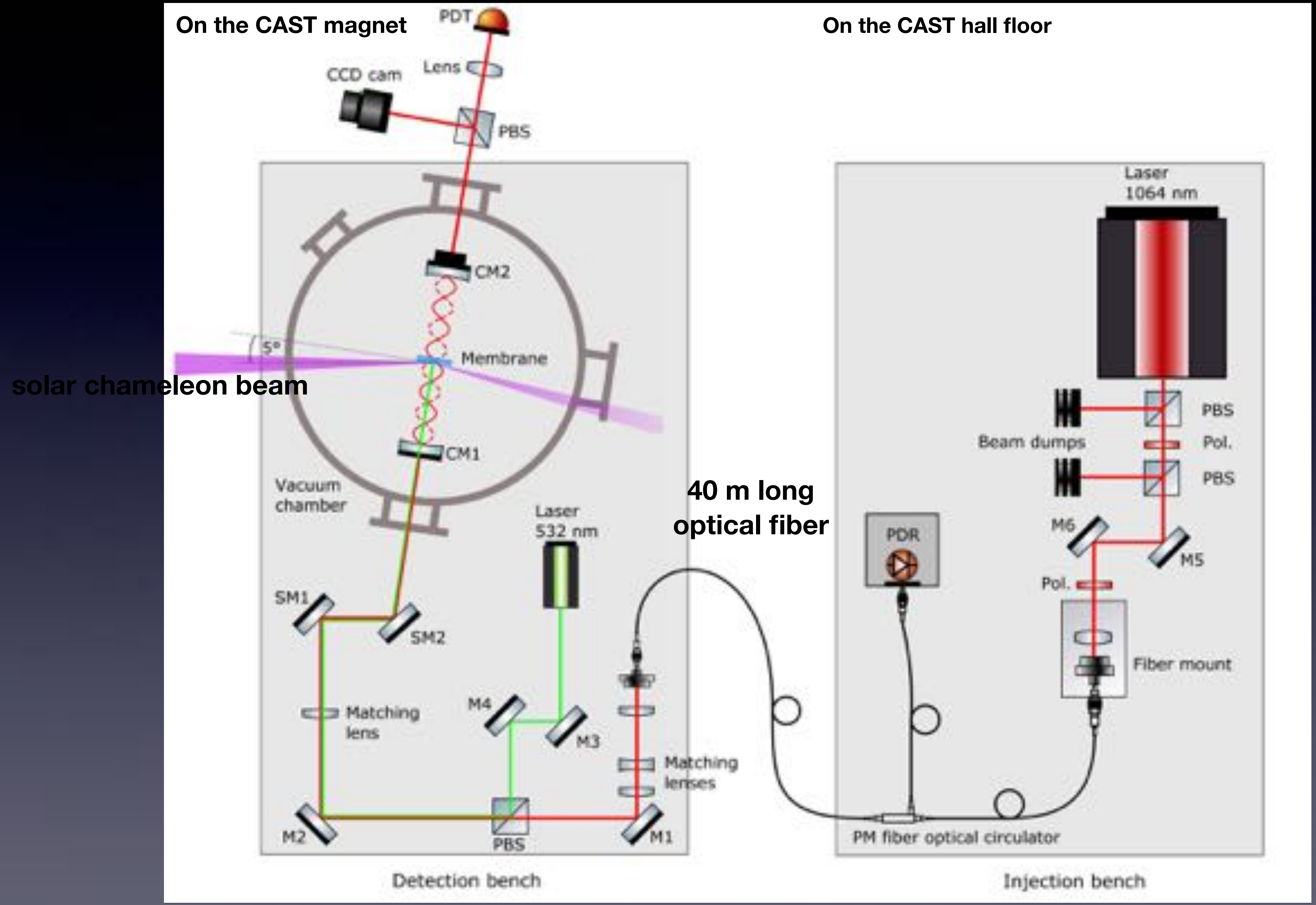
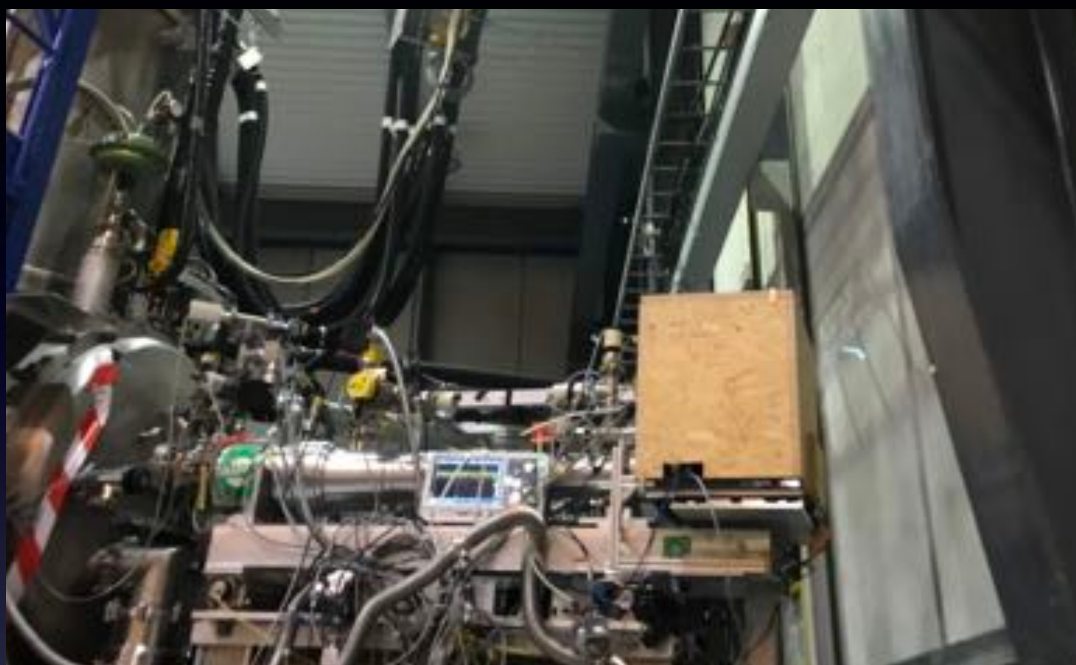


Figure courtesy of J. Baier

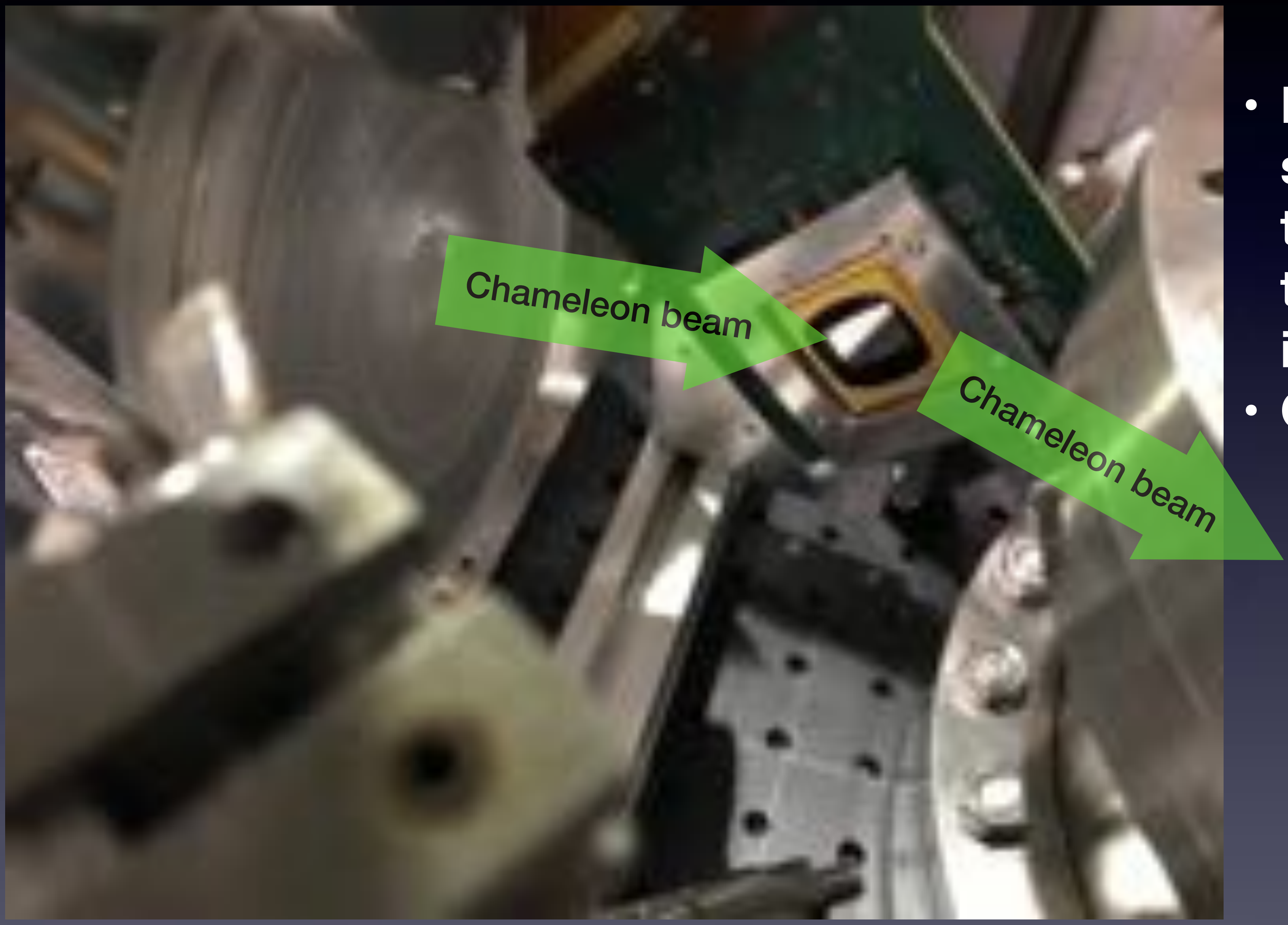
KWISP 2.5 on the CAST magnet

Detection bench

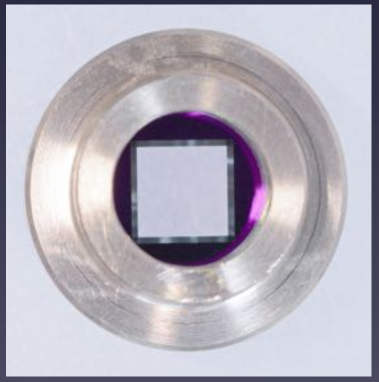


Injection bench

DLP-chip chopper

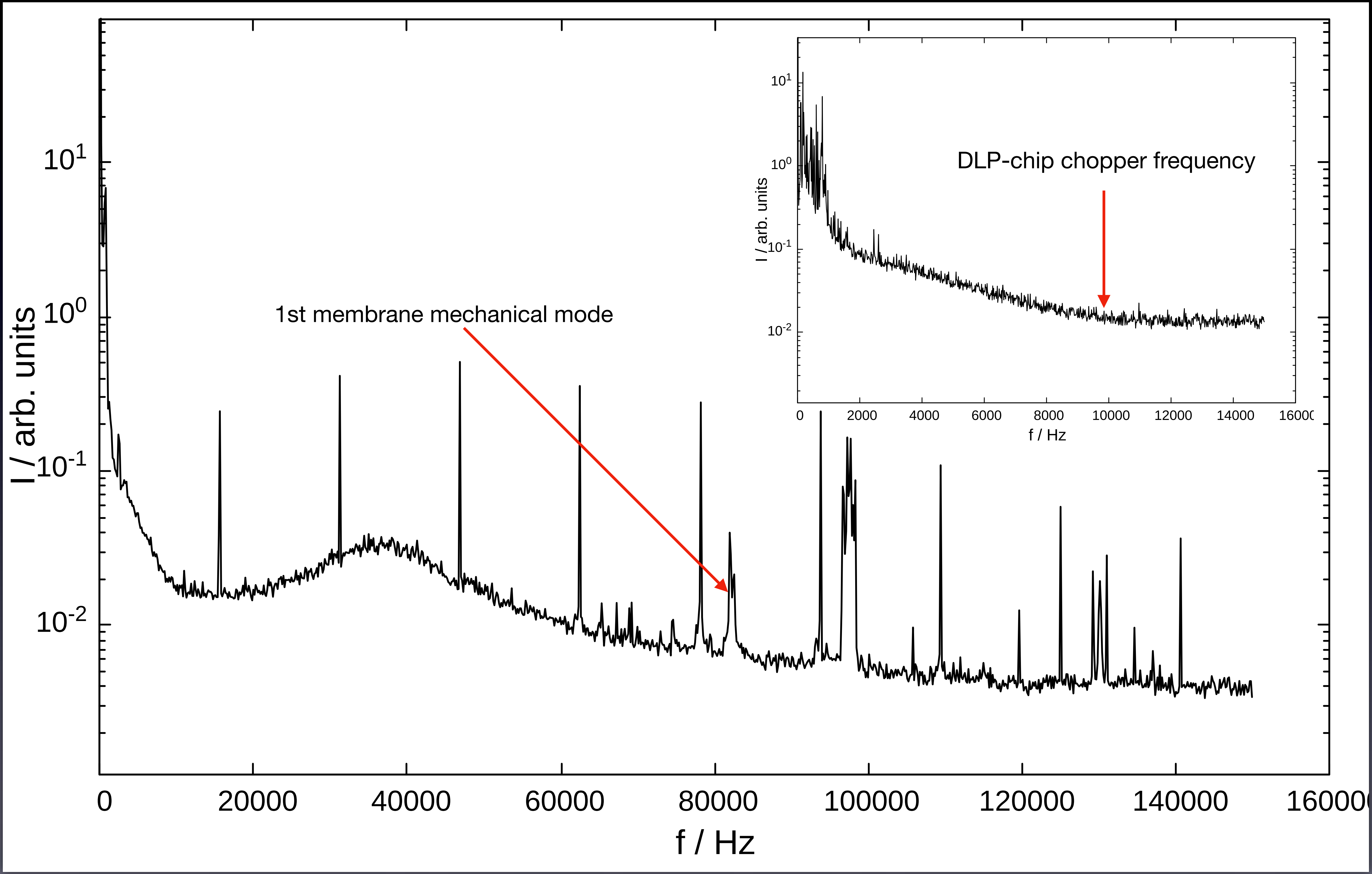


- **DLP-chip chopper (shiny surface) placed to intercept the chameleon beam (from the left) at a grazing incidence angle**
- **Chip operates at ~ 9.8 kHz**



5x5 mm^2 membrane

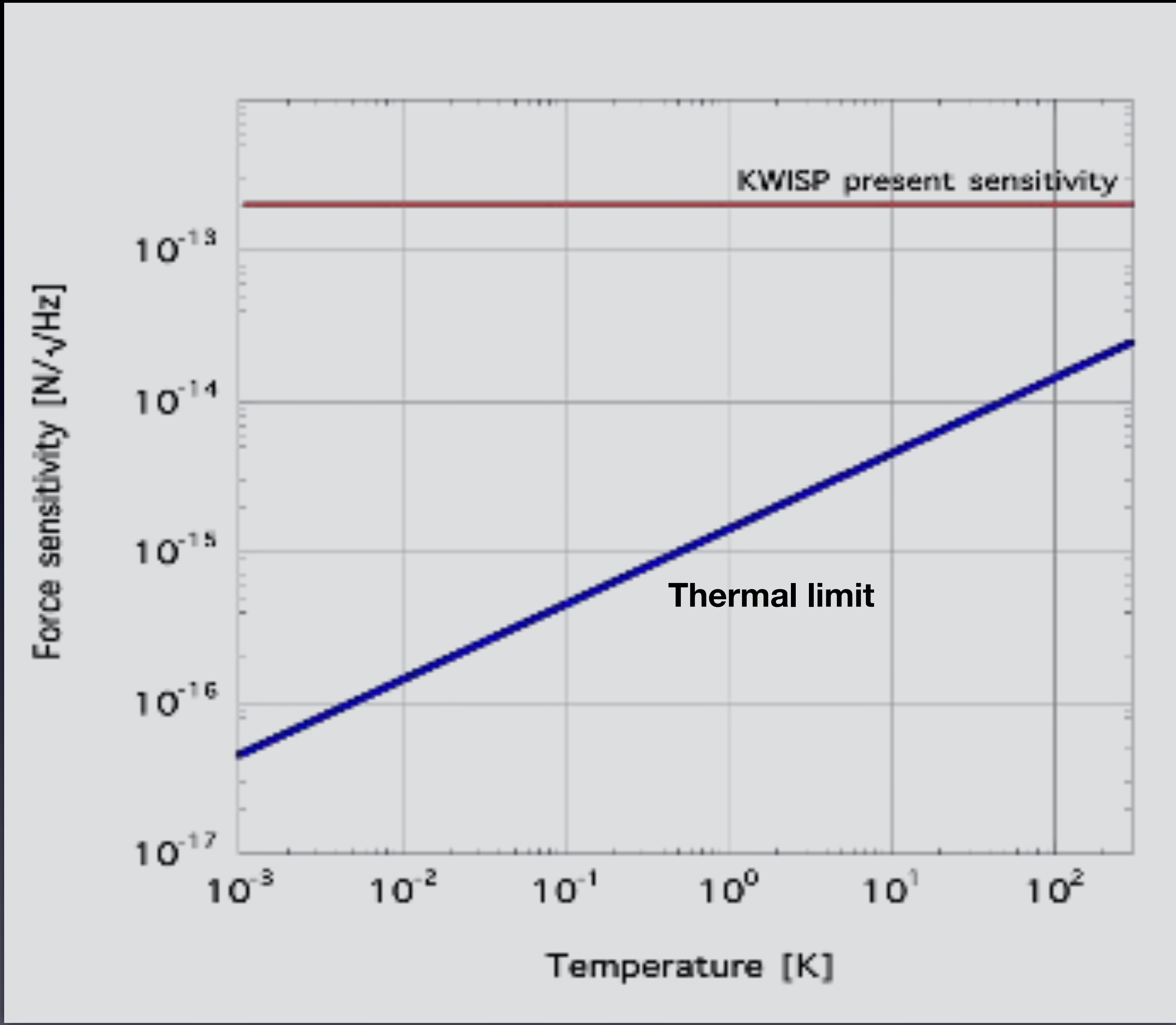
Membrane thermally excited peaks



KWISP 2.5 sensitivity

Location	INFN Trieste optics lab	CAST Laser lab at CERN	CAST exp. hall **off-beam**	CAST exp. hall **on-beam**
Sensitivity	$3 \cdot 10^{-15} \frac{\mathbf{m}}{\sqrt{\mathbf{Hz}}}$	$4 \cdot 10^{-15} \frac{\mathbf{m}}{\sqrt{\mathbf{Hz}}}$	$9 \cdot 10^{-15} \frac{\mathbf{m}}{\sqrt{\mathbf{Hz}}}$	$1 \cdot 10^{-14} \frac{\mathbf{m}}{\sqrt{\mathbf{Hz}}}$

Sensitivity vs. Temperature



$$S_f = \sqrt{\frac{4Kk_bT}{\omega_0 Q}} \quad (*)$$

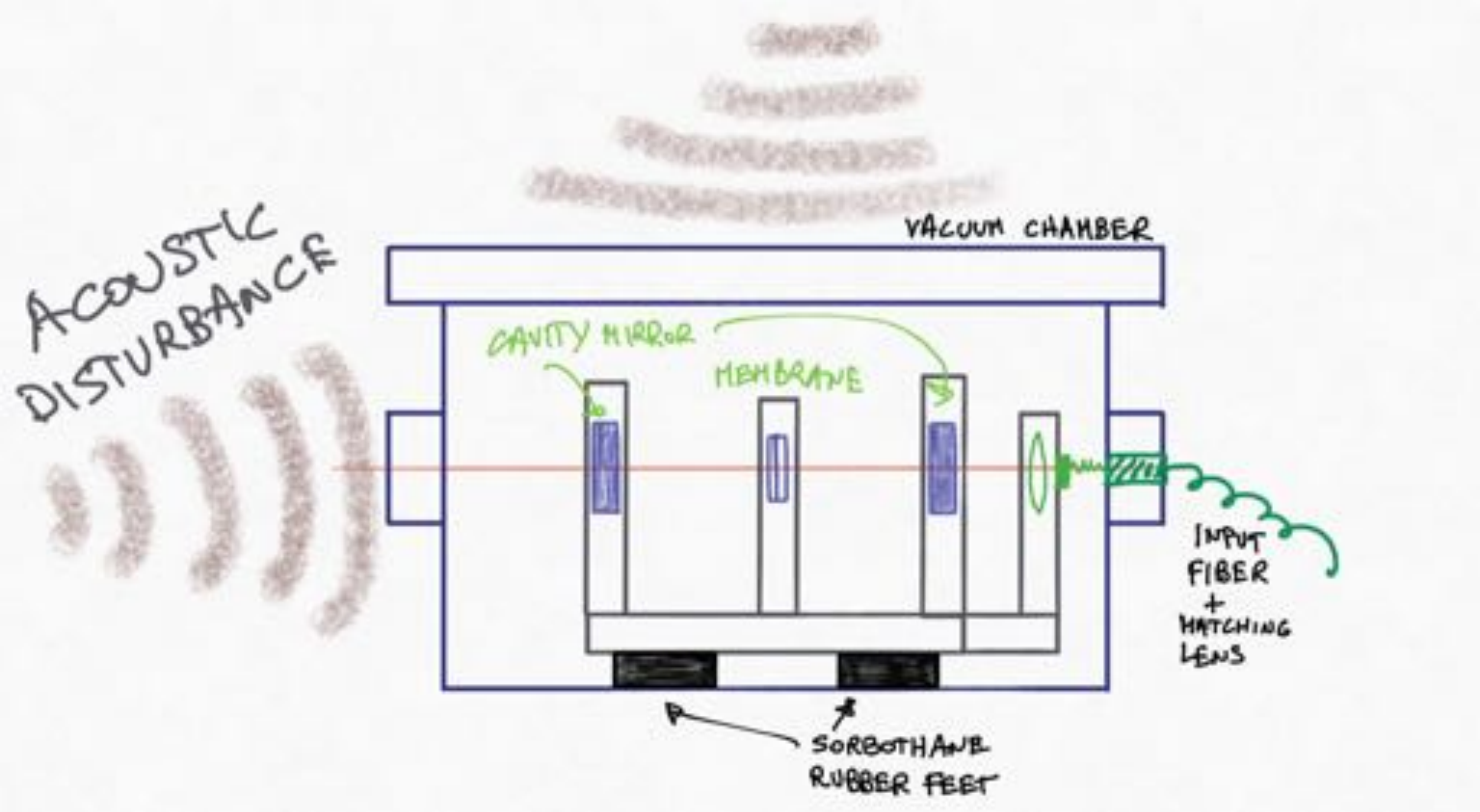
$K = 30$ **N/m** (*eq. spring constant*)
k_b *Boltzmann constant*
$\omega_0 = 82.5$ **kHz** (*membrane res. freq.*)
$Q = 10^5$ (*membrane quality factor*)

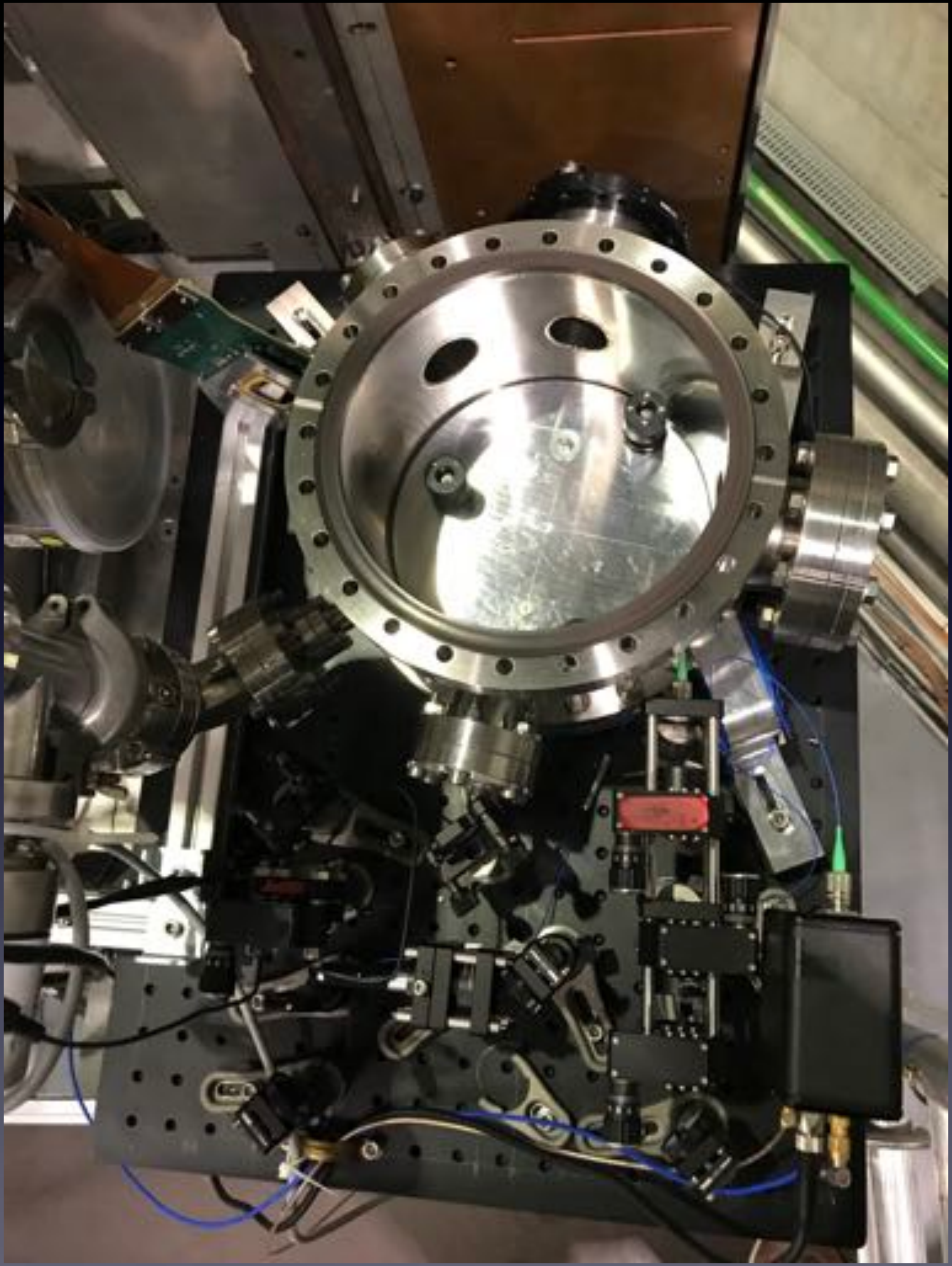
(*) following *S. Lamoreaux, arXiv:0808.4000*

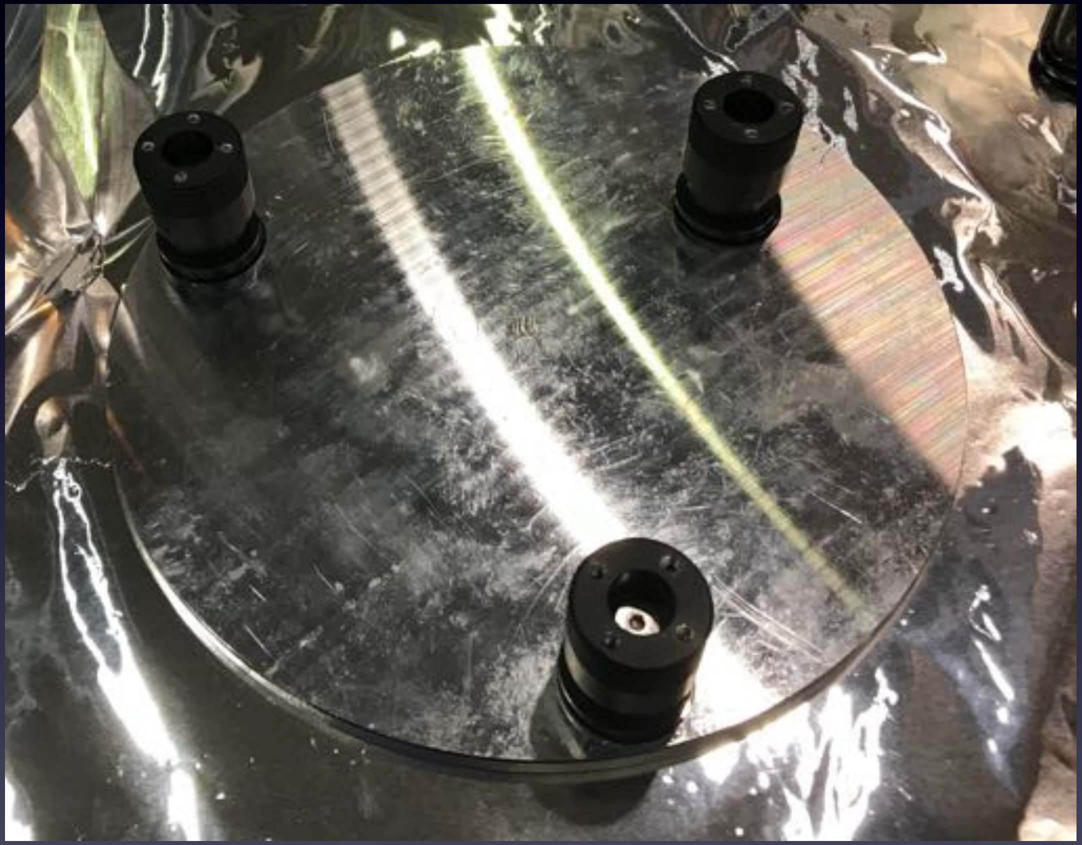
KWISP 3.0 main features

- Overall dimensions have been reduced by a factor 2 or more, keeping the F-P cavity of the same size
- The matching optics have been redesigned using smaller diameter components
- All the optics (in the detection bench) are mounted on a monolithic base machined out of a single piece of Al
- The entire base fits into the existing vacuum chamber and is mounted on special vibration isolation feet
- Light is fed into the system entirely through optical fibers.

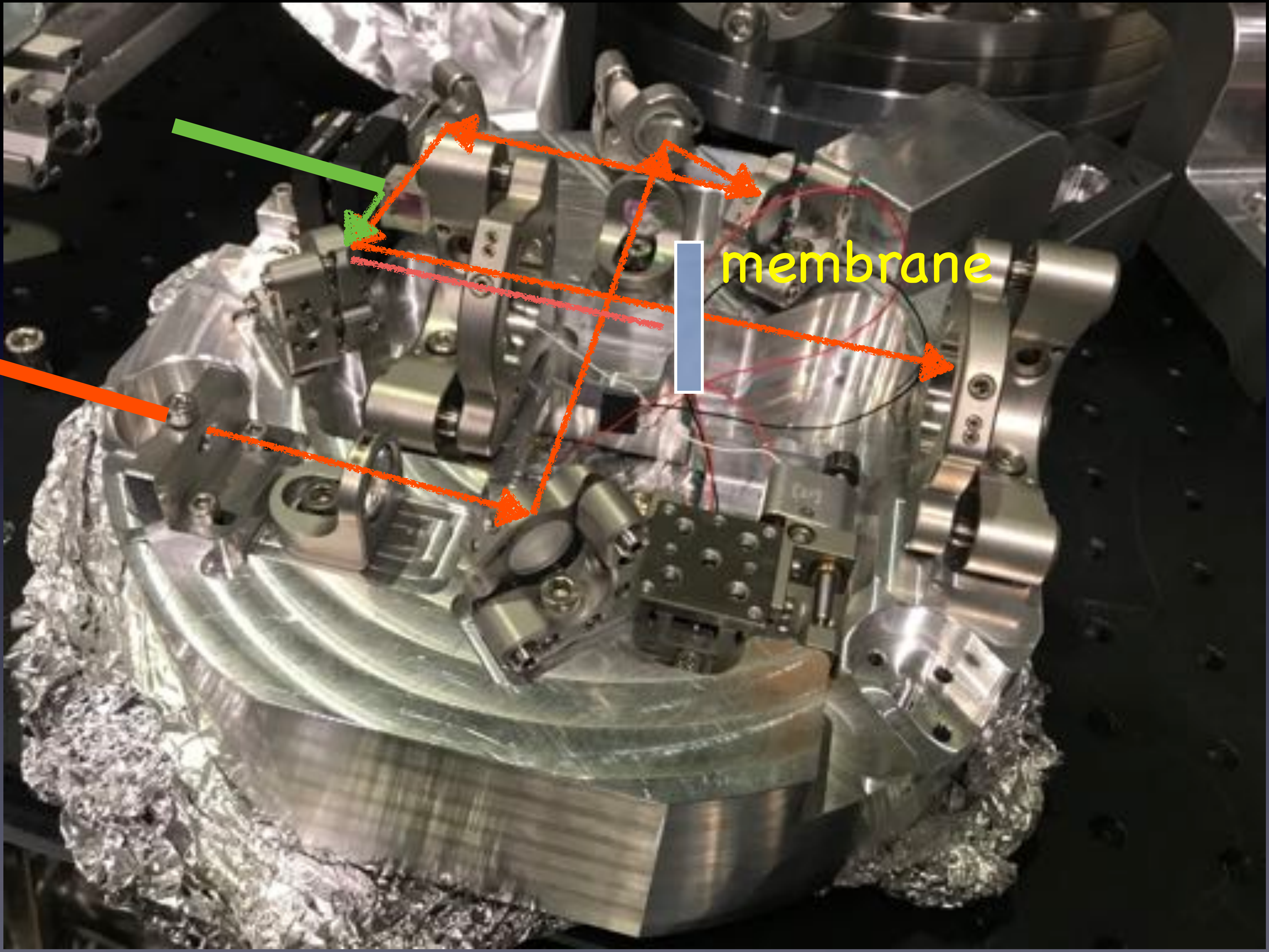
KWISP 3.0 basic principle





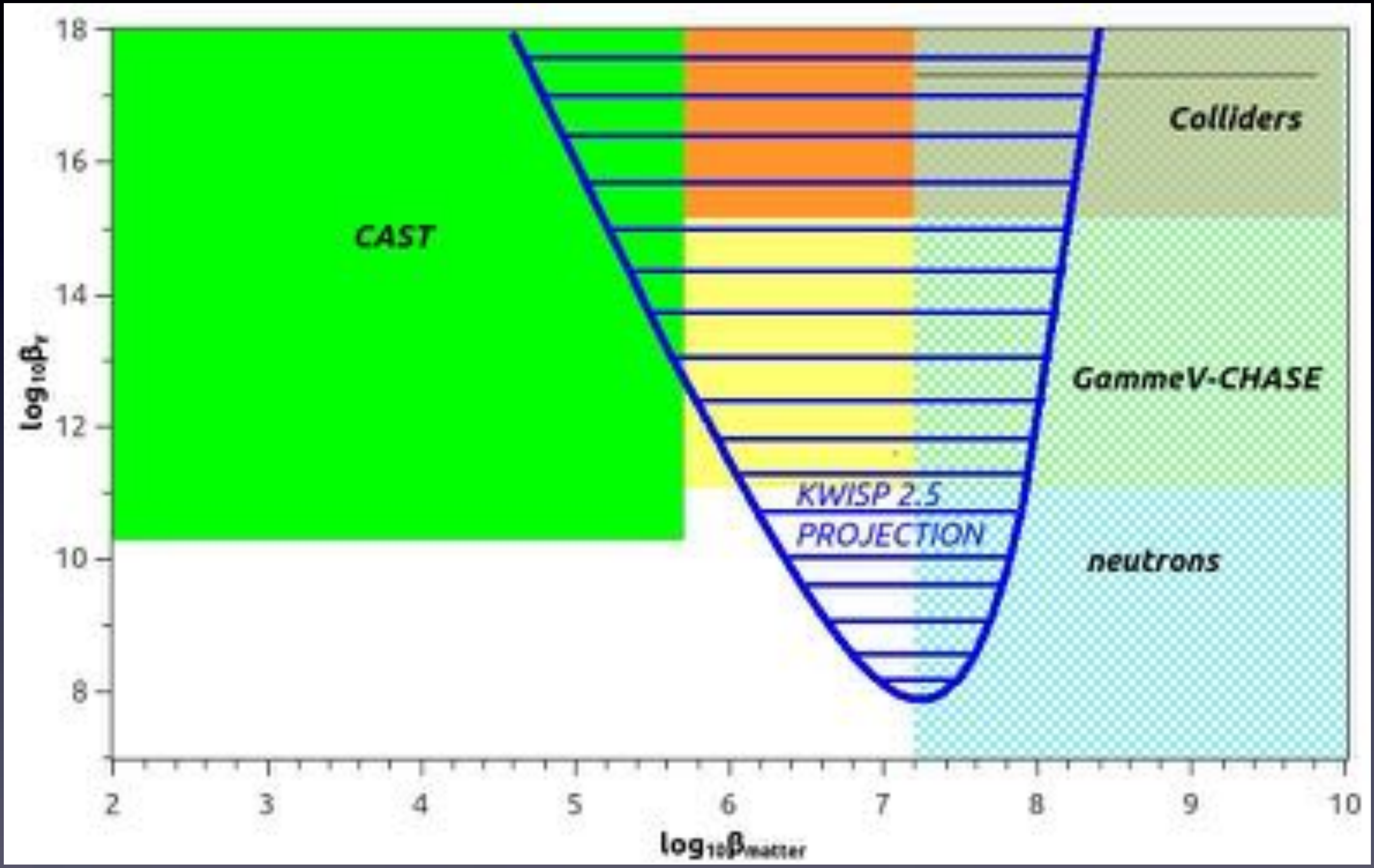


Monolithic optical bench



Chameleon studies with KWISP

- Projected chameleon exclusion achievable at CAST, assuming KWISP at 10 milli-Kelvin and an integration time of 10^6 s (6 months of solar tracking)



KWISP broadens the physics reach of CAST into the Dark Sector, making it the only CERN experiment actively searching both for Dark Matter and for Dark Energy.

Upcoming…

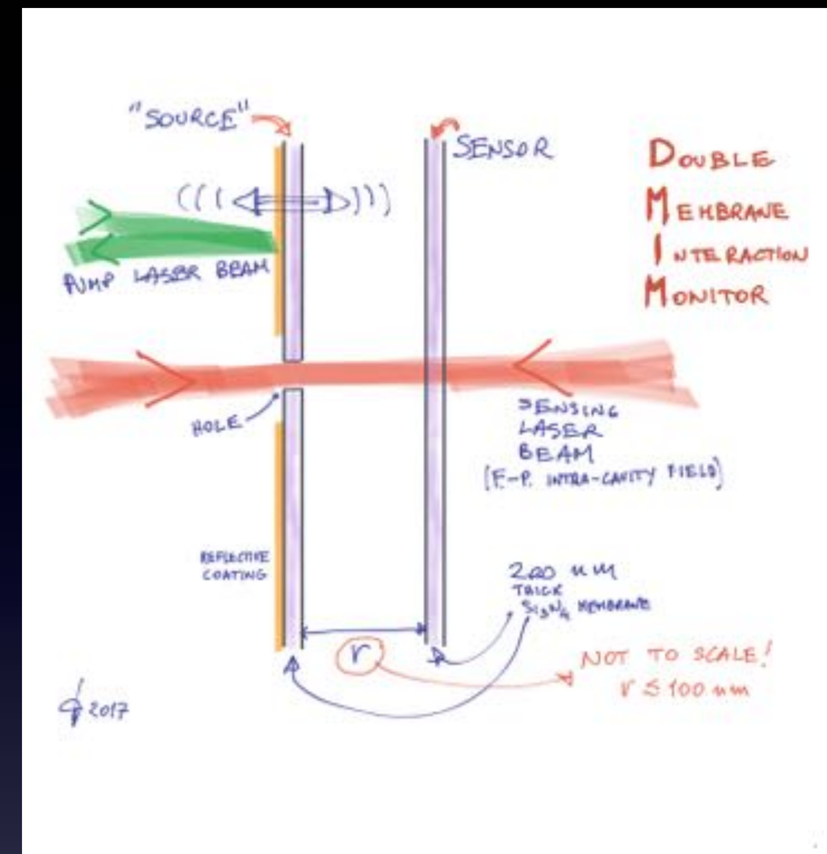
First Results on the Search for Chameleons with the KWISP Detector at CAST

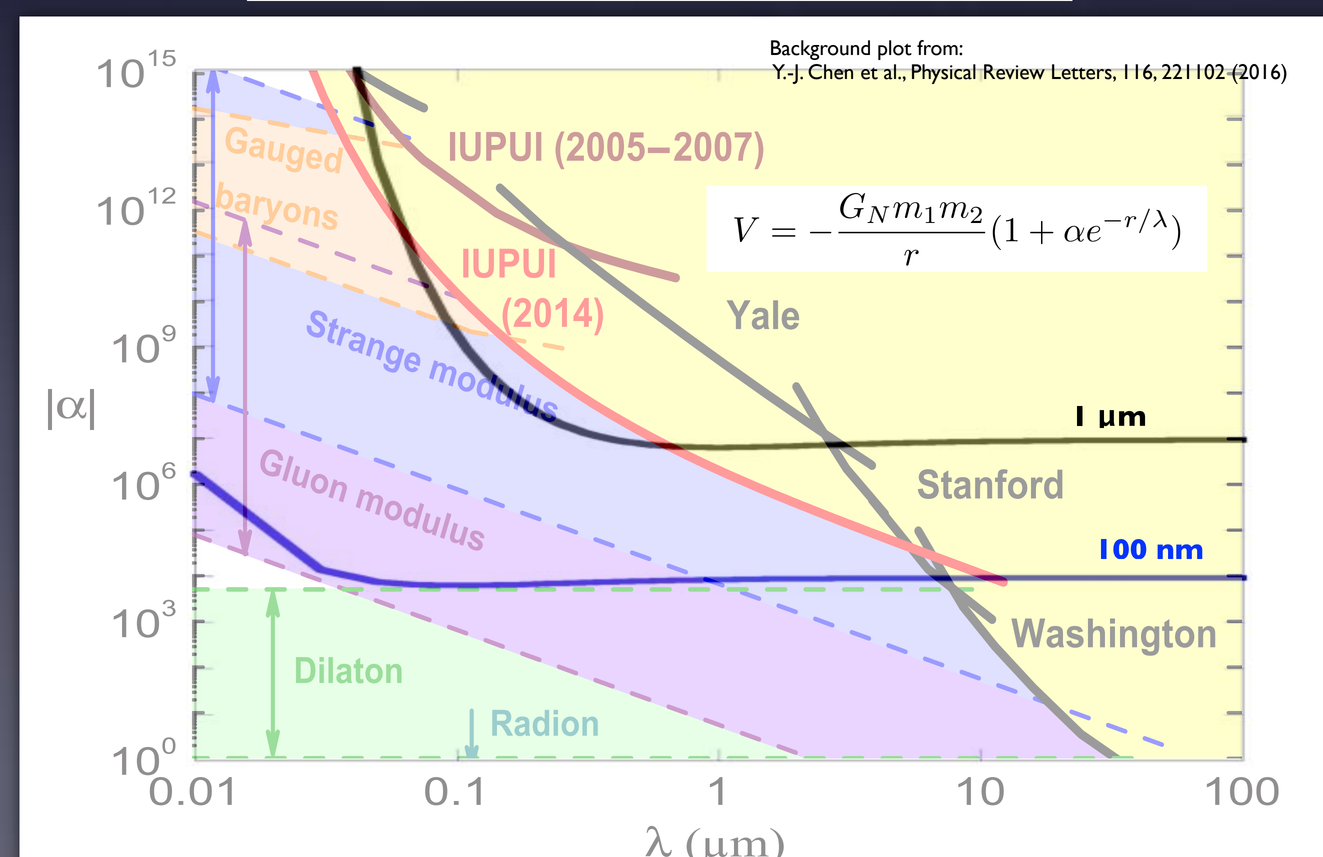
V. Anastassopoulos[i], J. Baier[h], K. Barth[b], S. Baum[v,w], A. Bayerli[a,1], A. Belov[c], H. Bräuninger[d], G. Cantatore[*e,f], J. M. Carmona[g], J. F. Castel[g], S. A. Cetin[a], T. Dafni[g], M. Davenport[b], A. Dermenev[c], K. Desch[q], B. Döbrich[b], H. Fischer[*h], W. Funk[b], J. A. García[g], A. Gardikiotis[i], J. G. Garza[g], S. Gninenko[c], M. D. Hasinoff[j], D. H. H. Hoffmann[k], F. J. Iguaz[g], I. G. Irastorza[g], K. Jakovčić[l], J. Kaminski[q], M. Karuza[*o,p,e], M. Krčmar[l], C. Krieger[q], B. Lakić[l], J. M. Laurent[b], A. Ljubičić[l], G. Luzón[g], M. Maroudas[i], L. Miceli[r], S. Neff[k], I. Ortega[g,b], A. Ozbey[a,2], M. J. Pivovaroff[m], M. Rosu[t], J. Ruz[m], E. Ruiz Chóliz[g], S. Schmidt[q], M. Schumann[h], Y. K. Semertzidis[r,s], S. K. Solanki[n], L. Stewart[b], I. Tsagris[i], T. Vafeiadis[b], J. K. Vogel[m], M. Vretenar[o], W. Wuensch[b], S. C. Yildiz[a,3], K. Zioutas[i,b]

Beyond: *advanced*-KWISP

*a*KWISP in a nutshell

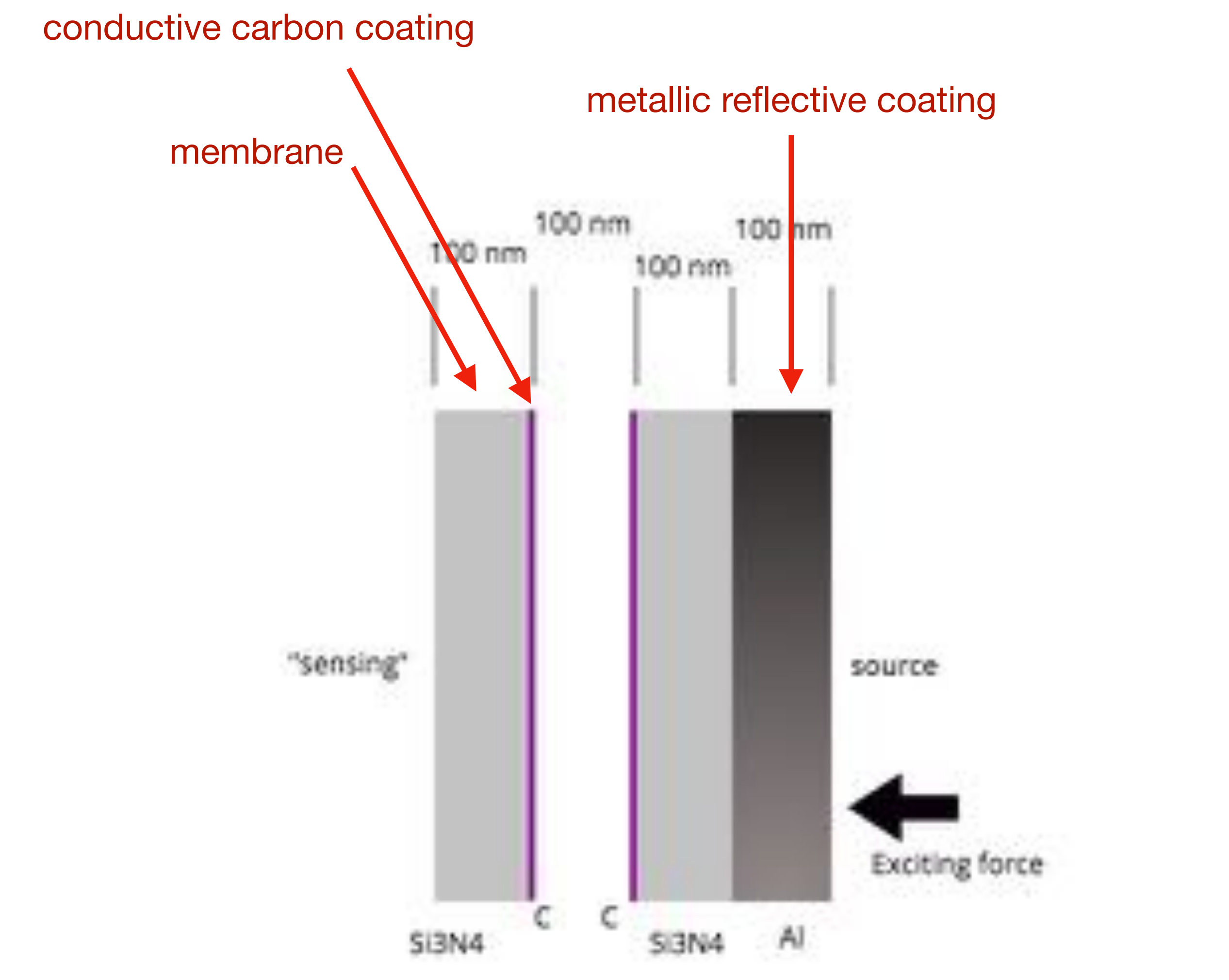
- **Motivation**
  - Short-Range Interactions (**SRIs**) between **macroscopic bodies** can probe a panoply of *beyond-the-Standard-Model* physical processes
- **Principle of the measurement**
  - Two micro-membranes set at a short (100 nm o less) separation distance. One acts as the "source mass" and moves under an external controlled force, while the second acts as the "sensing mass"
  - One looks for a dependence on the separation distance differing from the standard Newtonian interaction potential
- **Physics goals**
  - Axion-exchange interactions (using appropriate membrane surface configurations to have field gradient between the membranes).
  - Axion detection through the Topological Casimir Effect (requires magnetic field)
  - Quantized short range forces
  - Casimir force: only a limiting background force?
  - Scalar Dark Matter and extra-dimensions
  - …



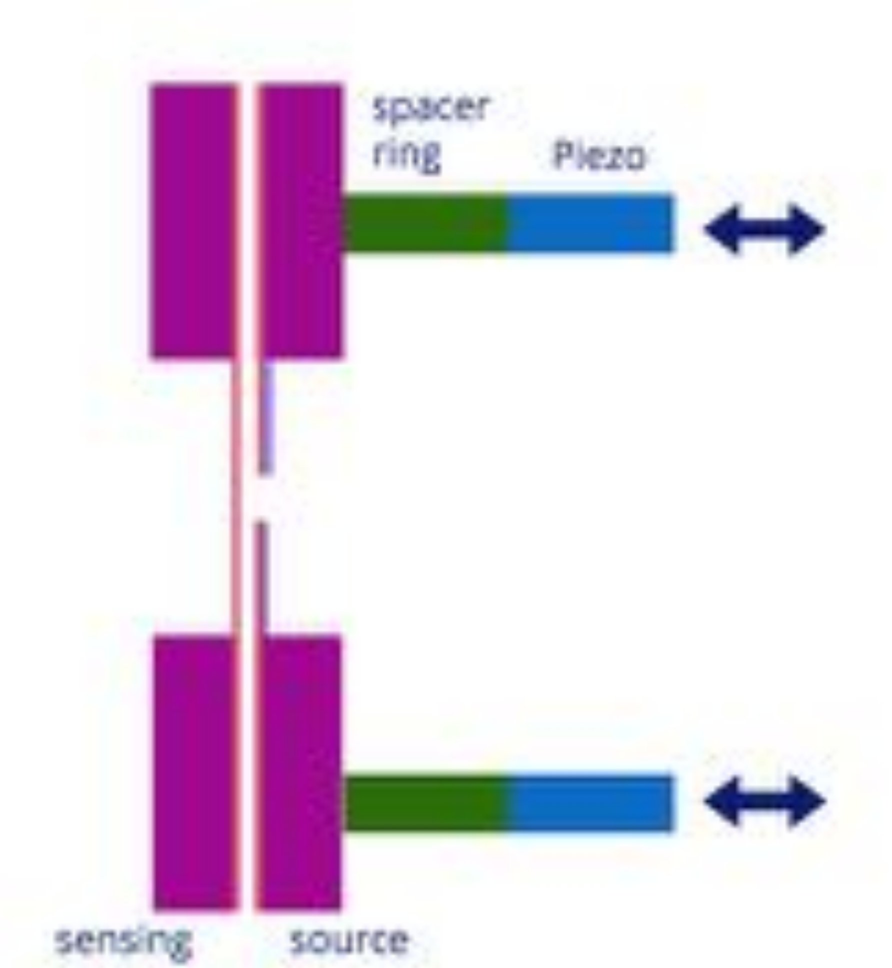


Double Membrane Interaction Monitor

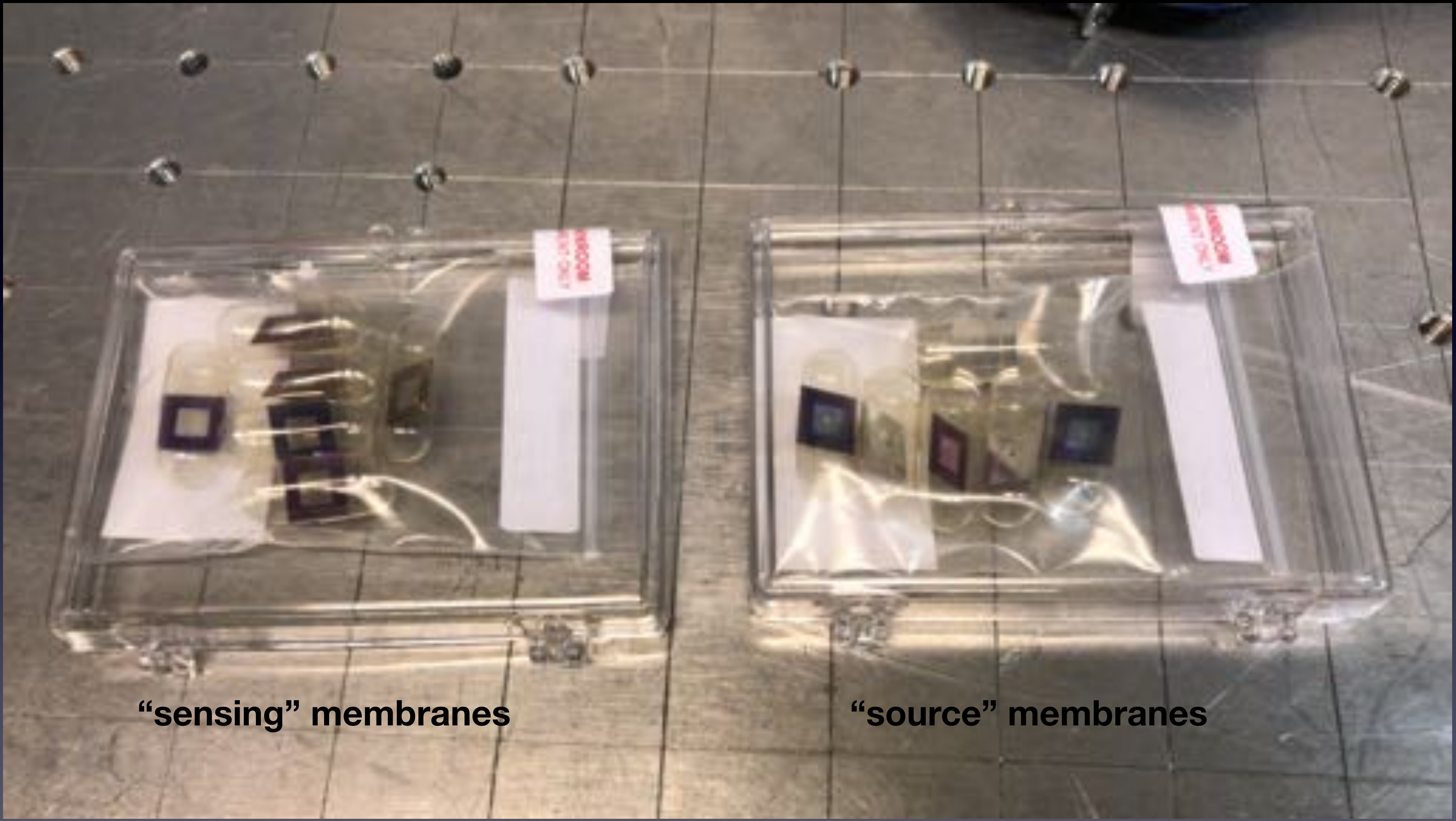
- The key element of aKWISP is the DMIM
  - "sensing" membrane coated with a 3 nm layer of C to drain static charges
  - "source" membrane coated with 3 nm C on one side and with 100nm of Al on the opposite side to provide a reflective surface; "source" also has a hole to pass the sensing laser beam undisturbed
- One possible assembly strategy is to mount one of the two membranes on piezo actuator to be able to change the separation distance
- Membranes of both types have already been procured in order to start with preliminary assembly tests



DMIM - Double Membrane Interaction Monitor



Schematic assembly possibility

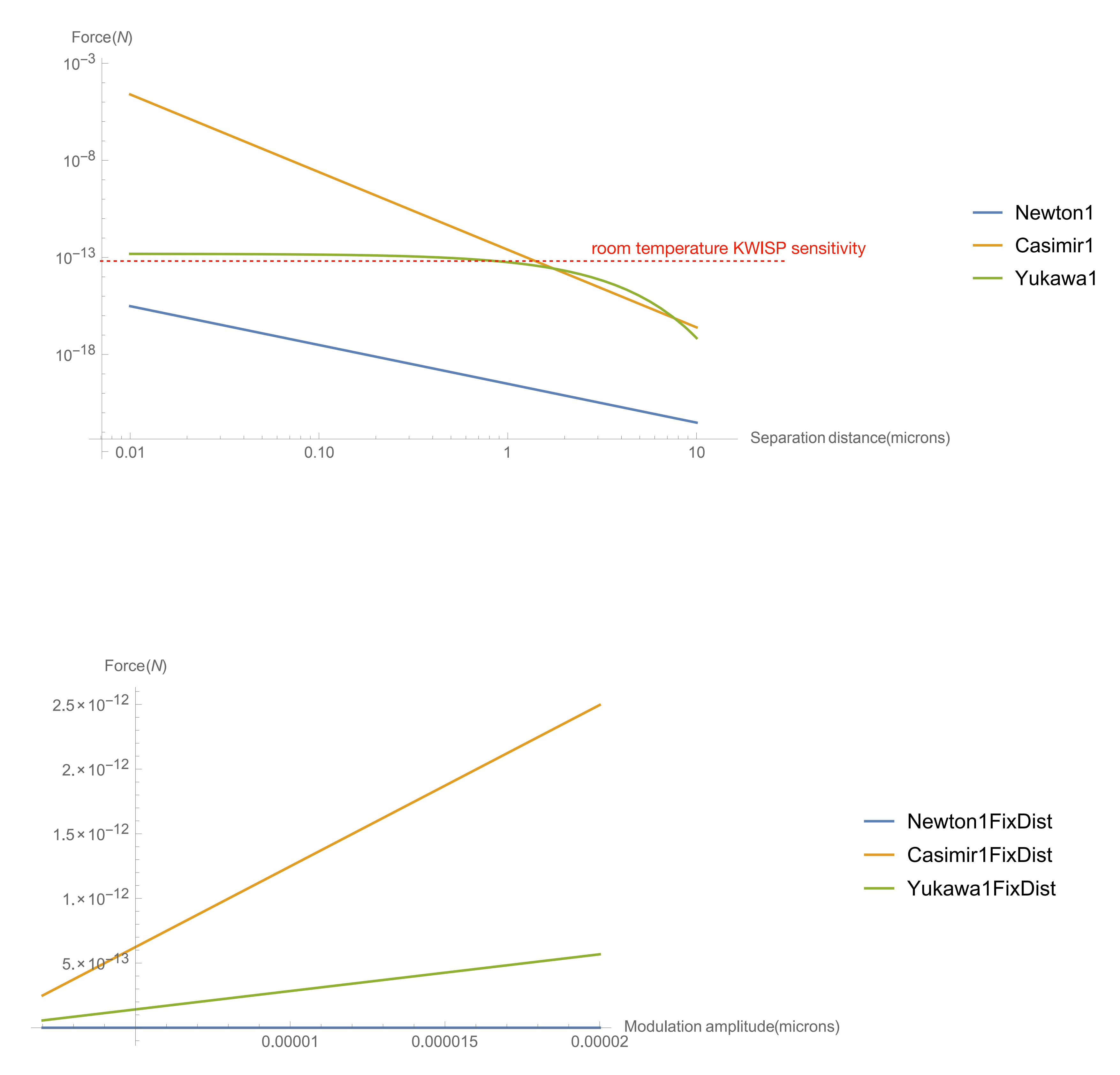

“sensing” membranes
“source” membranes

Sensing SR forces

In *a*KWISP, the interaction force between source and sensing mass is, to a first approximation, the sum of the "Newtonian", "Casimir" and "Yukawa", contributions, each depending differently on the separation distance **r**:

$$F_N = \frac{G}{r^2}\ ;\ F_C = \frac{B}{r^4}\ ; F_Y = \frac{G\alpha}{\lambda r^2}(r+\lambda)\, e^{-\frac{r}{\lambda}}$$

A possible measurement strategy to separate the contributions is to modulate the separation distance with a varying amplitude



Conclusions…

- CAST is a unique experiment and observatory potentially sensitive to both Dark Matter and Dark Energy
- The recent results from the CAST solar axion search program again set the reference bound over a wide axion mass range
- CAST is now pursuing a physics program centered on Dark Matter (relic axions with microwave cavities) and Dark Energy (chameleons with GridPix and KWISP)
- Trieste is a very active part with the novel **KWISP** opto-mechanical chameleon detector

...or beginnings!

- CAST is presently in shutdown mode: the magnet is open and the microwave cavities are being reinserted after a check-up, a new series of measurement campaigns will start in a few weeks
- The KWISP opto-mechanical detector has reached version 3.0, now in the installation phase on the CAST magnet
- There is the possibility of repeating a series of measurement on solar axions using a photon detector with Xe gas in the amplification region to eliminate a systematic effect due to an intrinsic emission line of Ar
- The *advanced*-KWISP project, a spin-off of the KWISP technologies pioneered in CAST could open a new window on hitherto unexplored physical processes beyond the standard Model


Thank you!
We have great ideas !!
... mo' ce tocca lavorà!