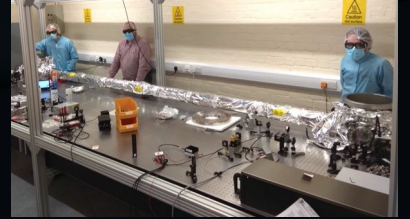
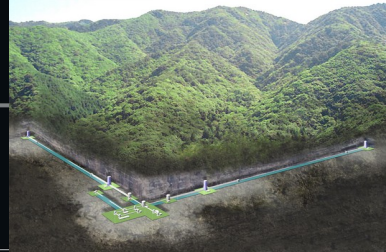


# Searching for Dark Matter with Laser interferometry



Hartmut Grote  
Dark Matter on all Scales  
Odense, 11 May 2026



# So what is the dark matter?

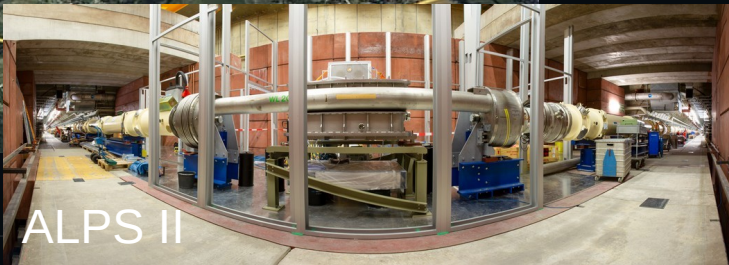
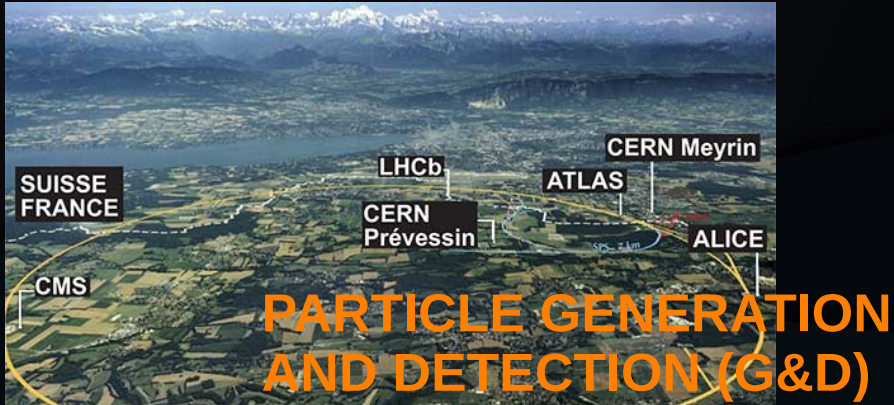
- WIMPs (miracle)
- Axions (and ALPs)
- Light scalar fields
- Dark Photons
- Sterile Neutrinos
- ...
- Black Holes, ...

ULTRA-LIGHT  
BOSONS



# Make it - or - Find it

- Make (dark matter) particles

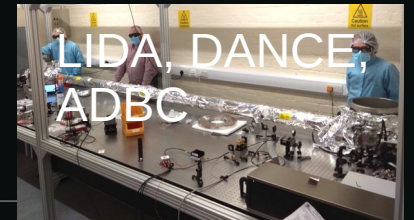


- Detect (dark matter) particles passing earth



XENON 1T...  
and many others.  
Last call: XLZD?

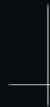
## HALOSCOPES



1) Laser-interferometric  
Gravitational-wave detectors  
(as Haloscopes)

2) Laser-interferometric  
OTHER detectors  
(as Haloscopes & LSW)

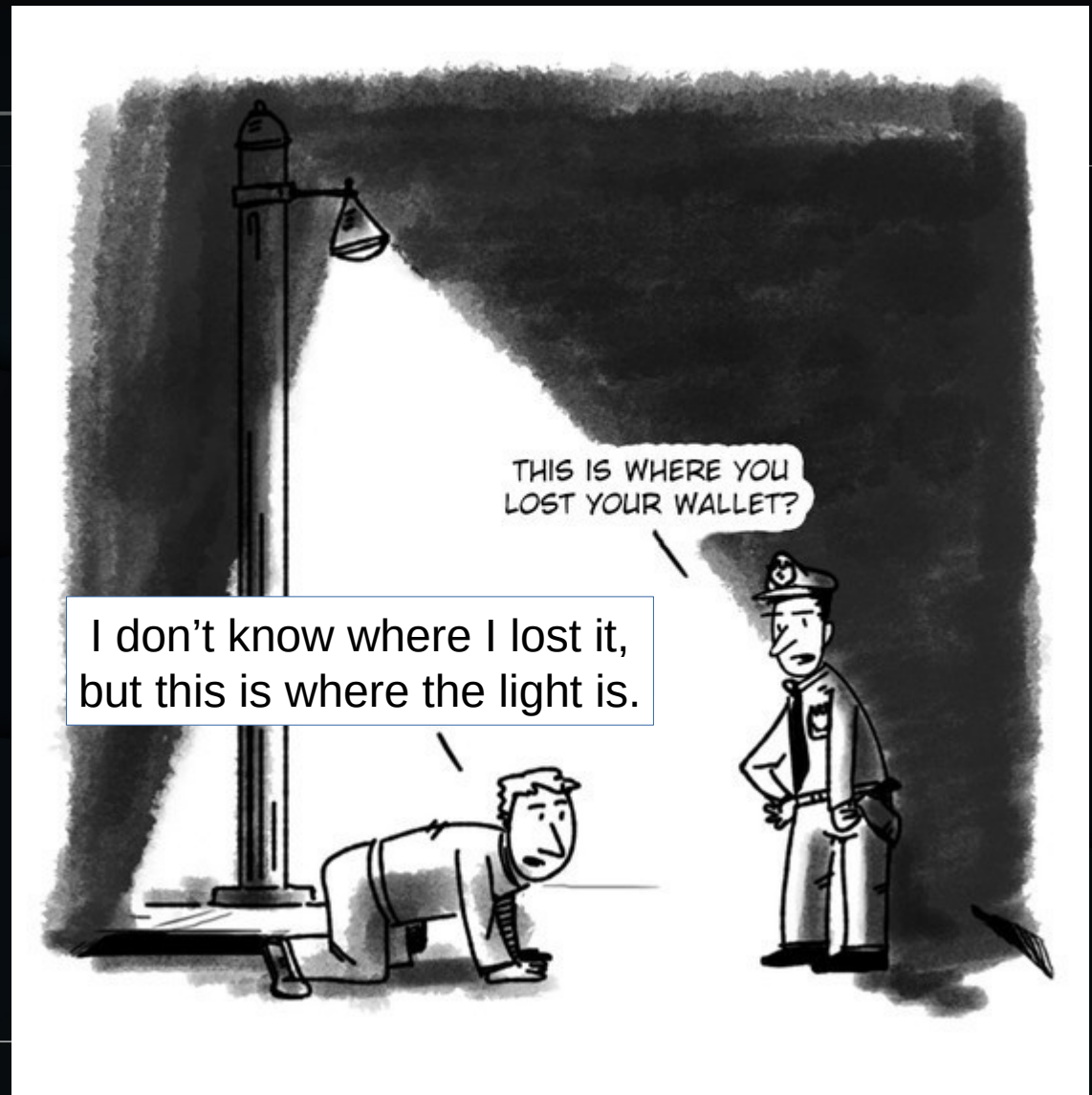
---



# Search where you can

'officially'  
recommended  
Strategy!

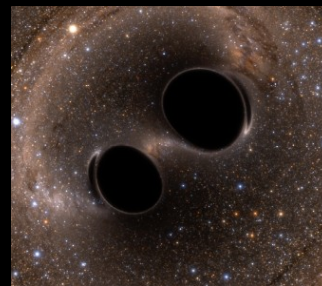
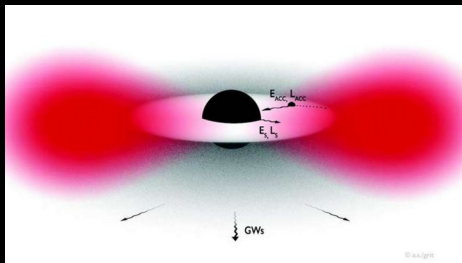
'no stone left unturned'  
Bertone, Tait 'A new era in the quest  
for dark matter' Nature 562, 51-56  
(2018)



# Indirect vs. Direct searches for Ultra-light Bosons With Gravitational-Wave Detectors

## Indirect (via GW detection)

- Ultra-Light Boson Clouds around spinning black holes search via continuous GW detection (not a Haloscope!)
- Impact of ultra-light boson clouds on binary black hole mergers
- Mass and spin gap studies of the BBH population
- Constraints from merger rates (e.g. accretion of DM in Neutron stars)
- Stochastic GW background from ultra-light bosons
- ...others/ongoing



# Indirect vs. Direct searches for Ultra-light Bosons With Gravitational-Wave Detectors

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- Stochastic GW background from ultra-light bosons
- ...others/ongoing

## Direct (interaction of DM with detector)

- Scalar field searches (with GEO, Holometer, and LIGO)
  - Vermeulen et al. 2021, Nature 600, 424
  - Aiello et al. 2022, PRL 128, 121101
  - Fukusumi et al. 2023, PRD 108, 095054
  - Göttel et al., 2024, PRL 133, 101001
- Dark Photon searches (with LIGO & KAGRA)
  - Guo et al. 2019, Nature comm. Phys 2, 155
  - Abbott et al. (LVK) 2022, PRD 105, 063030
  - Abac et al. (LVK) 2024, PRD 110, 042001
- Axion search (KAGRA and others)
  - Michimura et al. 2025, arXiv 2501.08930

# Direct Dark Matter Detection with GW Detectors

- Scalar Fields
- Dark Photons
- Axions



LIGO



GEO600



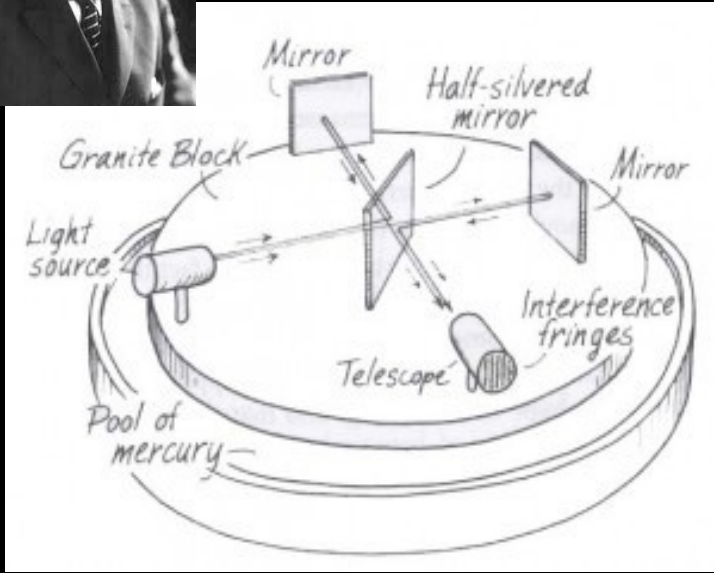
KAGRA



Virgo

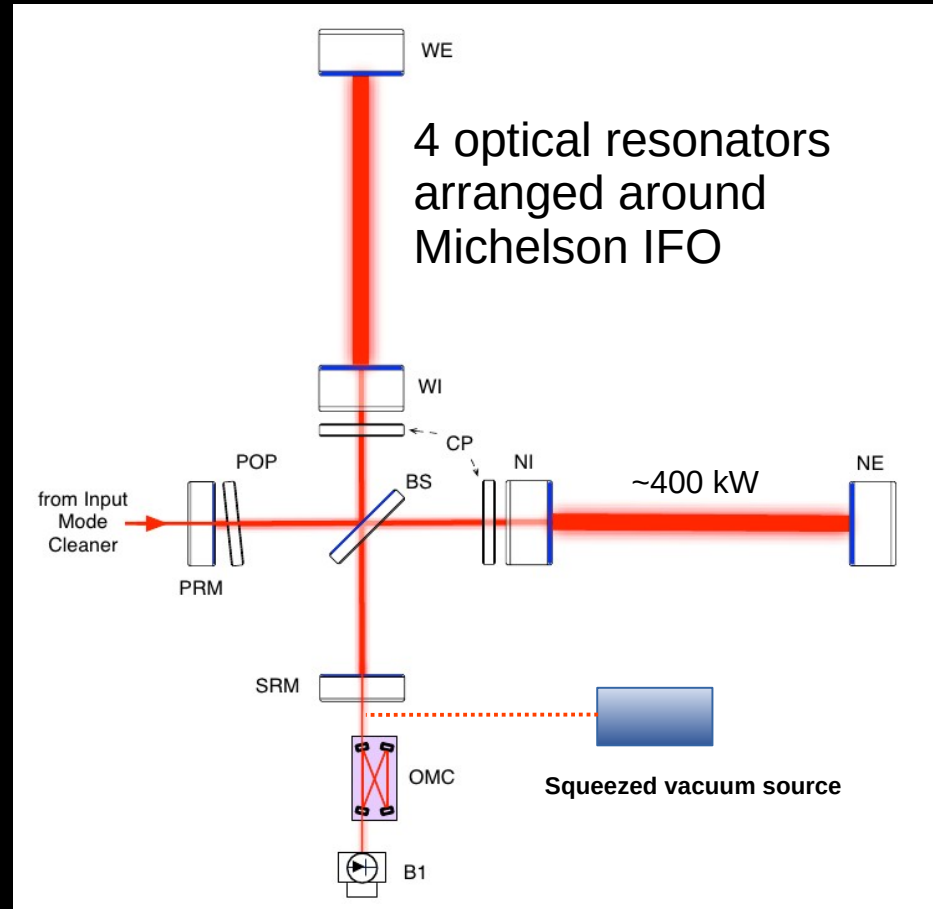


# Michelson, with additions...



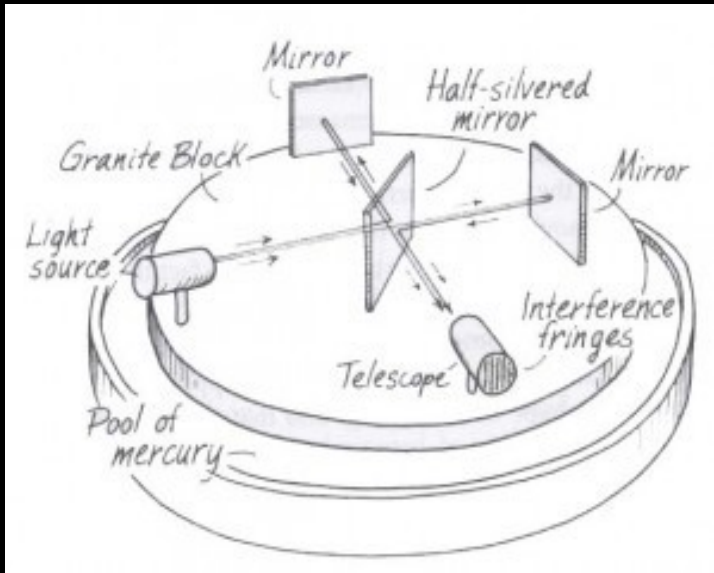
Michelson-Morley experiment:  
Accuracy:  $10^{-8}$  m ( $10^{-9}$  relative)

10m arm-length



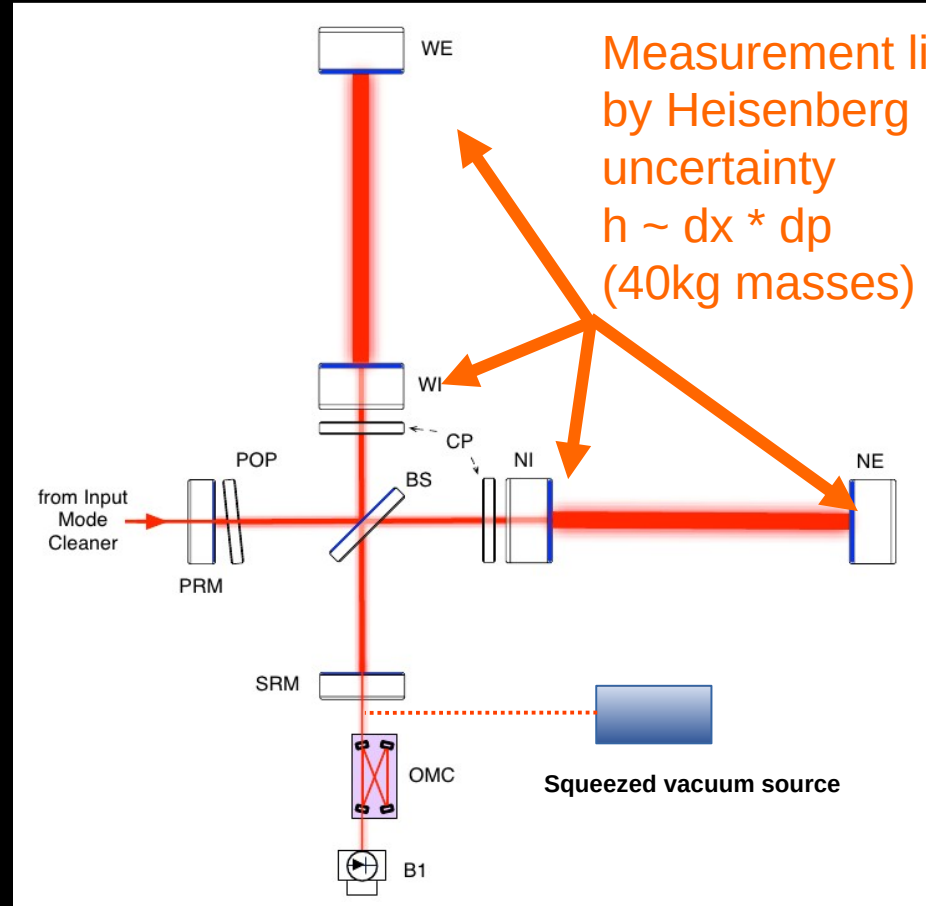
Advanced Interferometer: 3-4 km arm-length  
Accuracy:  $10^{-19}$  m ( $3 \times 10^{-23}$  relative), 100Hz BW

# Michelson, with additions...



Michelson-Morley experiment:  
Accuracy:  $10^{-8}$  m ( $10^{-9}$  relative)




10m arm-length



Measurement limited  
by Heisenberg  
uncertainty  
 $h \sim dx * dp$   
(40kg masses)

Advanced Interferometer: 3-4 km arm-length  
Accuracy:  $10^{-19}$  m ( $3 \times 10^{-23}$  relative), 100Hz BW

# Ultra-light Bosonic dark matter candidates and their coupling to GW detectors

Scalar fields:	coupling to test masses (size oscillation)	
Vector fields (dark photons):	coupling to test masses (acceleration oscillation)	
Axion-like fields:	coupling to light beam	

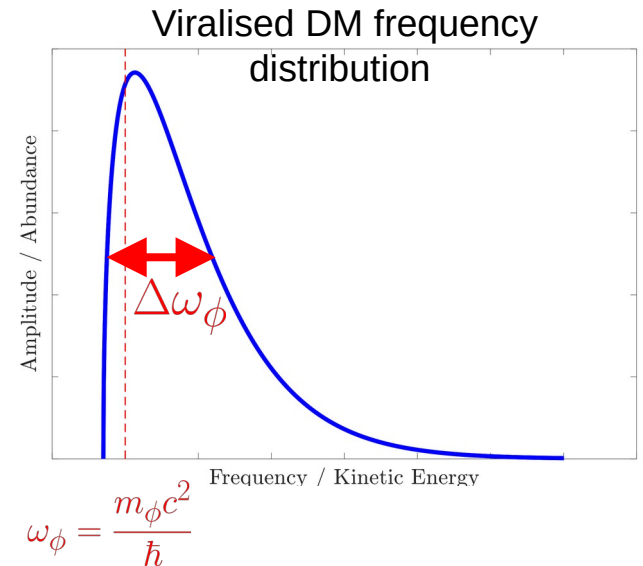
# Sub-eV scalar field Dark Matter

(includes Dilaton, Modulus, Relaxion, ...)

- Produced in early Universe by e.g. ‘misalignment mechanism’, manifests as oscillating field with **local density**  $\rho_{\text{local}}$

$$\phi(t, \vec{r}) = \left[ \frac{\hbar \sqrt{2 \rho_{\text{local}}}}{m_\phi c} \right] \cos \left( \omega_\phi t - \vec{k}_\phi \cdot \vec{r} \right)$$

- Trapped and virialised in gravitational potential wells of e.g. galaxies



# Scalar DM changes size and refractive index of solids

- Couples to SM photon and electron fields with **coupling strength**  $\Lambda_x$

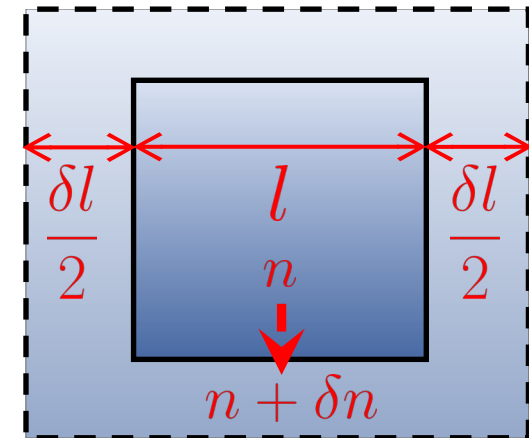
$$\mathcal{L}_{\text{int}} \supset \frac{\phi}{\Lambda_\gamma} \frac{F_{\mu\nu} F^{\mu\nu}}{4} - \frac{\phi}{\Lambda_e} m_e \bar{\psi}_e \psi_e$$

- Scalar DM changes electron mass  $m_e$  and fine structure constant  $\alpha$

$$\frac{\delta\alpha}{\alpha} = \frac{\phi}{\Lambda_\gamma} \quad \frac{\delta m_e}{m_e} = \frac{\phi}{\Lambda_e}$$

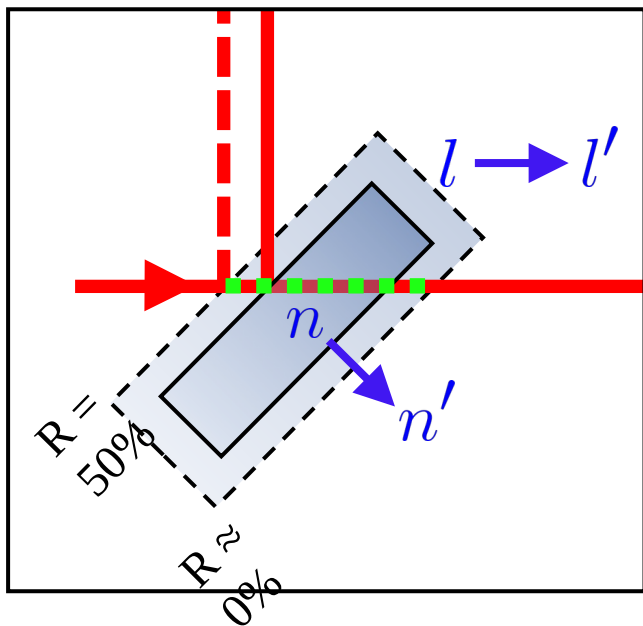
- Causes **oscillatory** changes of size  $l$  and refractive index  $n$  of solids

Grote & Stadnik, PRR (2019)

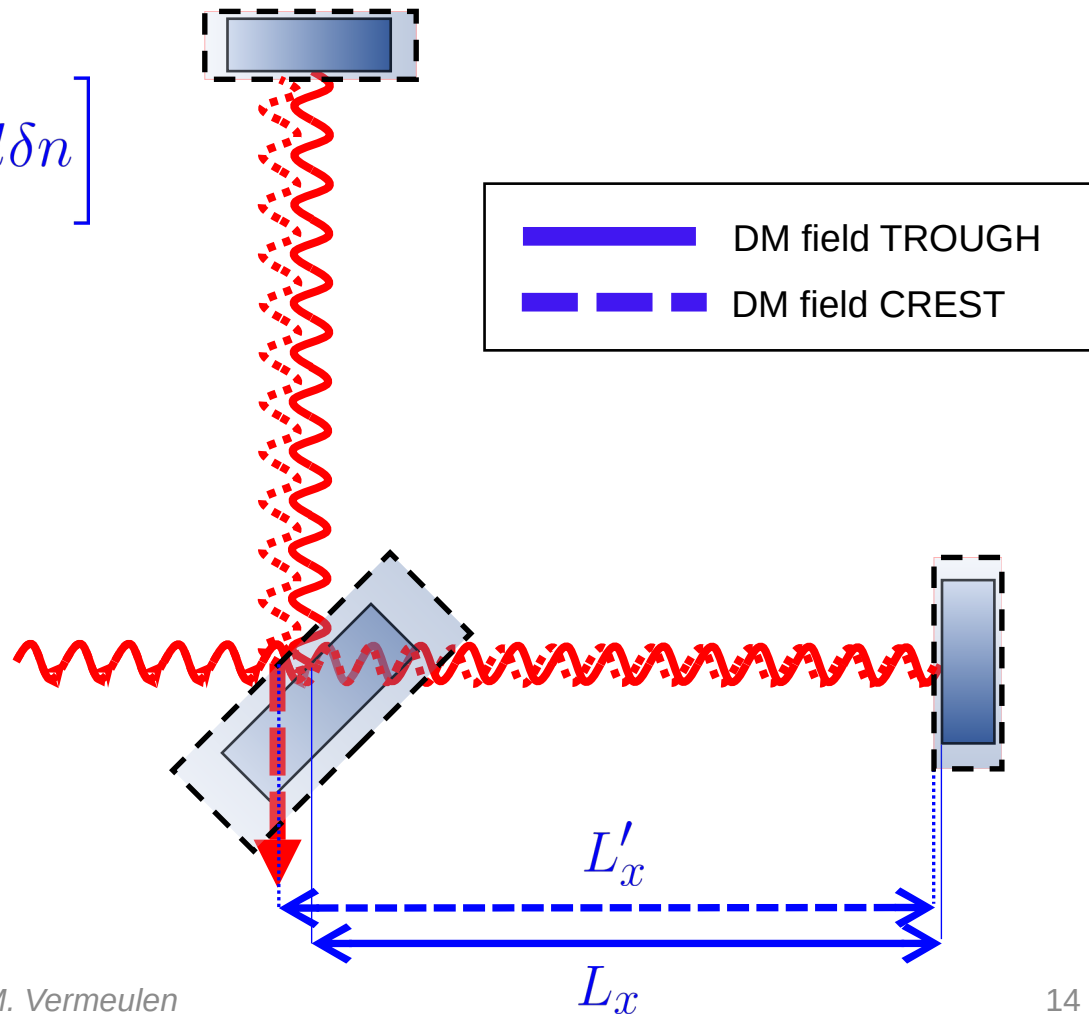


# Scalar DM Couples to an Interferometer

$$\delta(L_x - L_y) \approx \sqrt{2} \left[ \left( n - \frac{1}{2} \right) \delta l + l \delta n \right]$$



Grote & Stadnik, PRR (2019)

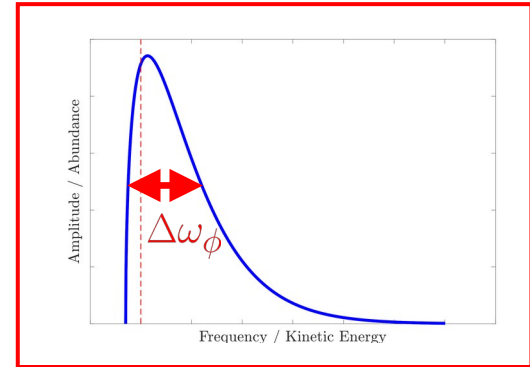
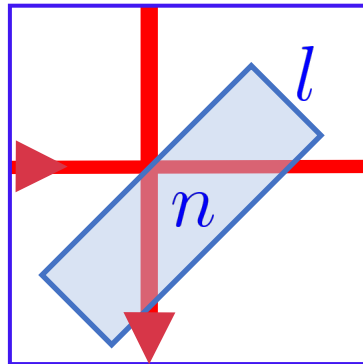


# Expected signal from scalar DM in an interferometer

$$\delta(L_x - L_y) \approx \underbrace{\left( \frac{1}{\Lambda_\gamma} + \frac{1}{\Lambda_e} \right)}_{\text{DM coupling parameter}} \underbrace{(n l)}_{\text{Beamsplitter properties}} \underbrace{\left( \frac{\hbar \sqrt{2 \rho_{\text{local}}}}{m_\phi c} \right)}_{\text{DM abundance}} \underbrace{\cos(\omega_{\text{obs}} t)}_{\text{Spectral linewidth}}$$

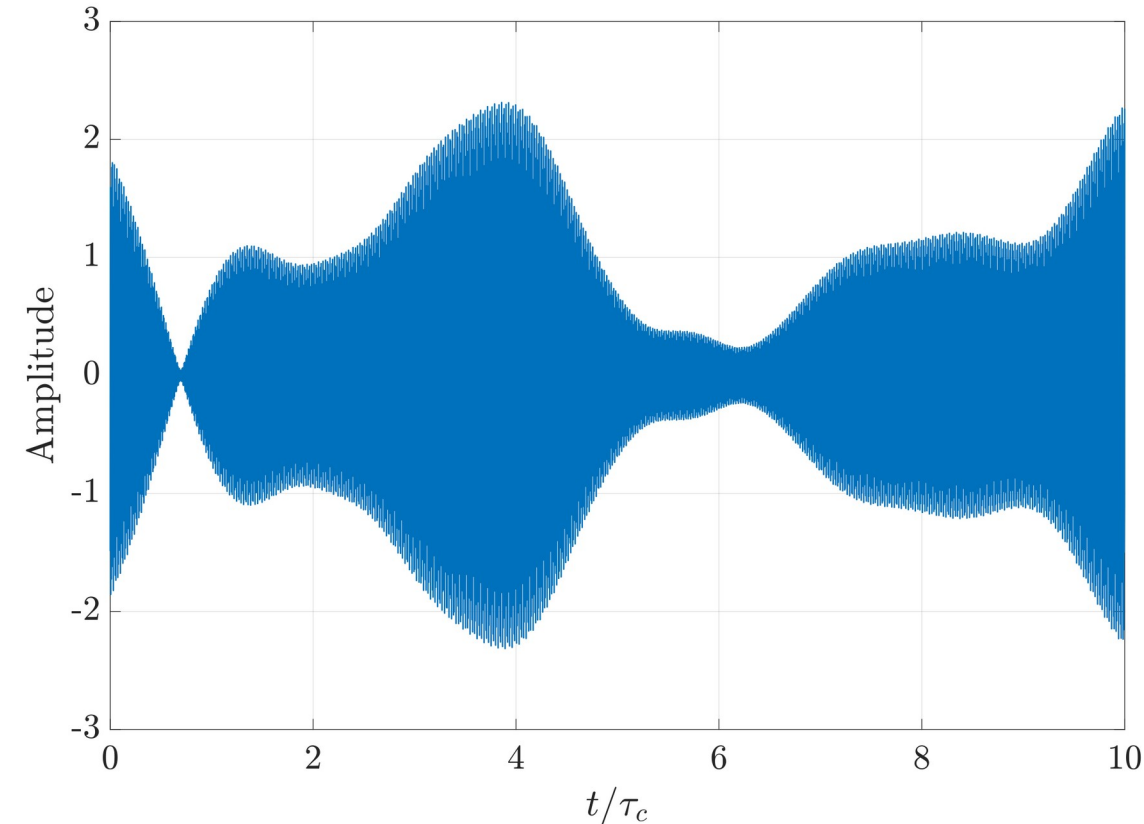
Frequency set by DM mass  
 $\omega_\phi \propto m_\phi$

$\Delta\omega_\phi \approx 10^{-6} \omega_\phi$



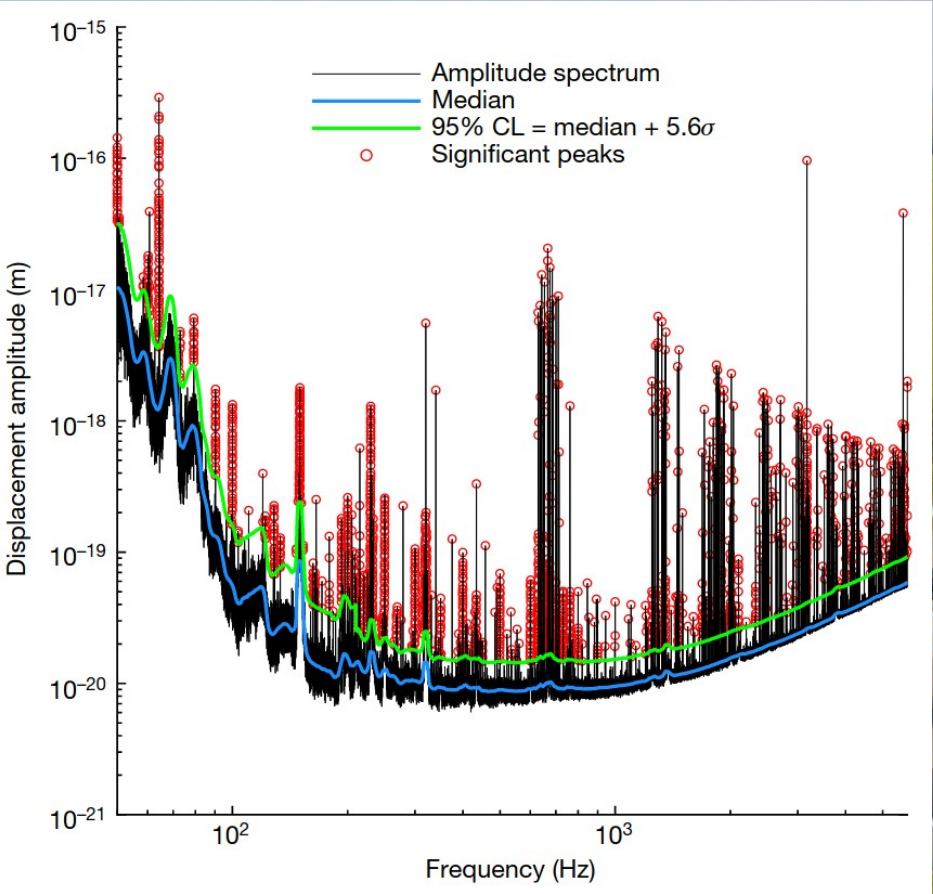
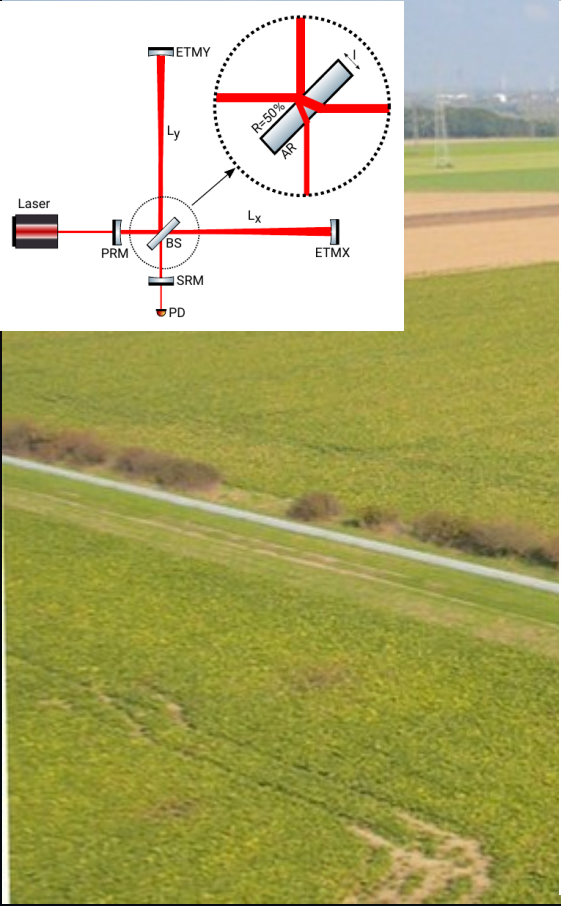
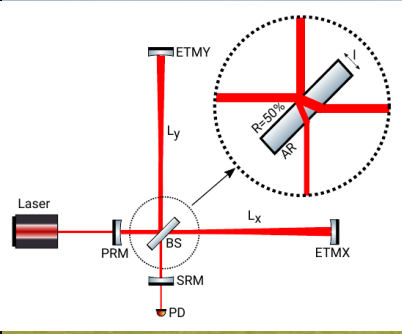
# Dark matter signal is pseudo-coherent

Quasi-monochromatic signals □ Challenges with spectral analysis

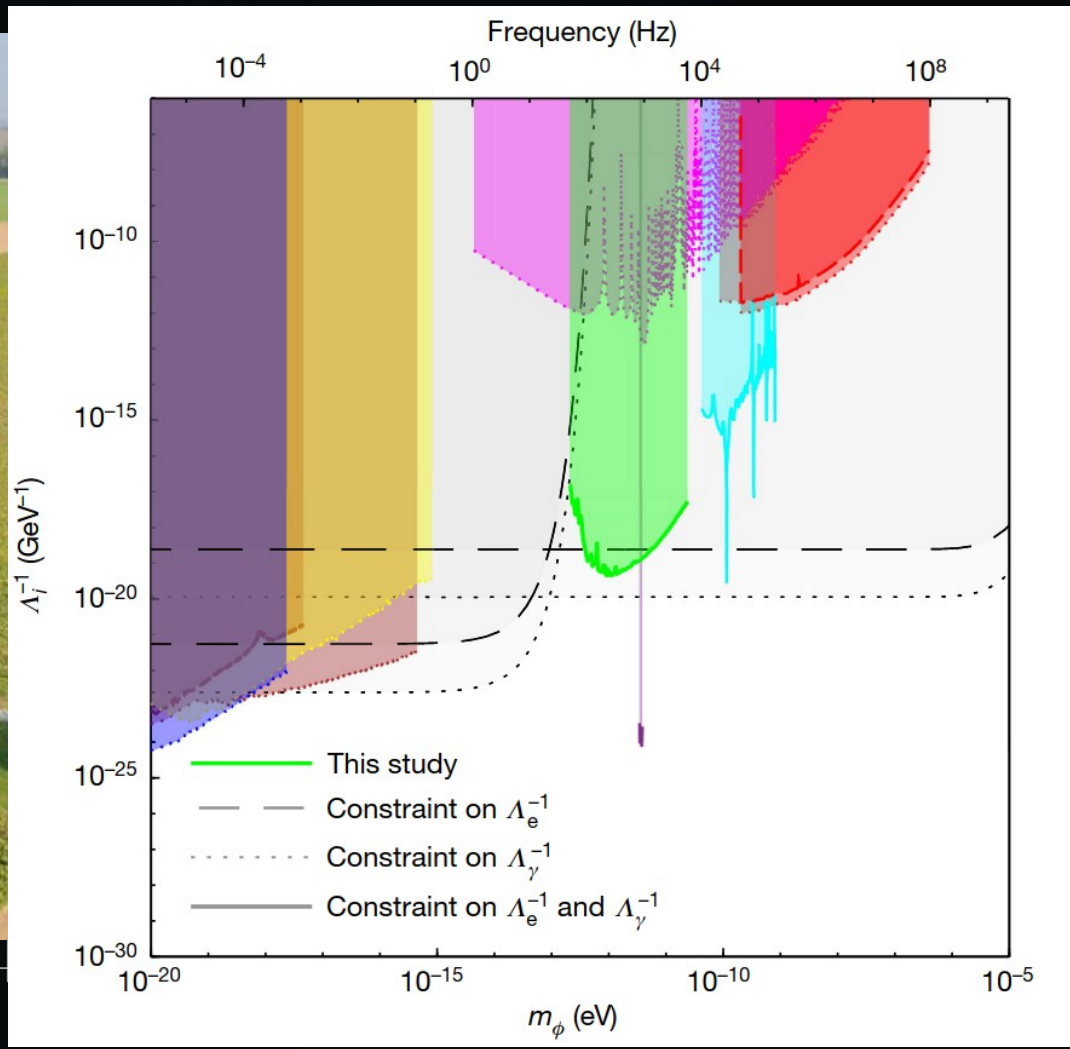
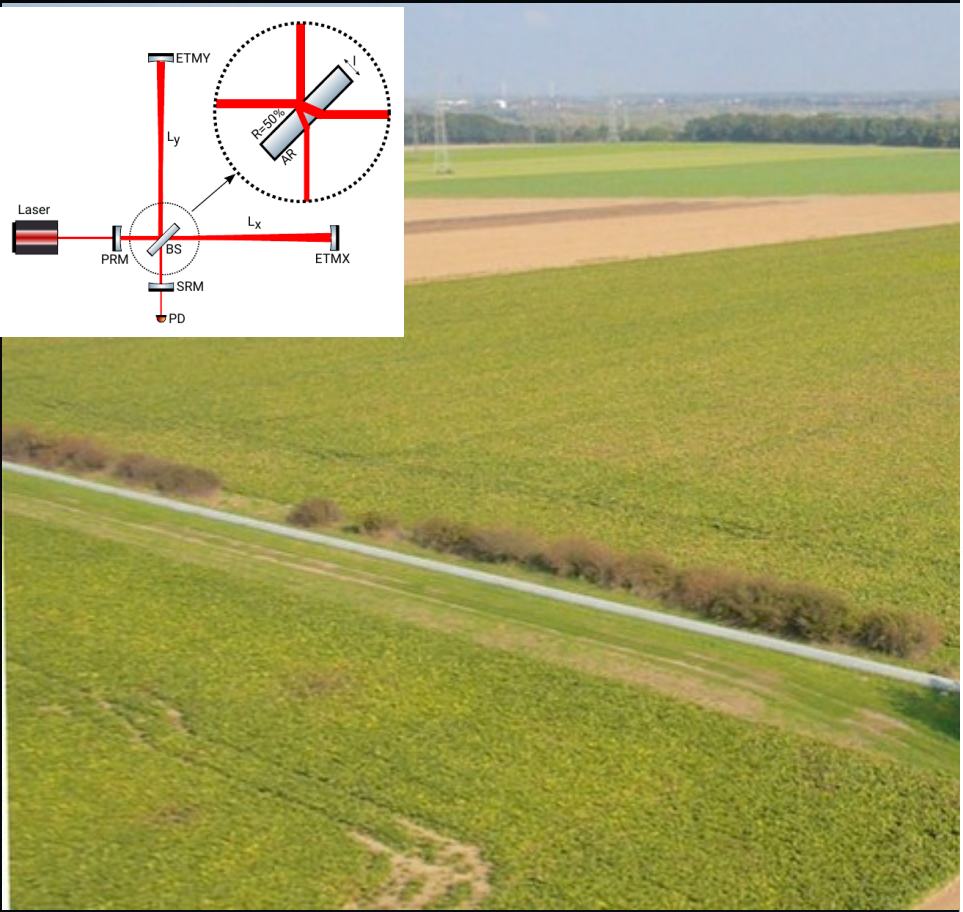
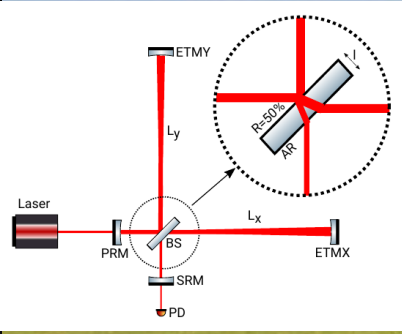


- Signal becomes incoherent with itself for  $T_{\text{DFT}} > \tau_{\text{coh}}$
- Large spectral measurement uncertainty for  $T_{\text{DFT}} < \tau_{\text{coh}}$
- Optimal FFT binning technique for  $1e-6$  linewidth

# Search for scalar field dark matter with GEO600

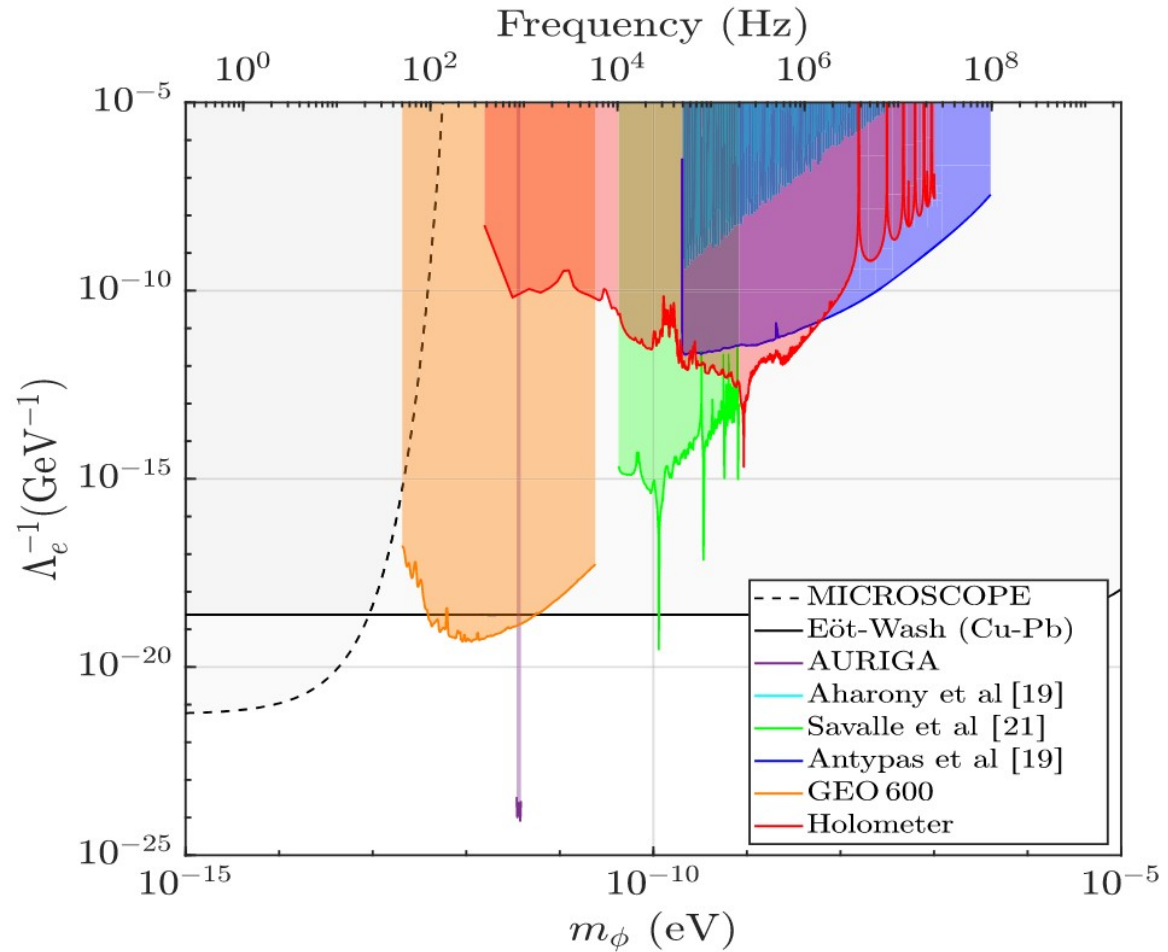


# Search for scalar field dark matter with GEO600

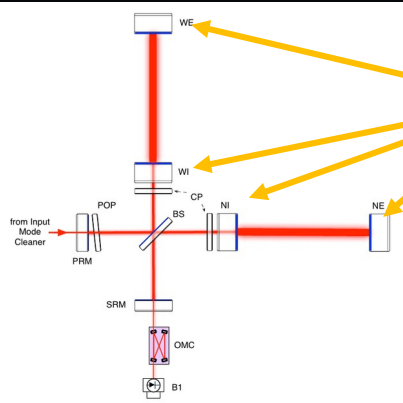


Nature 600, 424-428 (2021)

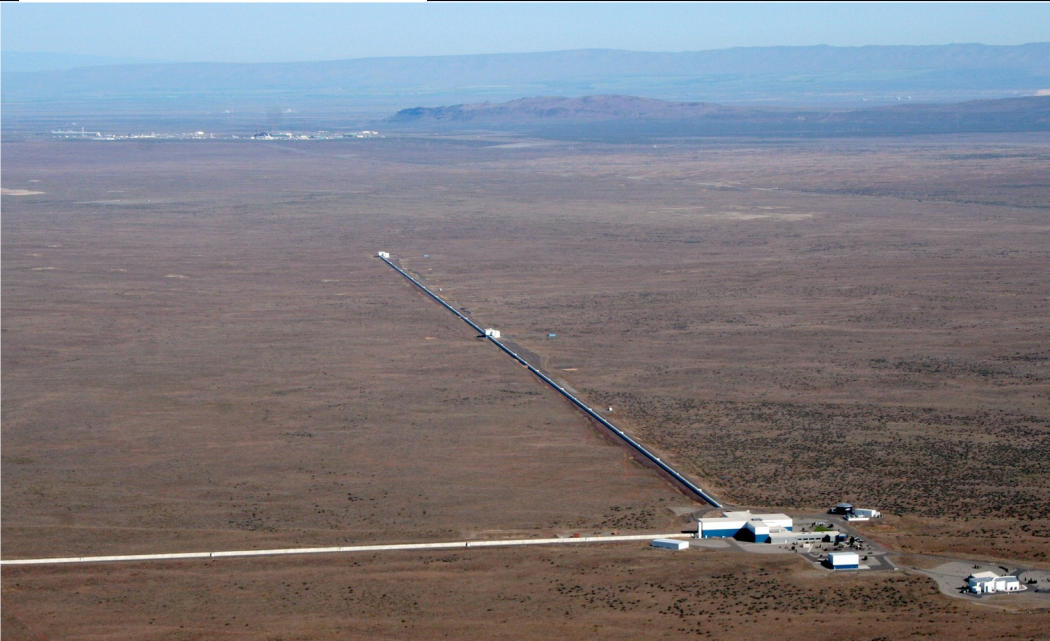
# Search for scalar field DM from co-located Michelson Interferometers



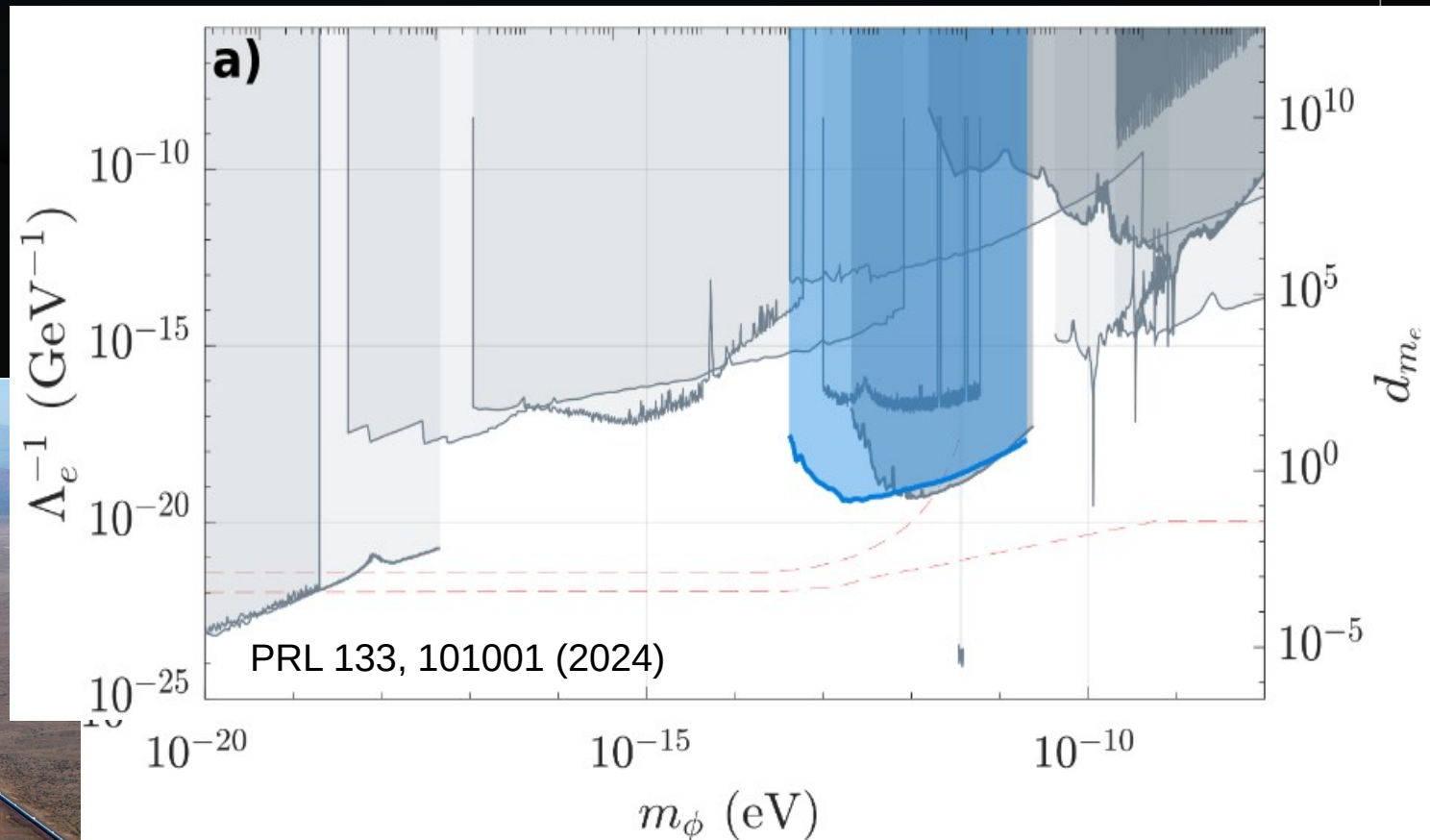
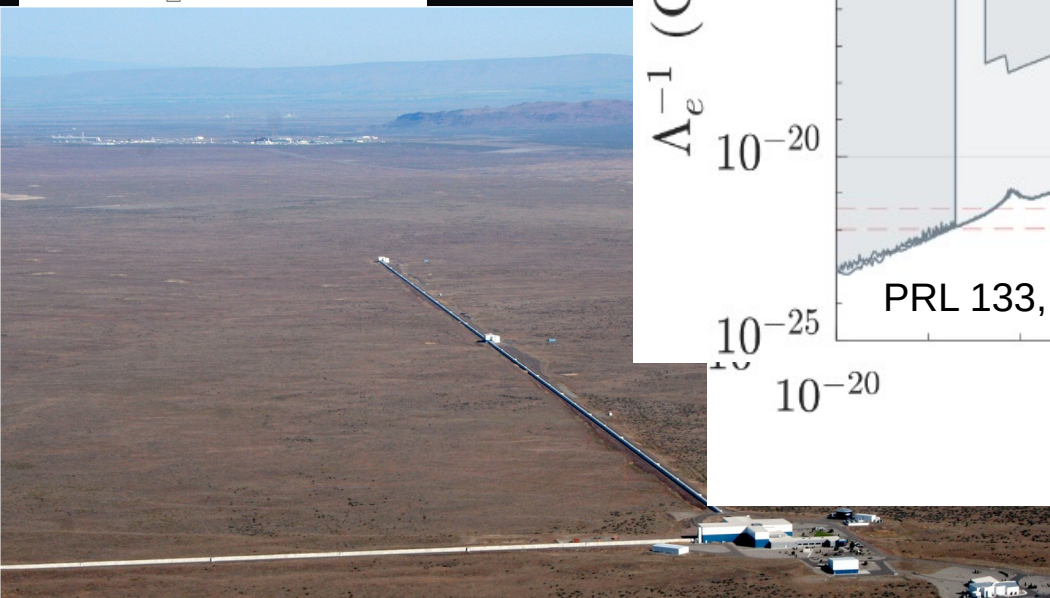
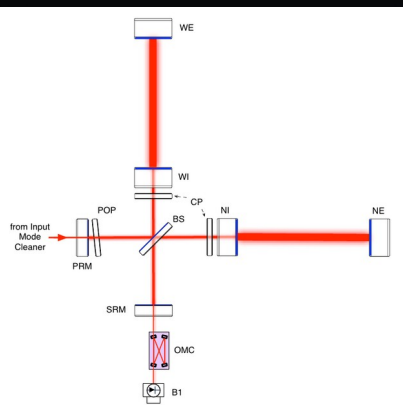
# Search for scalar field dark matter with LIGO



Also analysing effect from thickness differences in arm test-masses. For now (O1 to O4) these are of order 0.1mm, and so the Beam-splitter dominates the signal.



# Search for scalar field dark matter with LIGO



Latest work (O4a data) on arXiv: 2510.27022

# Dark Photons

- Are gauge boson of a U(1) extension of the standard model
- Have a vector potential (like ordinary photons) of an equivalent
- 'electric' field caused by the 'dark charge'
- Cause sinusoidal force on matter carrying dark charge
- (baryon or neutron number)

Acceleration  
of object

Random phase factor

Dark 'charge'

$$\vec{a}(t, \vec{x}) \simeq \epsilon e \frac{q}{M} \omega \vec{A} \cos(\omega t - \vec{k} \cdot \vec{x} + \phi)$$

Coupling constant

Object position

Wave vector

Charge normalization

Mass of object

Compton freq, set by mass

Polarization

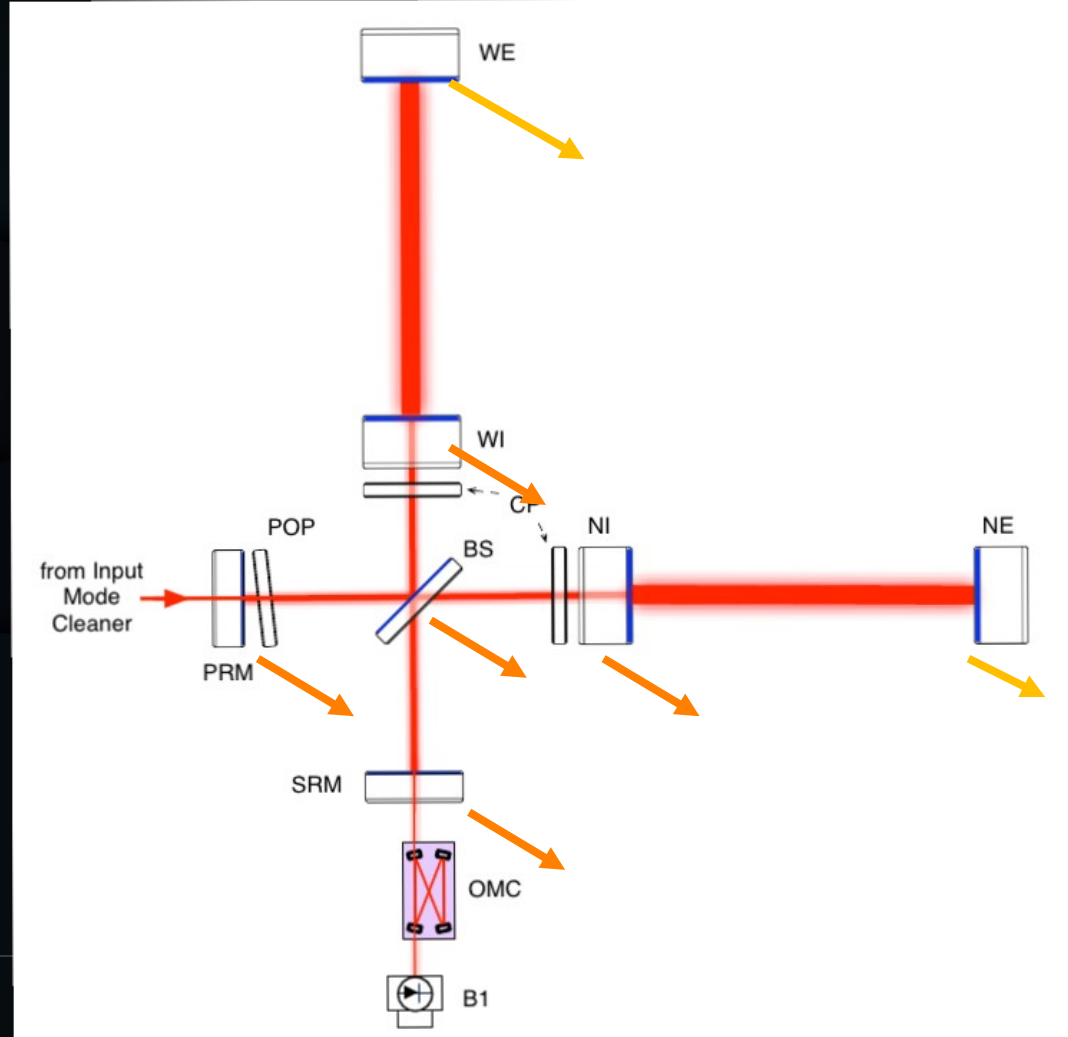
# Dark Photon coupling to Interferometers

Acceleration common to all mirrors,  
Except for small phase shifts from  
Finite de Broglie wavelength  
( $\sim 3\text{e}9\text{m}$  at  $100\text{Hz}$ )

→ signal strength depends  
on arm-length

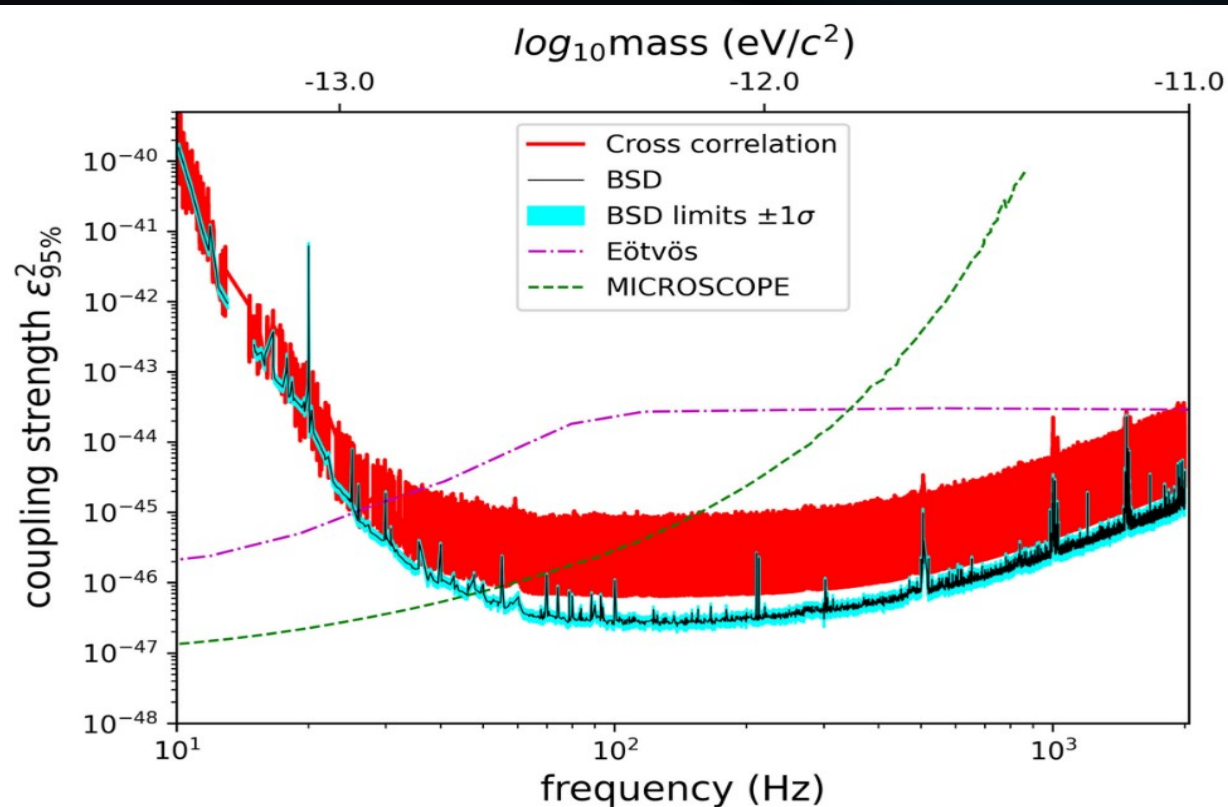
Additional effect from finite light  
travel time

Signal also depends on direction of  
wave which can be averaged over



# Dark Photon search with LIGO and Virgo

- First search on LIGO O1 data (2019)
- Added effect from light travel time,
- and increased sensitivity in O3, and using LIGO and Virgo data (2022):



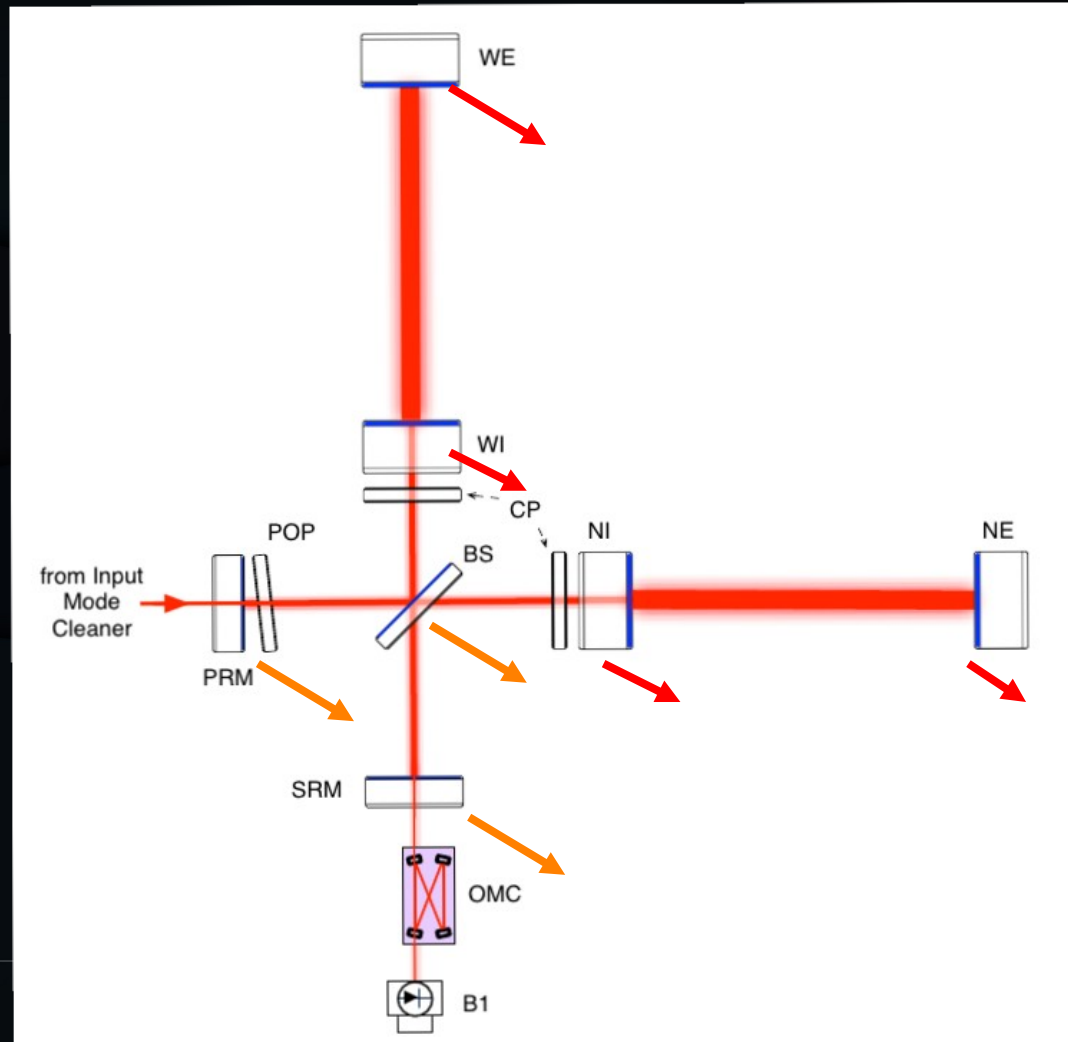
Abbott et al. 2022, PRD 105, 063030  
Abbott et al. 2024, PRD 109, 089902(E)  
Arxiv 2025: 2510.27022,  
Also first search for tensor bosons

# Dark Photon coupling to Interferometers

Can get larger signal using different Materials.

→ KAGRA detector: arm test masses Made of sapphire


→ Look for signals in 'auxiliary' Channels. E.g. the 'small Michelson'



1) Laser-interferometric  
Gravitational-wave detectors  
(as Haloscopes)

2) Laser-interferometric  
OTHER detectors  
(as Haloscopes & LSW)

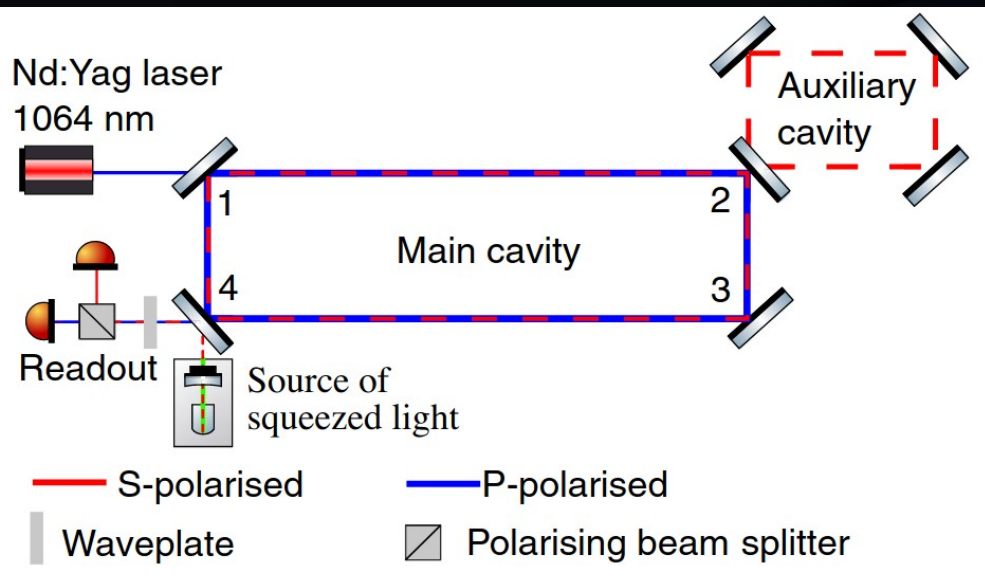
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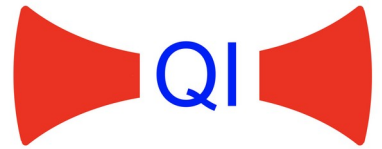


# Other ideas with interferometry: Axion-Like-Particles

- Proposal for (galactic halo) ALP's detection in GW detectors
- GW detectors not optimized for polarization effects
- → evolved to table-top proposals, now pursued in Tokyo, MIT, and Birmingham, exploring axion-photon interaction that leads to birefringence of the light:
- Laser-Interferometric Haloscopes

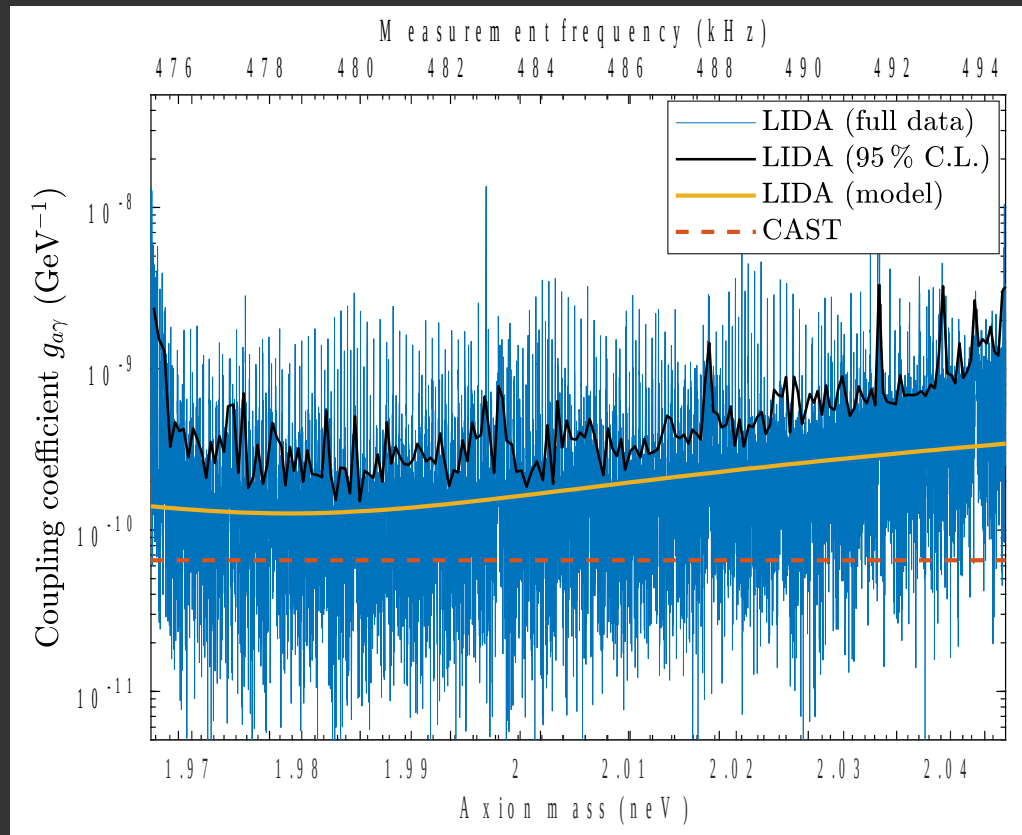
Phys. Rev. D **98**, 035021 (2018), Phys. Rev. Lett. **121**, 161301 (2018),  
Phys. Rev. D **100**, 023548 (2019), **Phys. Rev. D 101**, 095034 (2020)





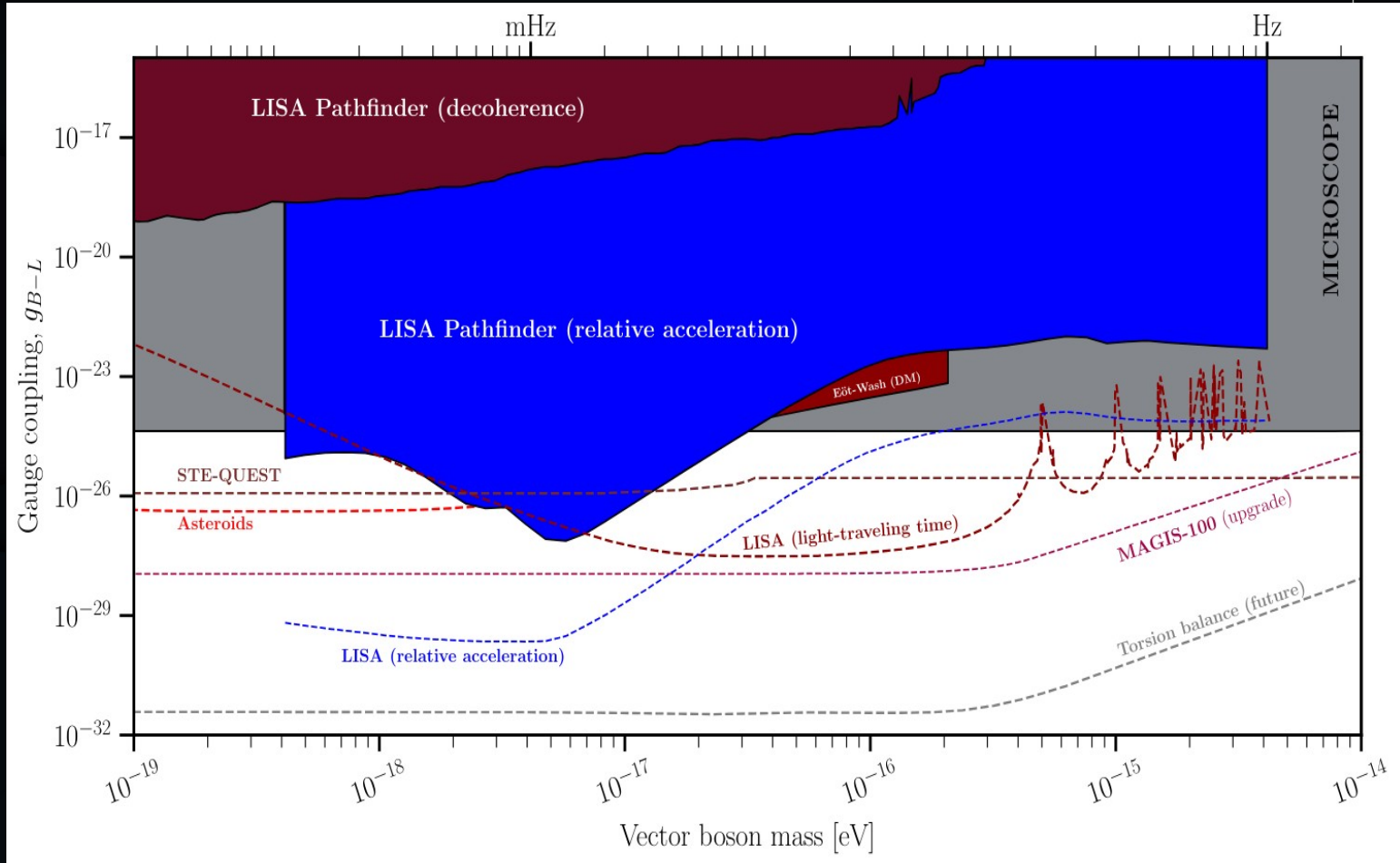
# LIDA: Astrophysical results

- World record of laser intensity in precision interferometry.
- LIDA is a front-runner in axion interferometry.
- Set competitive constraints for the axion masses of 2 neV.



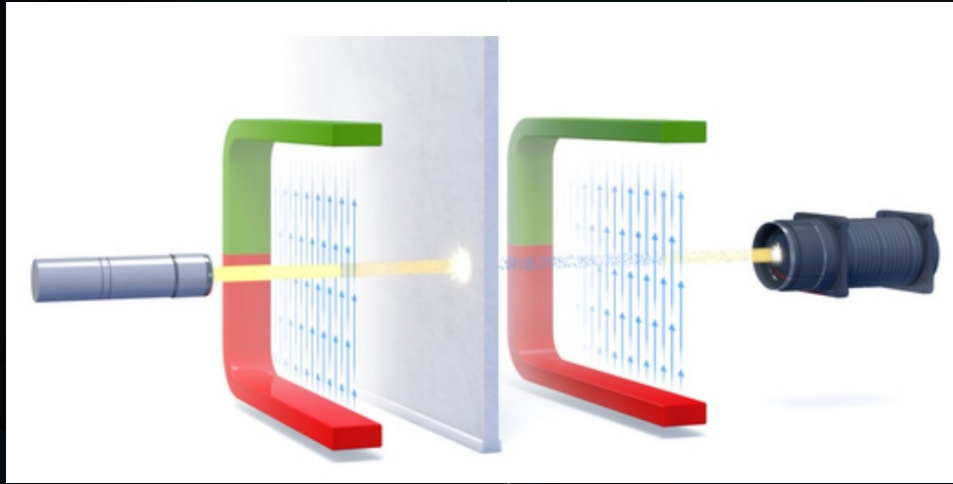
Phys. Rev. Lett. **132**, 191002 (2024)

# Limits on dark photon DM from LTP

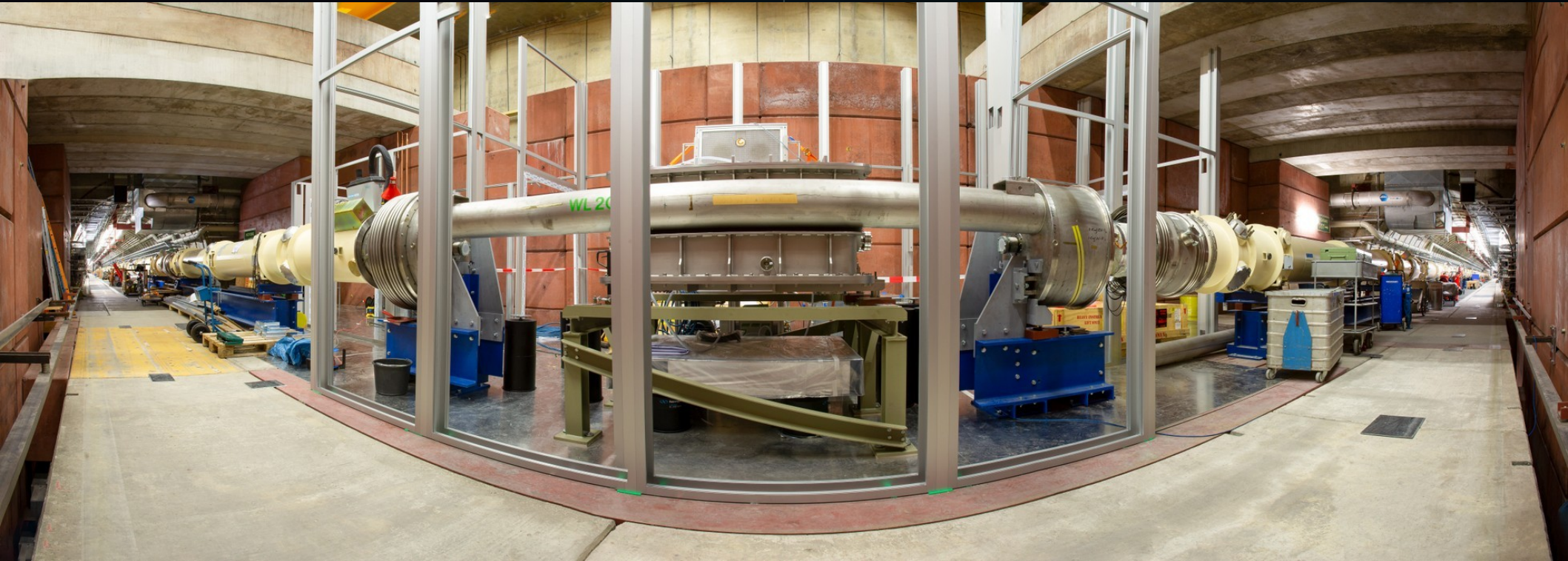


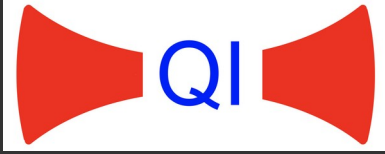
# Light-Shining-through-Wall (LSW)

Principle

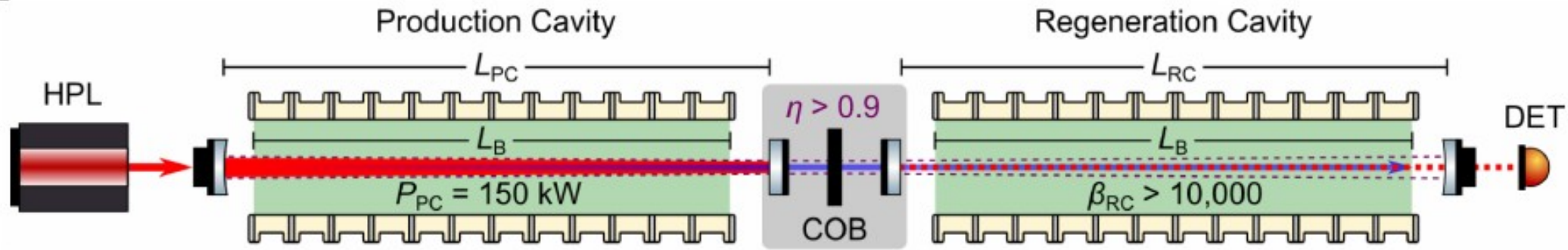


# NON-HALOSCOPE interferometric search: ALPS II at DESY (LSW)





# ALPS @ DESY, Germany



arXiv:2009.14294

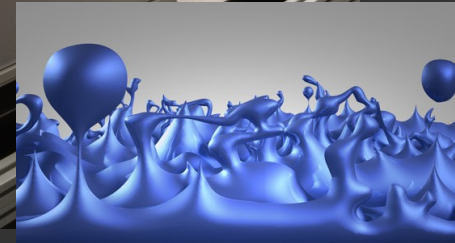
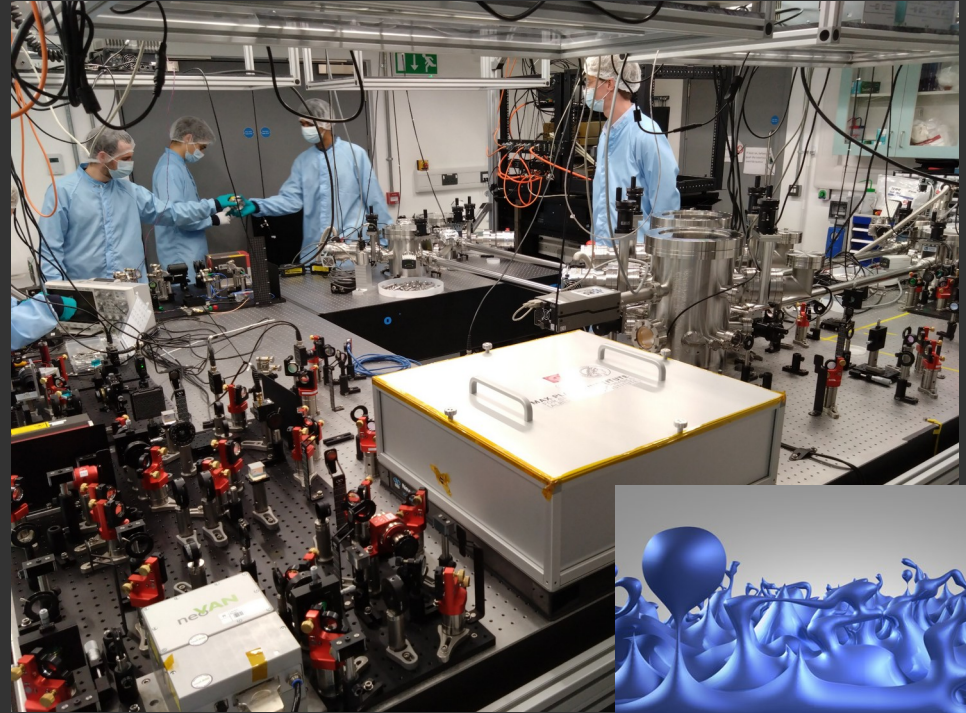
- International collaboration (DESY, U Florida, AEI Hannover, Odense, Cardiff)
- Constructed in former HERA accelerator tunnel at DESY
- First Science run completed

arXiv 2512.14110, 2601.18684



# Quantum-Enhanced Space-Time experiment (QUEST)

- Only table-top co-located interferometer in the world (Caltech started gQuEst experiment)
- Main science target is quantum gravity, but also sensitive to dark matter and VHF gravitational waves



# Summary

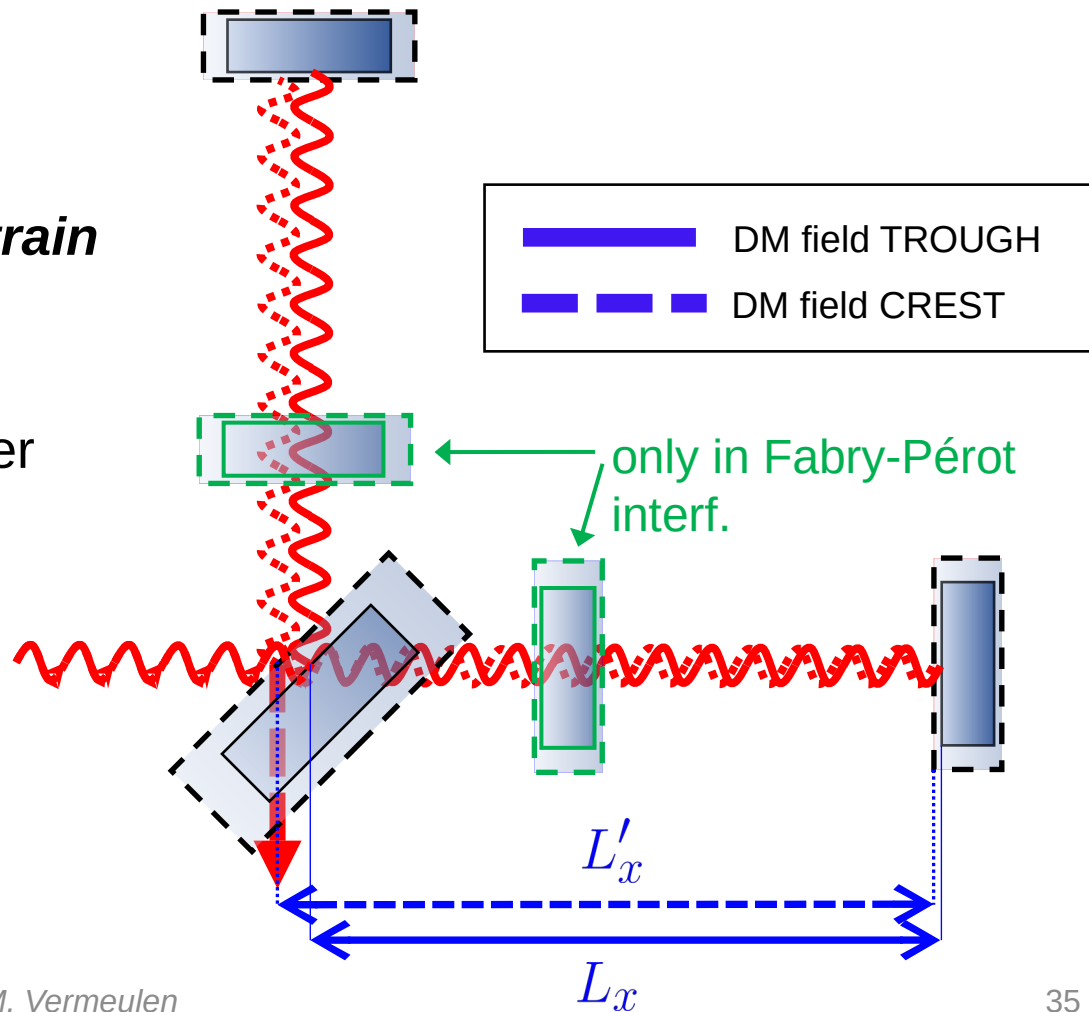
- Gravitational-wave detectors
- Indirect (via GW's) dark matter searches
- Direct dark matter searches with GW detectors: scalar fields (GEO, Holometer, LIGO), dark photons (LIGO, KAGRA), axions (KAGRA)
- Dedicated laser-interferometry experiments
- Axion search with Haloscopes (LIDA, ADBC, DANCE)
- Haloscope scalar field searches with QUEST, GqQUEST
- Axion search with light-shining-through-wall experiments (ALPS)
- List not complete, and very Likely more is possible...

# Scalar DM Couples to an Interferometer

- LIGO/Virgo/KAGRA have high arm **strain** sensitivity, relatively lower **phase** sensitivity

□ GEO600 most sensitive interferometer for signal from the beamsplitter

→ but arm mirror thickness *differences* do matter



# “Dark GEO”: Interferometry Haloscope scaling up

