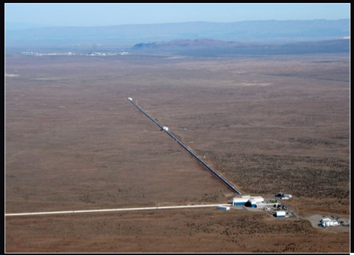
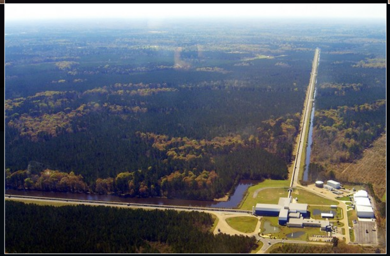
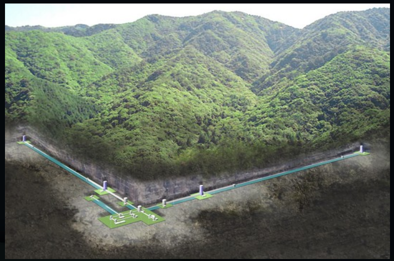
Direct Searches for Ultra-Light FIPs with Gravitational-Wave Detectors



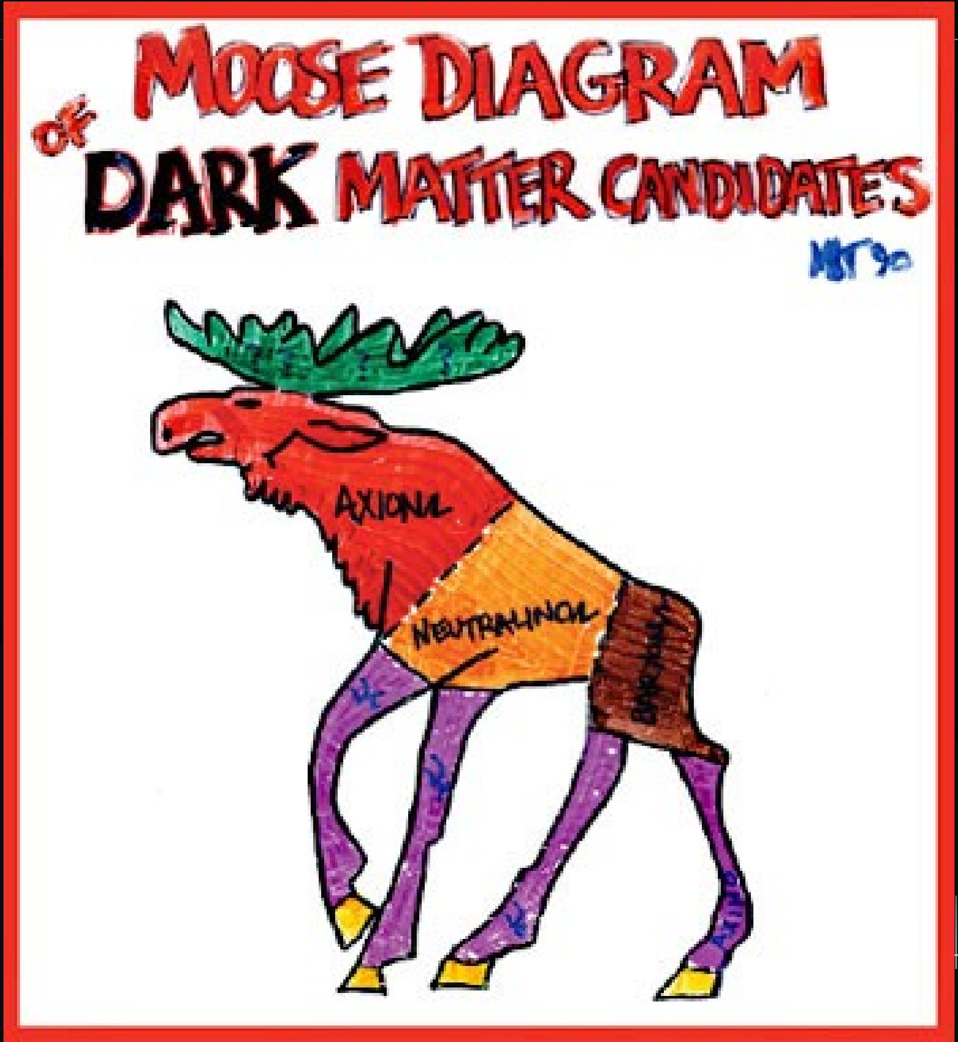
Hartmut Grote
FIPs CERN workshop
18/10/2022



CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

So what is the dark matter?

- WIMPs (miracle)
- Axions (and ALPs)
- Ultra-light bosons (VULFs)
- Sterile Neutrinos
- …
- Black Holes, ...

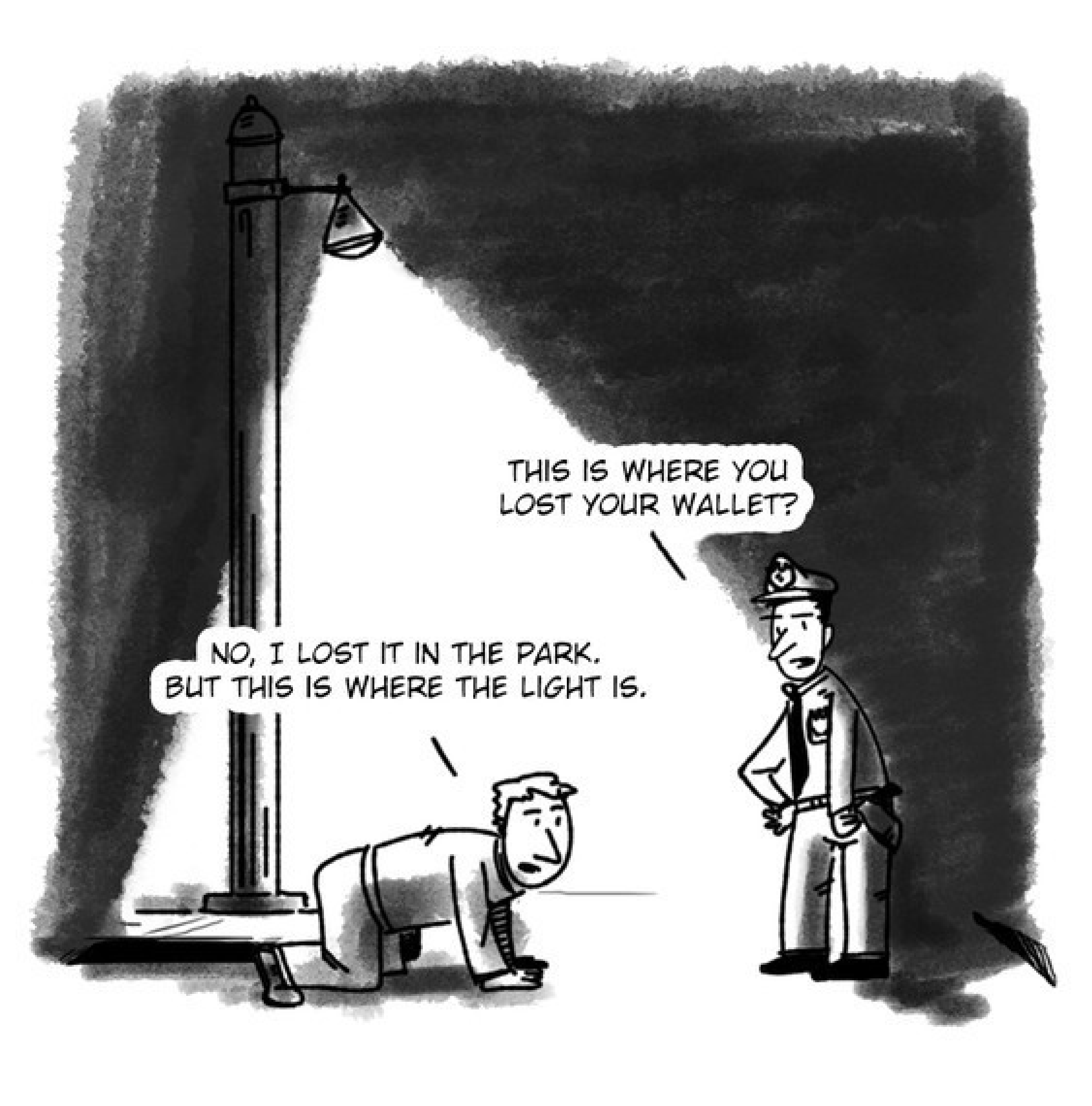


Courtesy Michael Turner (1990)

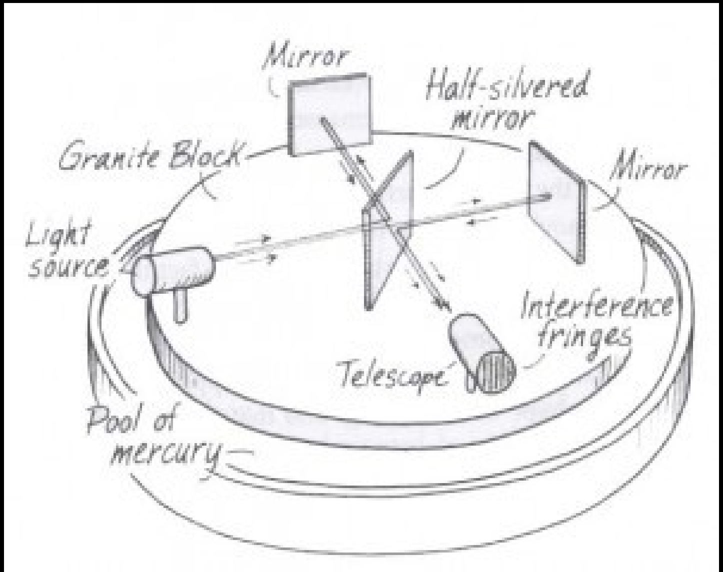
Search where you can

‘officially’
recommended
Strategy!

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



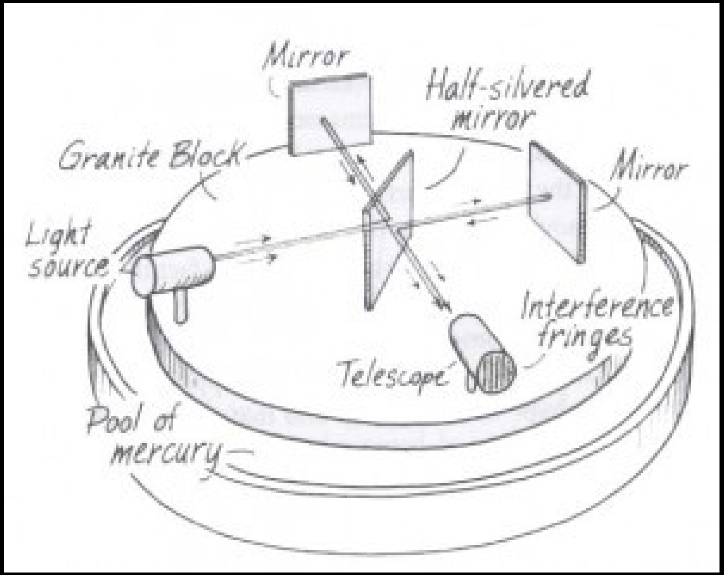
Michelson Interferometer



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

10m arm-length

Michelson, with additions...



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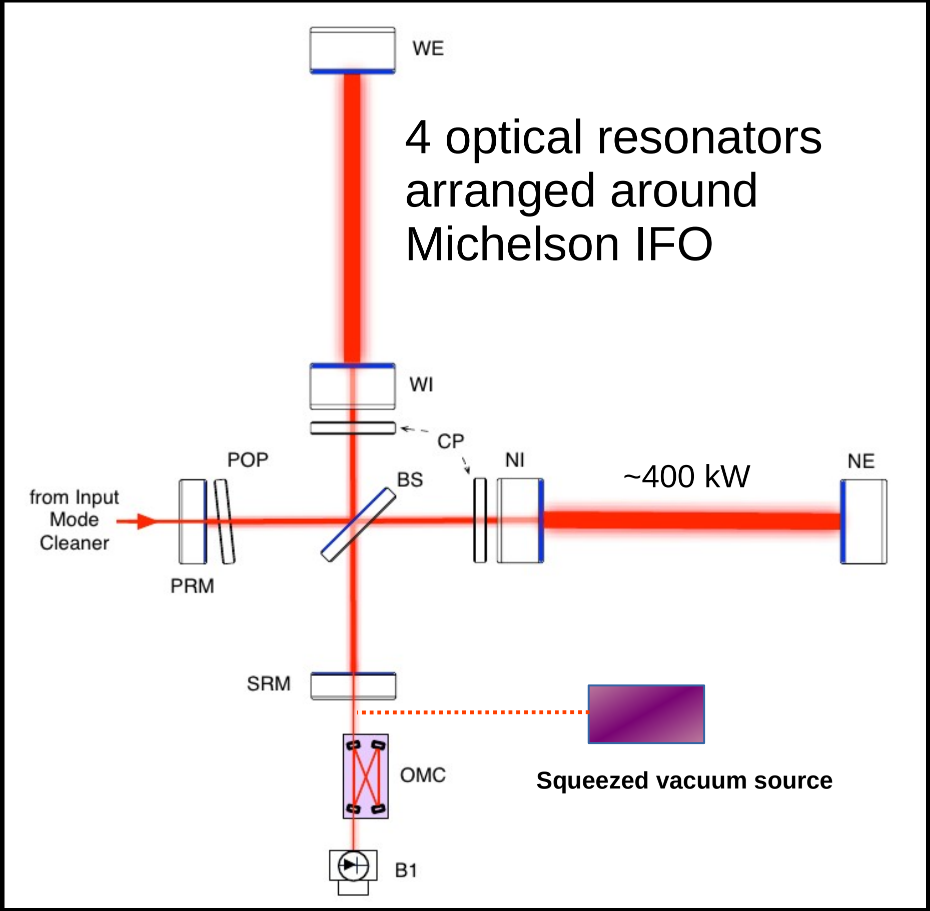

Advanced Interferometer: 3-4 km arm-length
Accuracy: 10^-19 m (3 x 10^-23 relative), 100Hz BW

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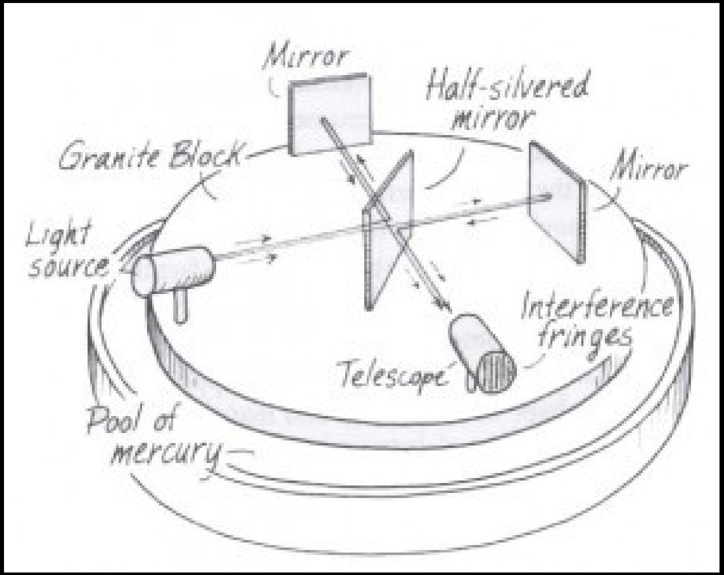

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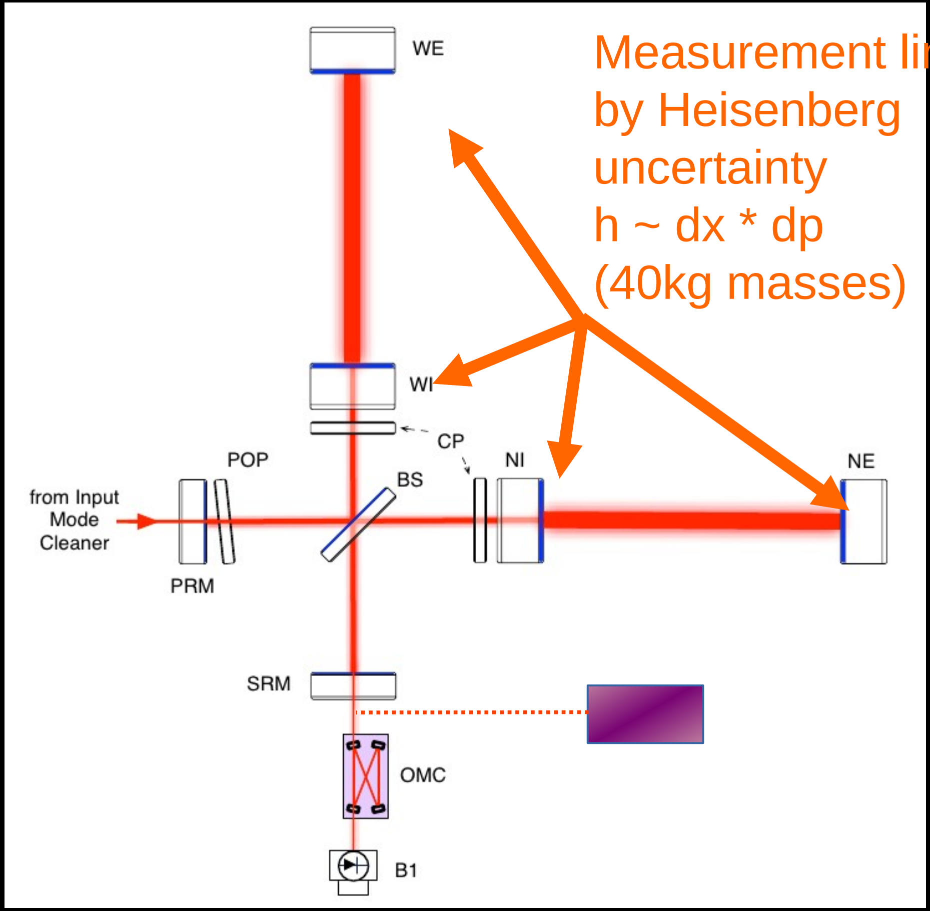

Measurement limited by Heisenberg uncertainty
h ~ dx * dp
(40kg masses)

Advanced Interferometer: 3-4 km arm-length
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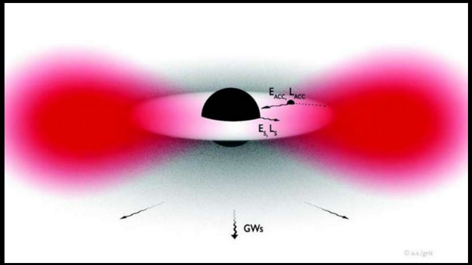
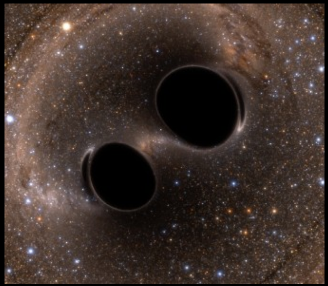
Indirect vs. Direct FIPs searches With Gravitational-Wave Detectors

Indirect

- Ultra-Light Boson Cloud around spinning black holes search via continuous GW detection
  - D’Antonio et al. 2018, PRD 98, 103017
  - Palomba et al. 2019, PRL 123, 171101
  - Sun et al. 2019 PRD 101, 063020
- Impact of ultra-light boson clouds on binary black hole mergers
  - Baumann et al. 2019, PRD 99, 044001
  - Yang et al. 2018, Res. Astron. Astrophys. 18, 065
  - Choudhary et al. 2021, PRD 103, 044032
- Stochastic GW background from ultra-light bosons
  - Tsukada et al. 2019, PRD 99, 103015
- ...others / ongoing





Indirect vs. Direct FIPs searches
With Gravitational-Wave Detectors

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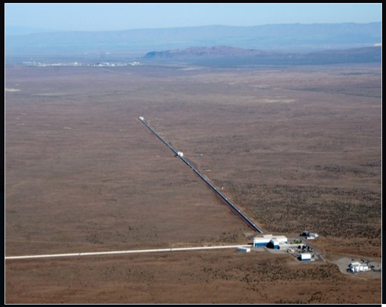
- ...others / ongoing

Direct

- Scalar field search (with GEO and Holometer)
  - Grote & Stadnik 2019, PRR 1, 033187
  - Vermeulen et al. 2021, Nature 600, 424
  - Aiello et al. 2022, PRL 128, 121101
- Dark Photon search (with LIGO)
  - Pierce et al. 2018, PRL 121, 061102
  - Guo et al. 2019, Nature comm. Phys 2, 155
  - Abbott et al. 2022, PRD 105, 063030
- ...others / ongoing

Direct Dark Matter Detection with GW Detectors

- Scalar Field
- Dark Photon
- (Axions ?)



LIGO

GEO600

Virgo

KAGRA

Sub-eV scalar field Dark Matter

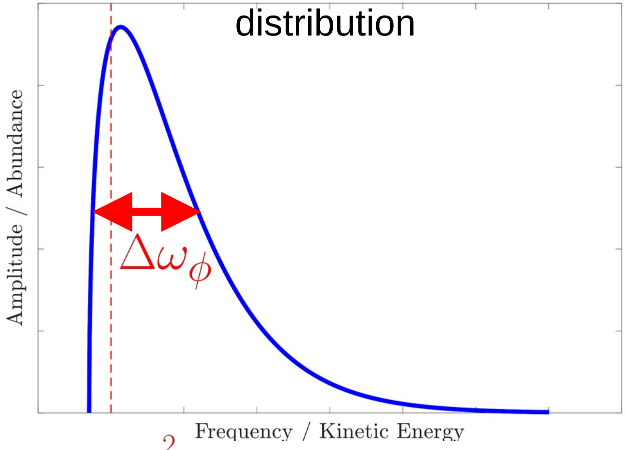
(includes WISP/VULF, Dilaton, Modulus, Relaxion, …)

- Produced in early Universe by e.g. ‘misalignment mechanism’, manifests as oscillating field with local density ρ_{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

Viralised DM frequency distribution



$$\omega_\phi = \frac{m_\phi c^2}{\hbar}$$

Scalar DM changes size and refractive index of solids

- Couples to SM photon and electron fields with coupling strength Λ_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 α

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

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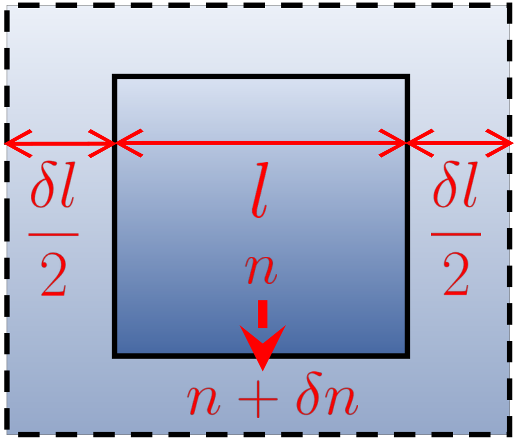
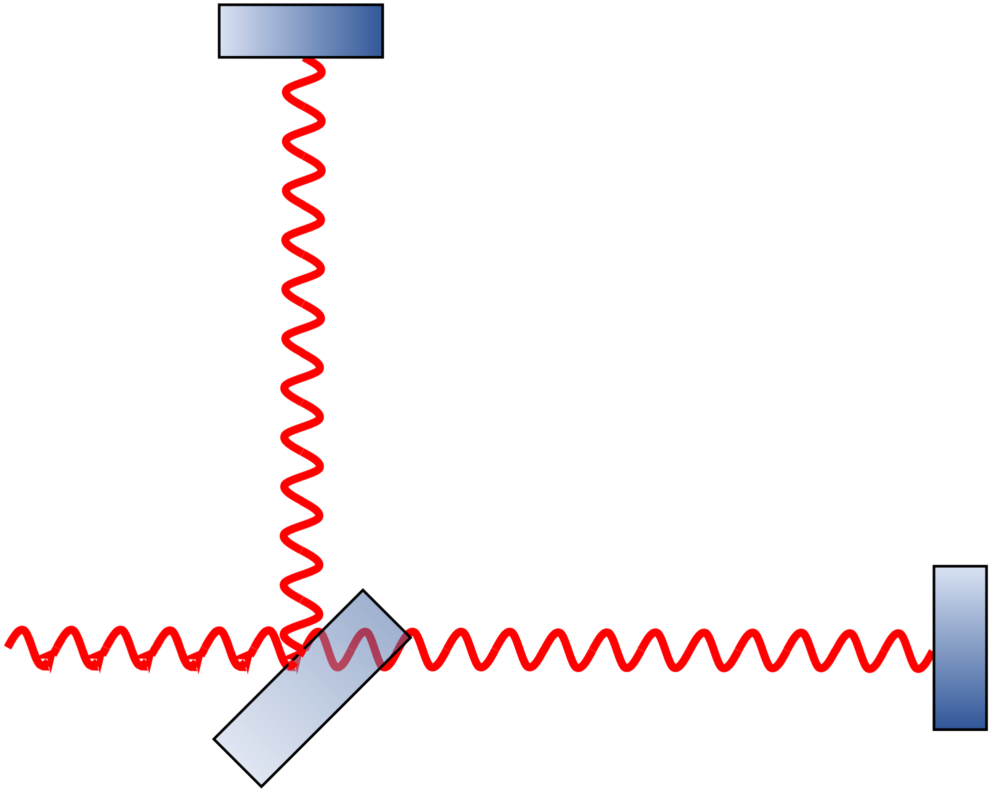
$$\frac{\delta\alpha}{\alpha} = \frac{\phi}{\Lambda_\gamma} \qquad \frac{\delta m_e}{m_e} = \frac{\phi}{\Lambda_e}$$

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



Grote & Stadnik, PRR (2019)

Scalar DM Couples to an Interferometer



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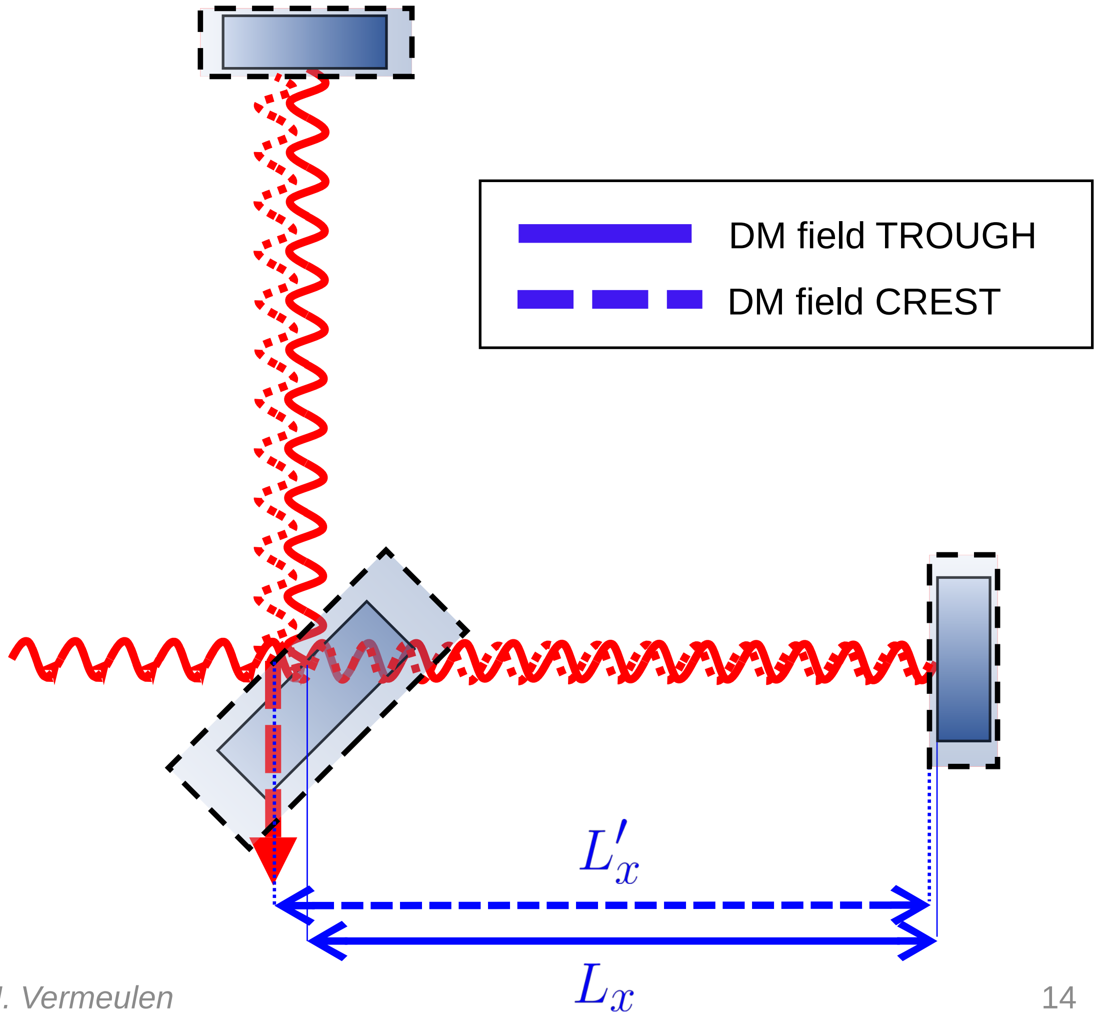
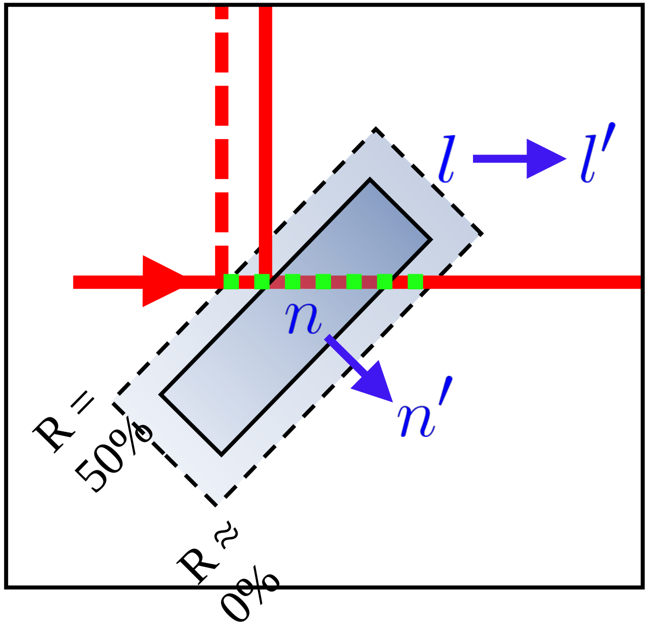
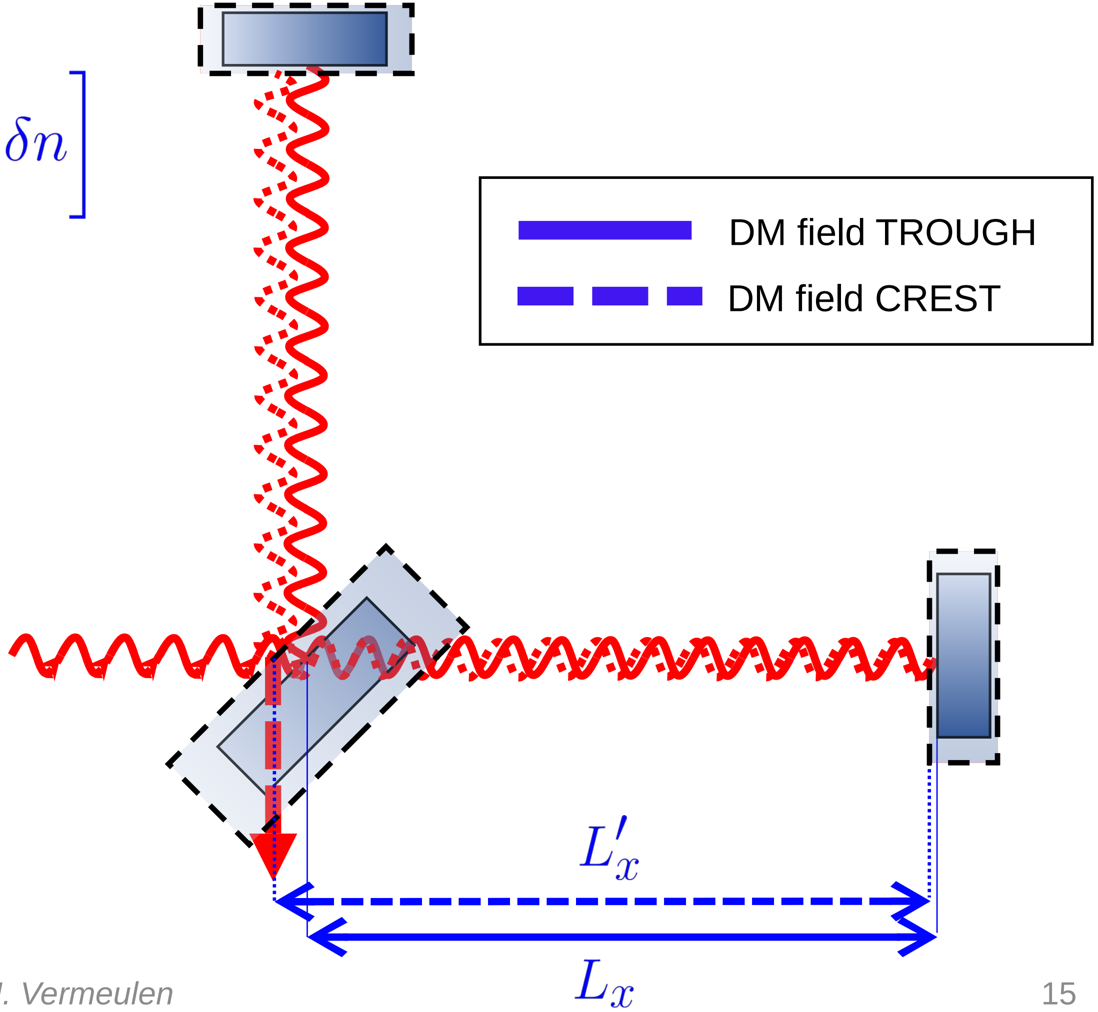


Grote & Stadnik, PRR (2019)

Scalar DM Couples to an Interferometer

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





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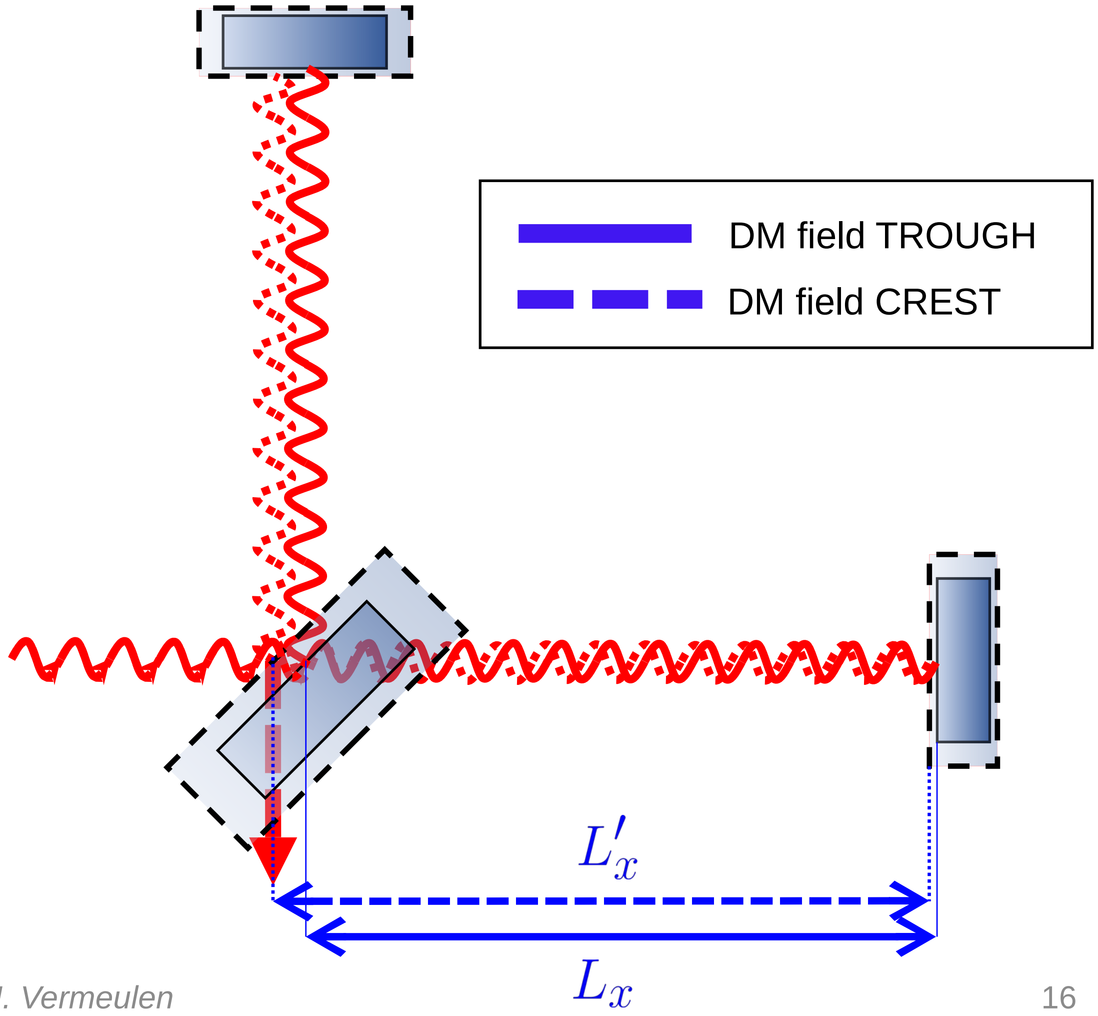
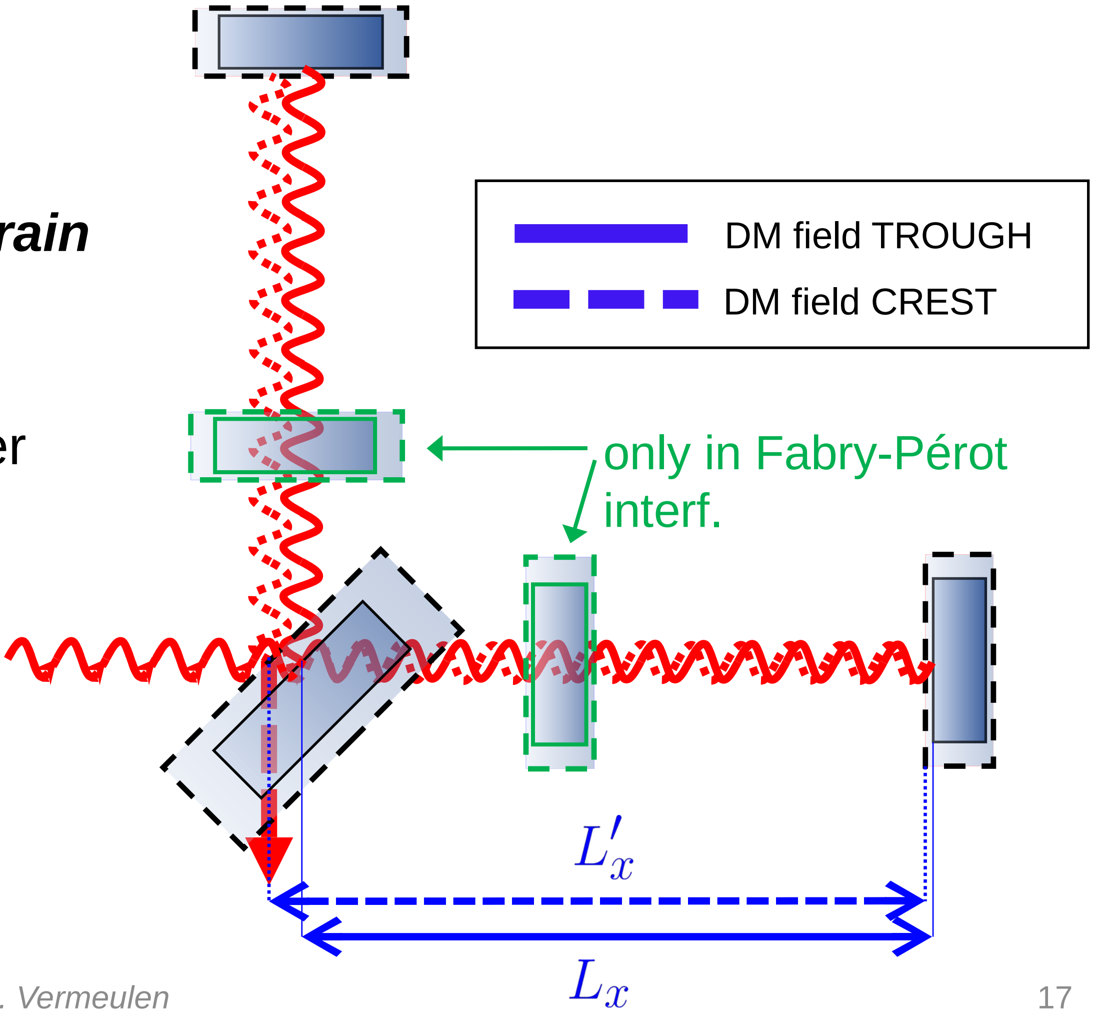


Scalar DM Couples to an Interferometer

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

 GEO600 most sensitive interferometer for this signal



Expected signal from scalar DM in an interferometer

DM abundance

Frequency set by DM mass

$\omega_\phi \propto m_\phi$

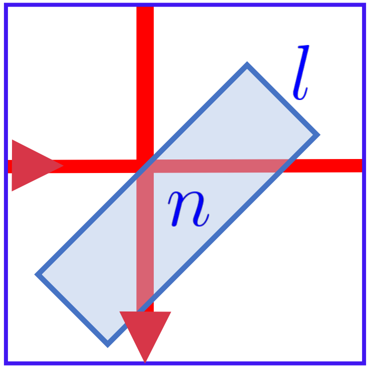
$$\delta(L_x - L_y) \approx \left(\frac{1}{\Lambda_\gamma}+\frac{1}{\Lambda_e}\right)(n\,l)\left(\frac{\hbar\sqrt{2\,\rho_{\text{local}}}}{m_\phi\, c}\right)\cos\left(\omega_{\text{obs}} t\right)$$

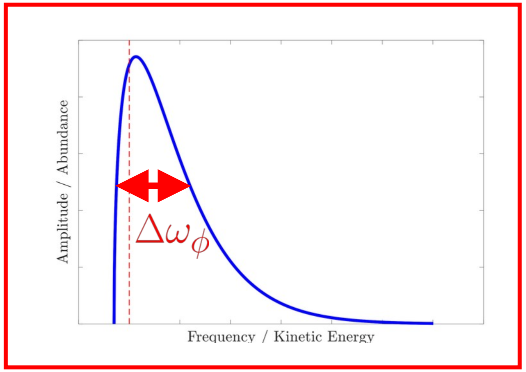
DM coupling parameter

Beamsplitter properties

Spectral linewidth

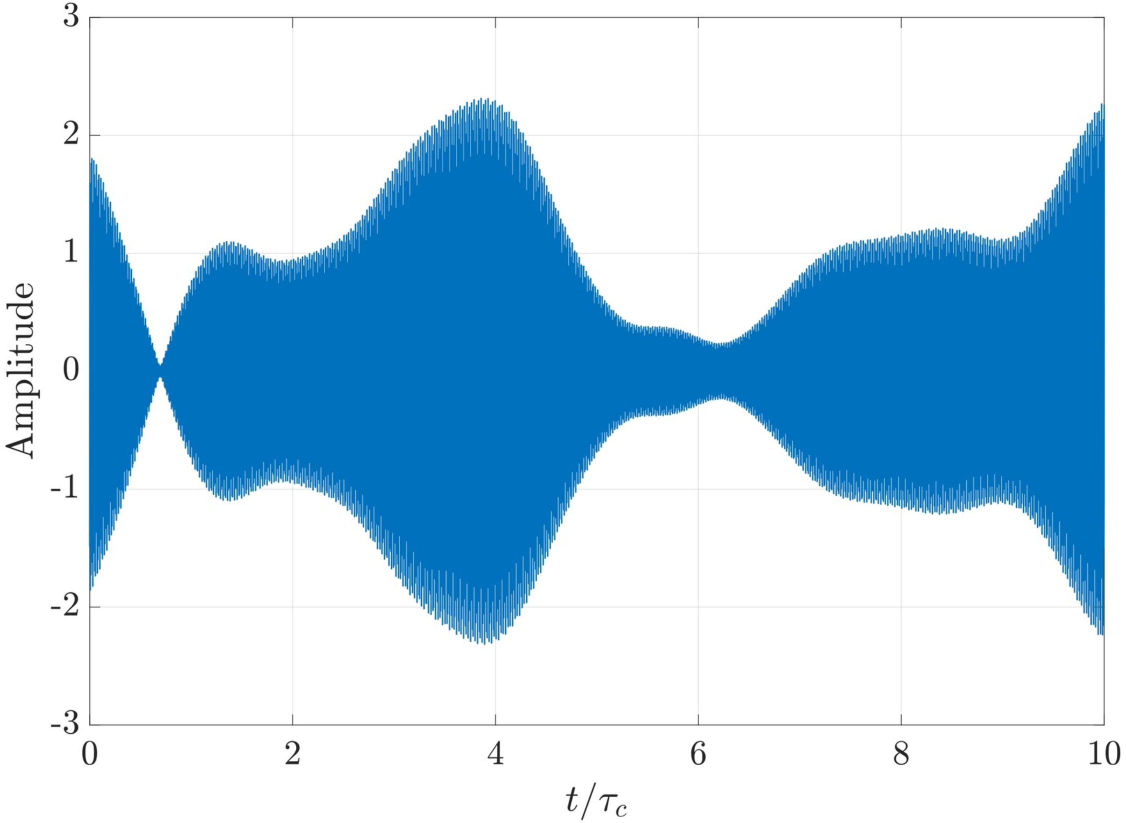
$\Delta\omega_\phi \approx 10^{-6}\omega_\phi$





Dark matter signal is pseudo-coherent

Quasi-monochromatic signals Problems with spectral analysis



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

Upper limits on scalar field dark matter with GEO600

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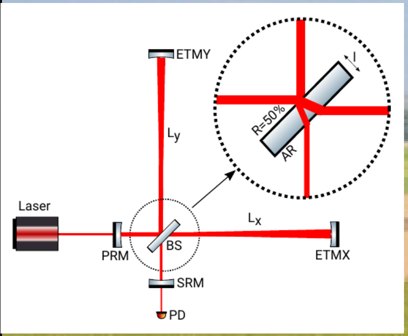
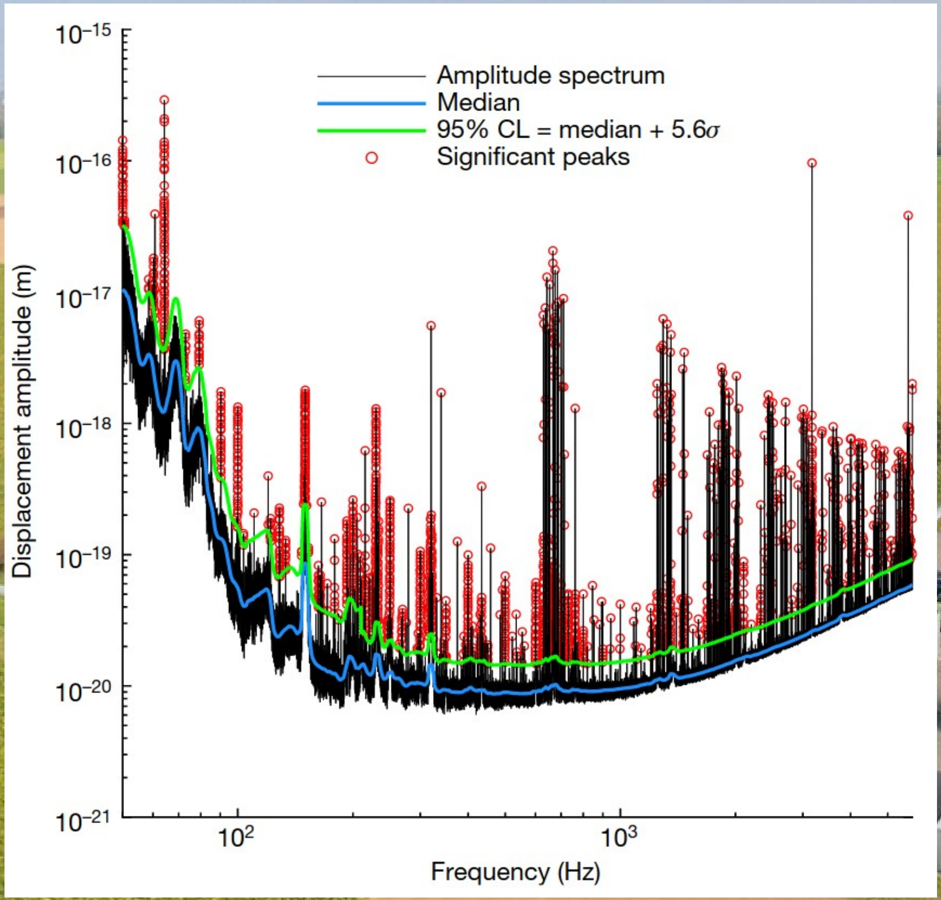
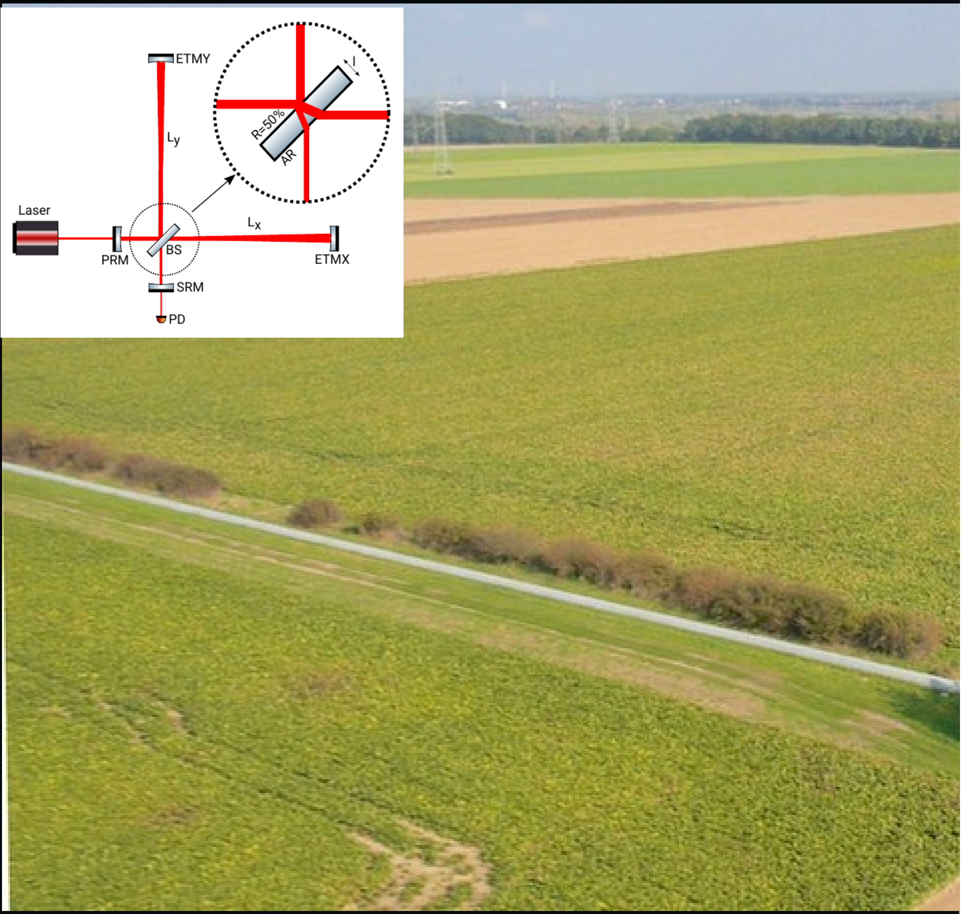
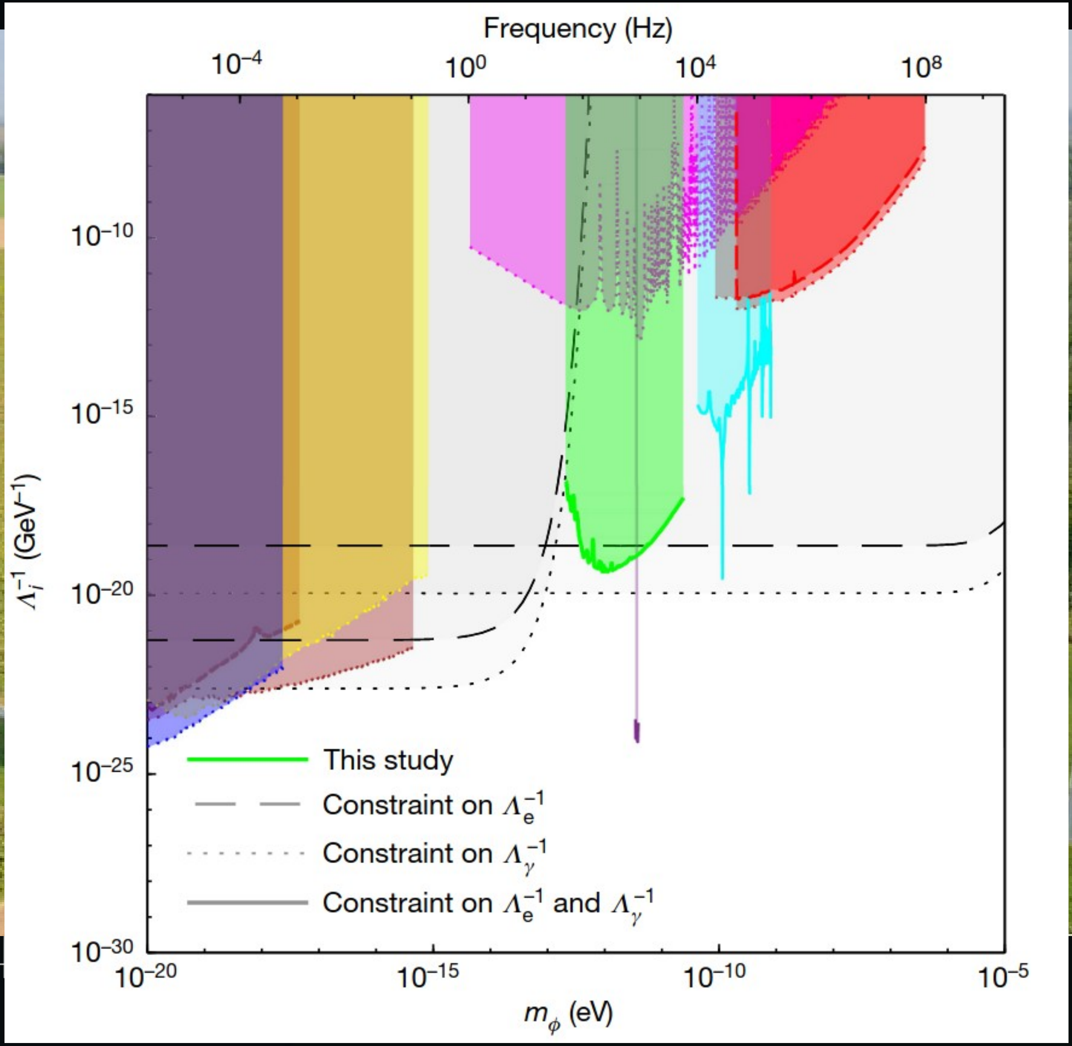




Nature 600, 424-428 (2021)

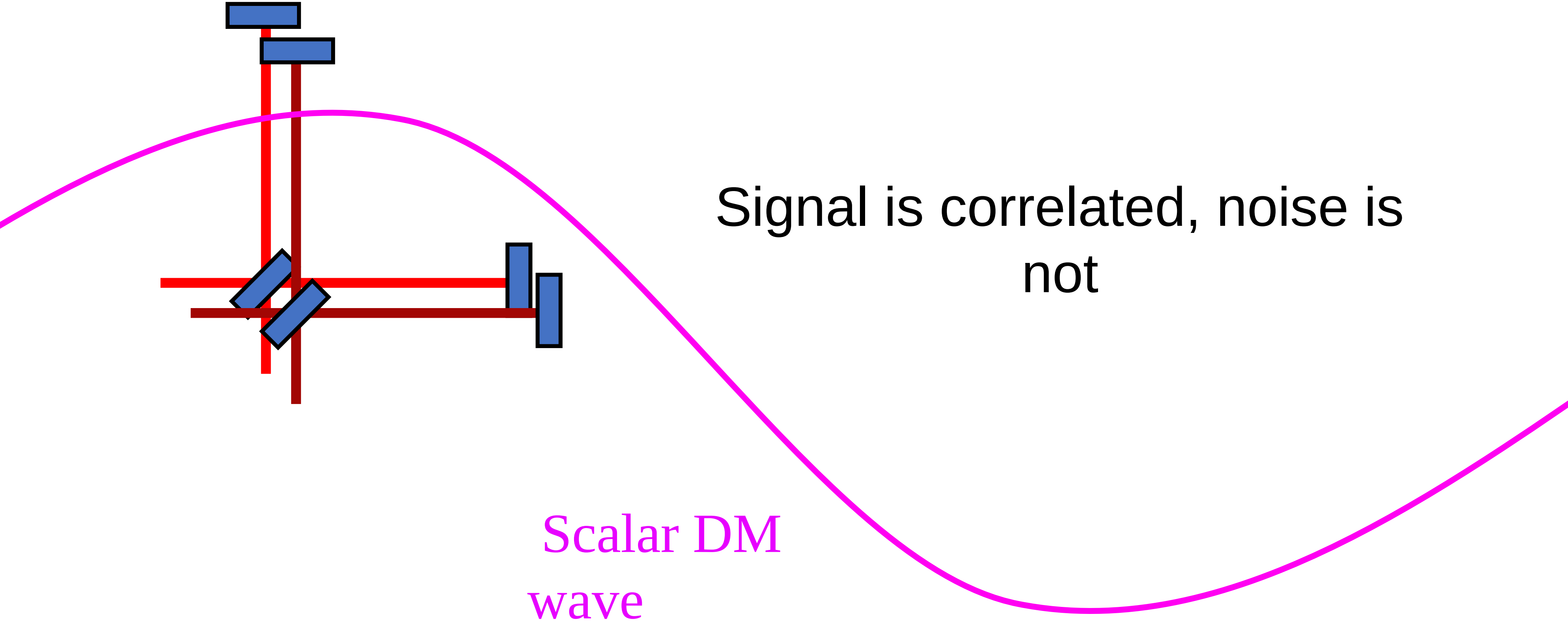
Upper limits on scalar field dark matter with GEO600





Nature 600, 424-428 (2021)

DM search w/ co-located interferometers



Signal is correlated, noise is not

Constraints on Scalar field DM from co-located Michelson Interferometers

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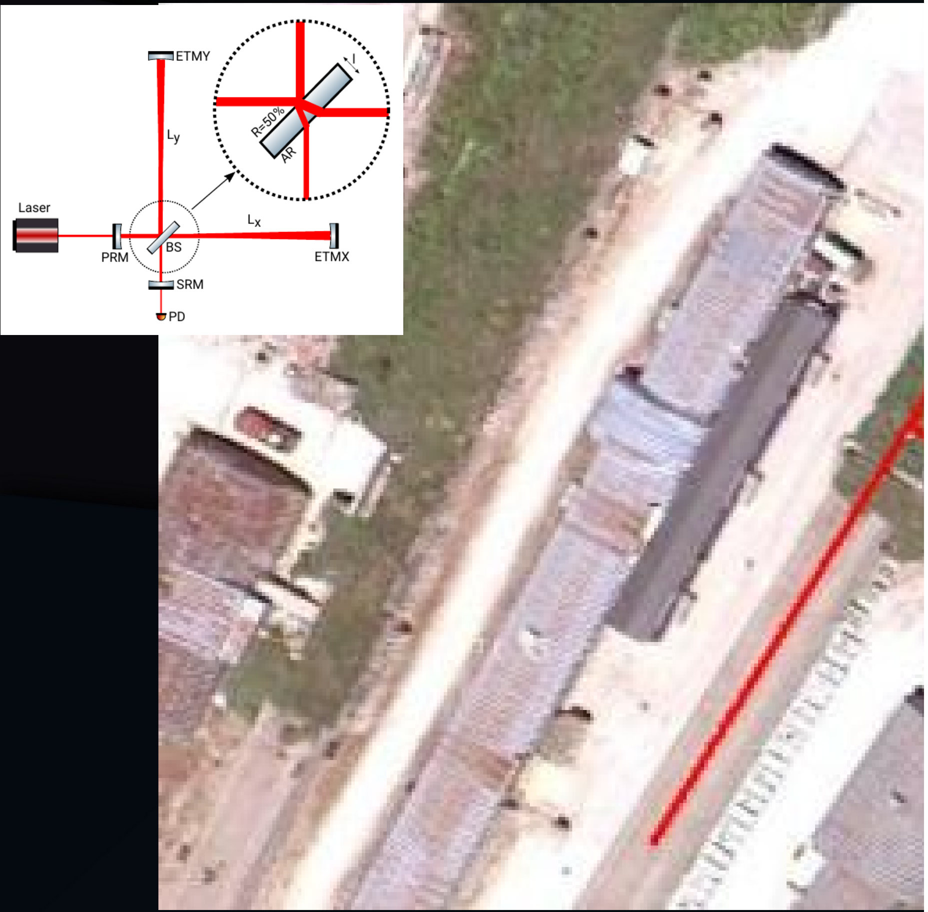
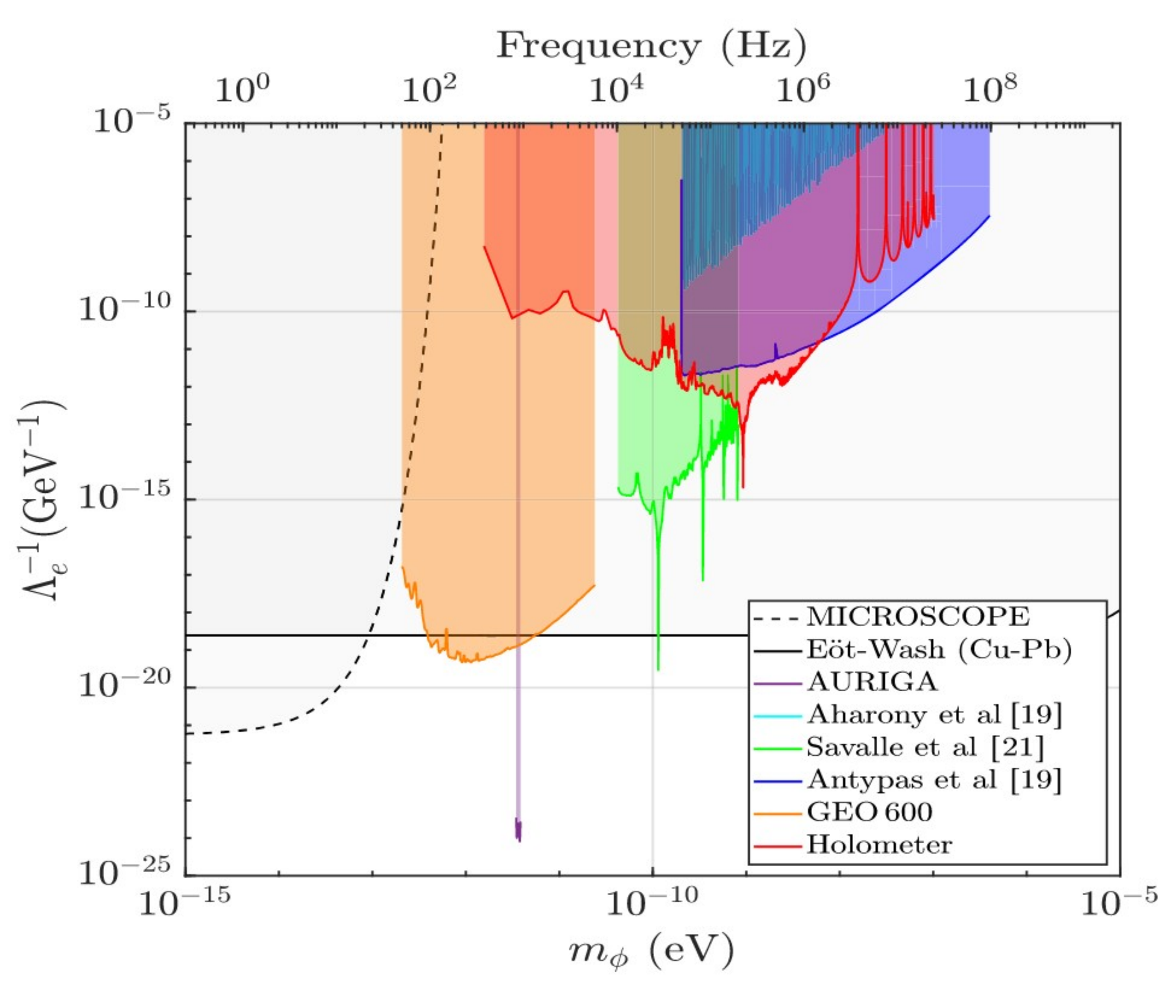


Phys. Rev. Lett. 128, 121101 (2022)



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 sinosoidal force on matter carrying dark charge (baryon or neutron number)

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Acceleration of object

Dark ‘charge’

Random phase factor

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

Object position

Wave vector

Coupling constant

Mass of object

Compton freq, set by mass

Charge normalization

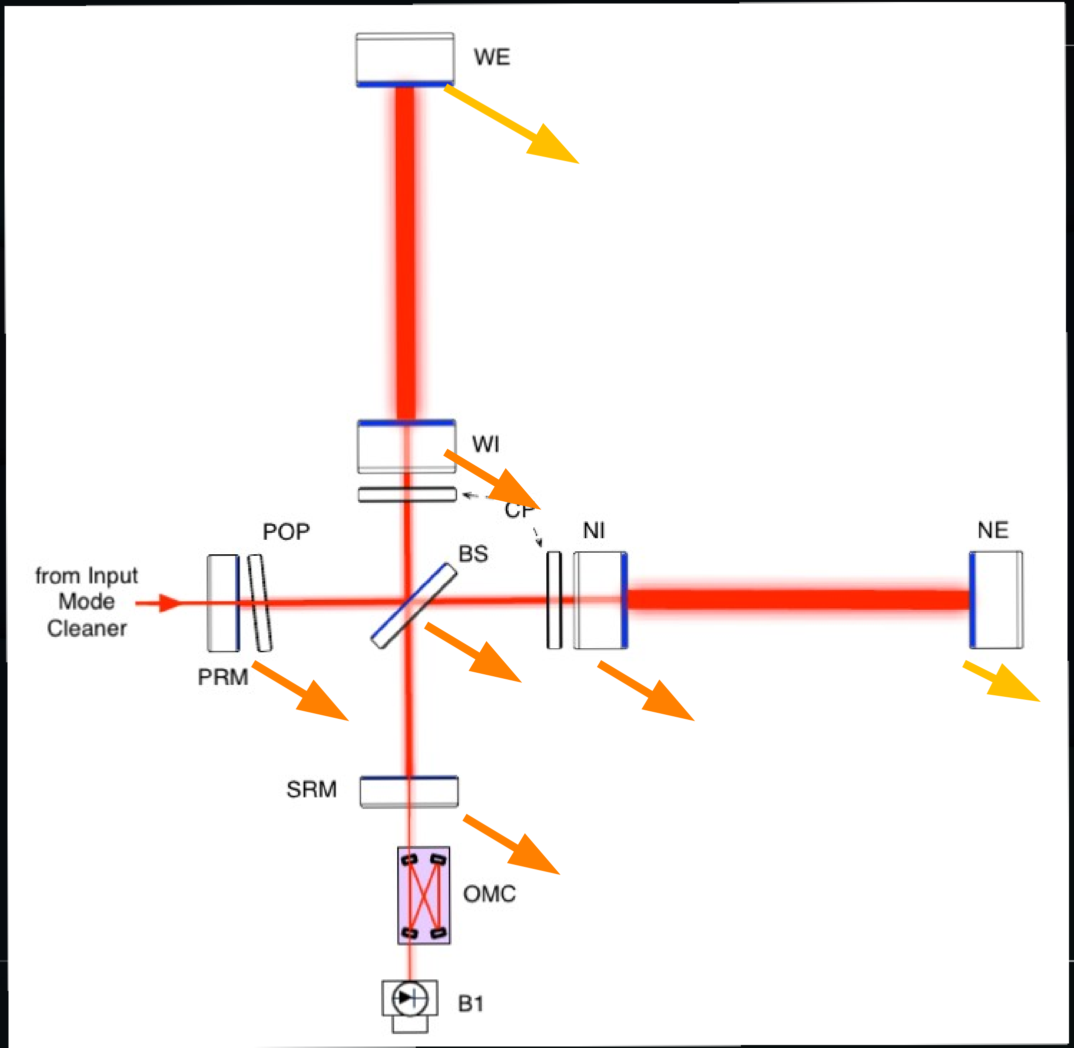
Polarization

Dark Photon coupling to Interferometers

Acceleration common to all mirrors,
Except for small phase shifts from
Finite de Broglie wavelength
(~3e9m at 100Hz)

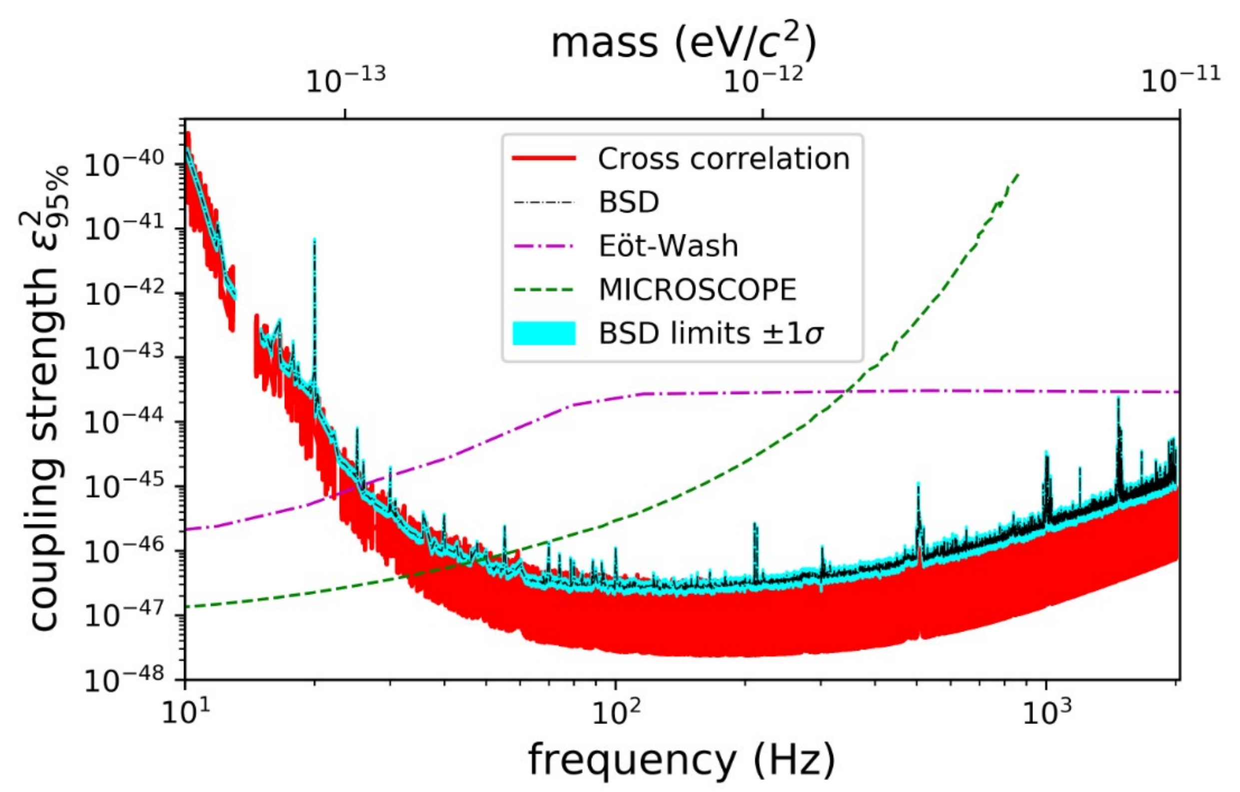
→singal strength depends
on arm-length

Signal depends on direction of wave
Which can be averaged over



Dark Photon search with LIGO and Virgo

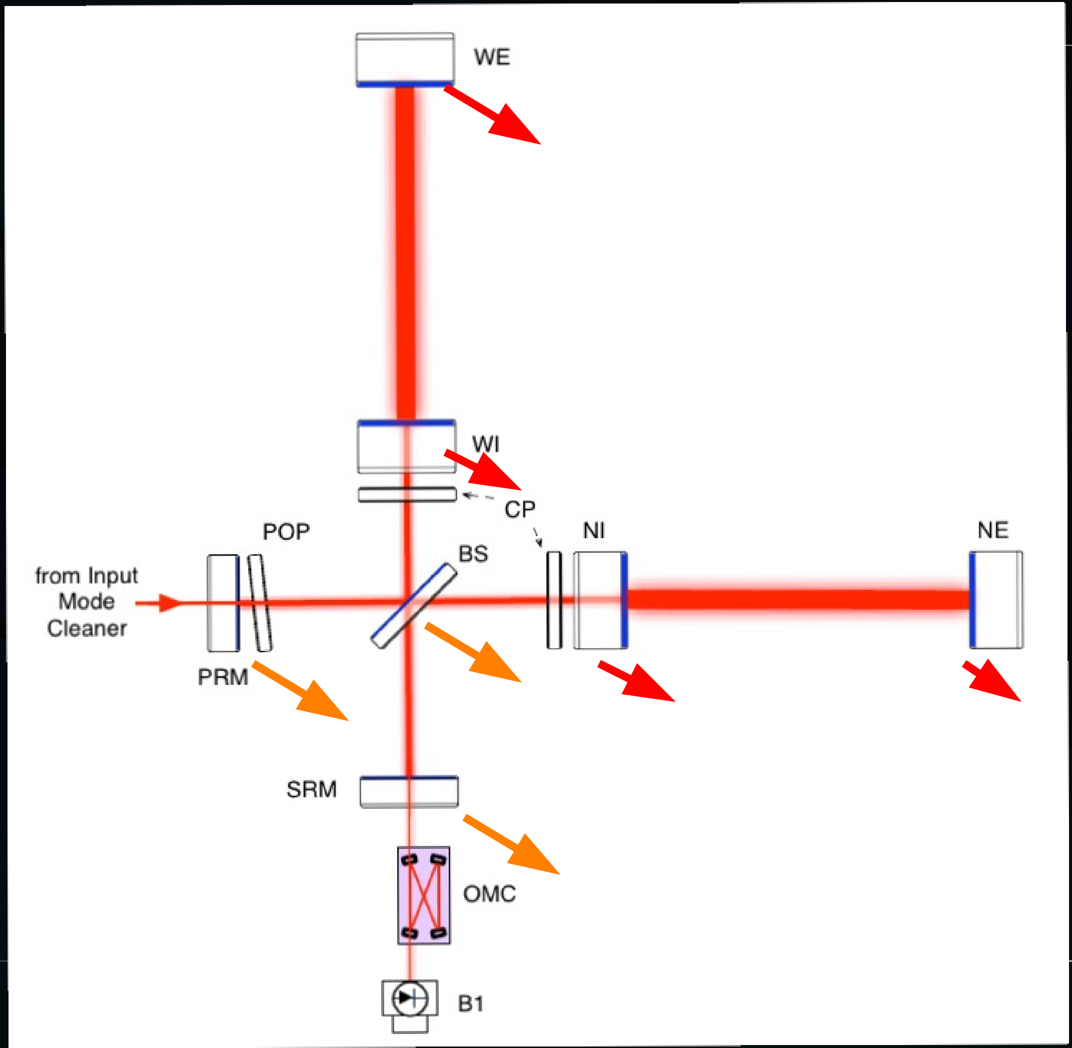
- First search on LIGO O1 data (2019)
- Added effect from light travel time,
  and increased sensitivity in O3, and using LIGO and Virgo data (2022):



Abbott et al. 2022, PRD 105, 063030

Dark Photon coupling to Interferometers

Can get larger signal using different Materials.
→ KAGRA detector: arm test masses Made of sapphire



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 and Birmingham

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

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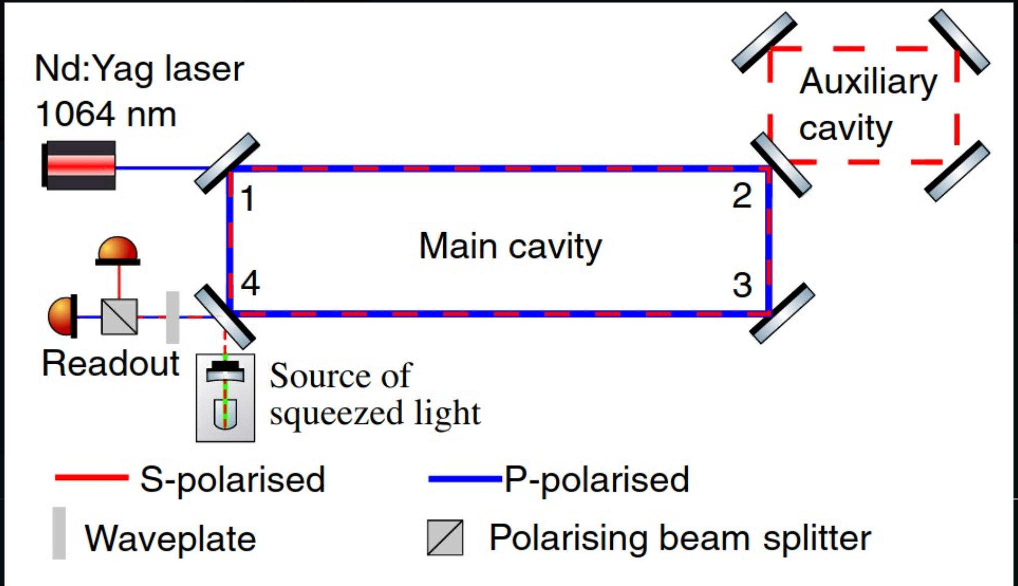
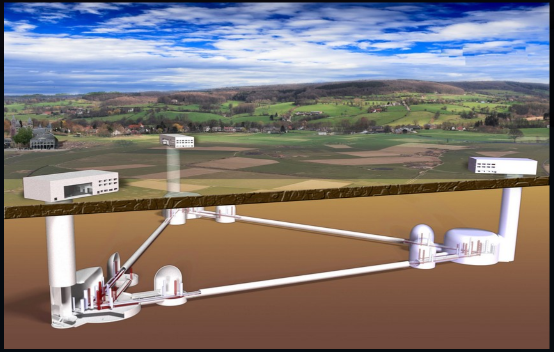
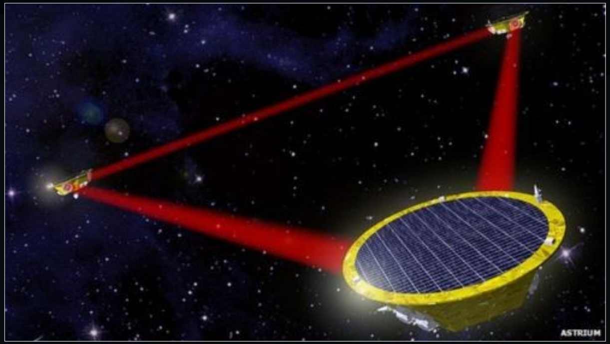
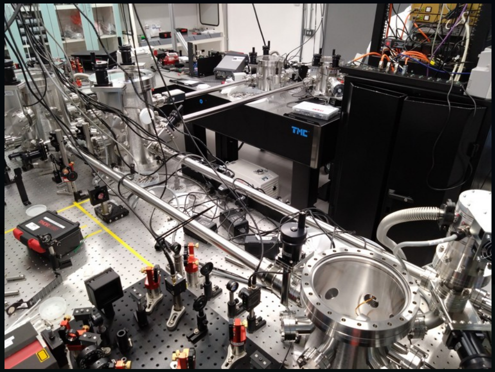


Future Work and Detectors

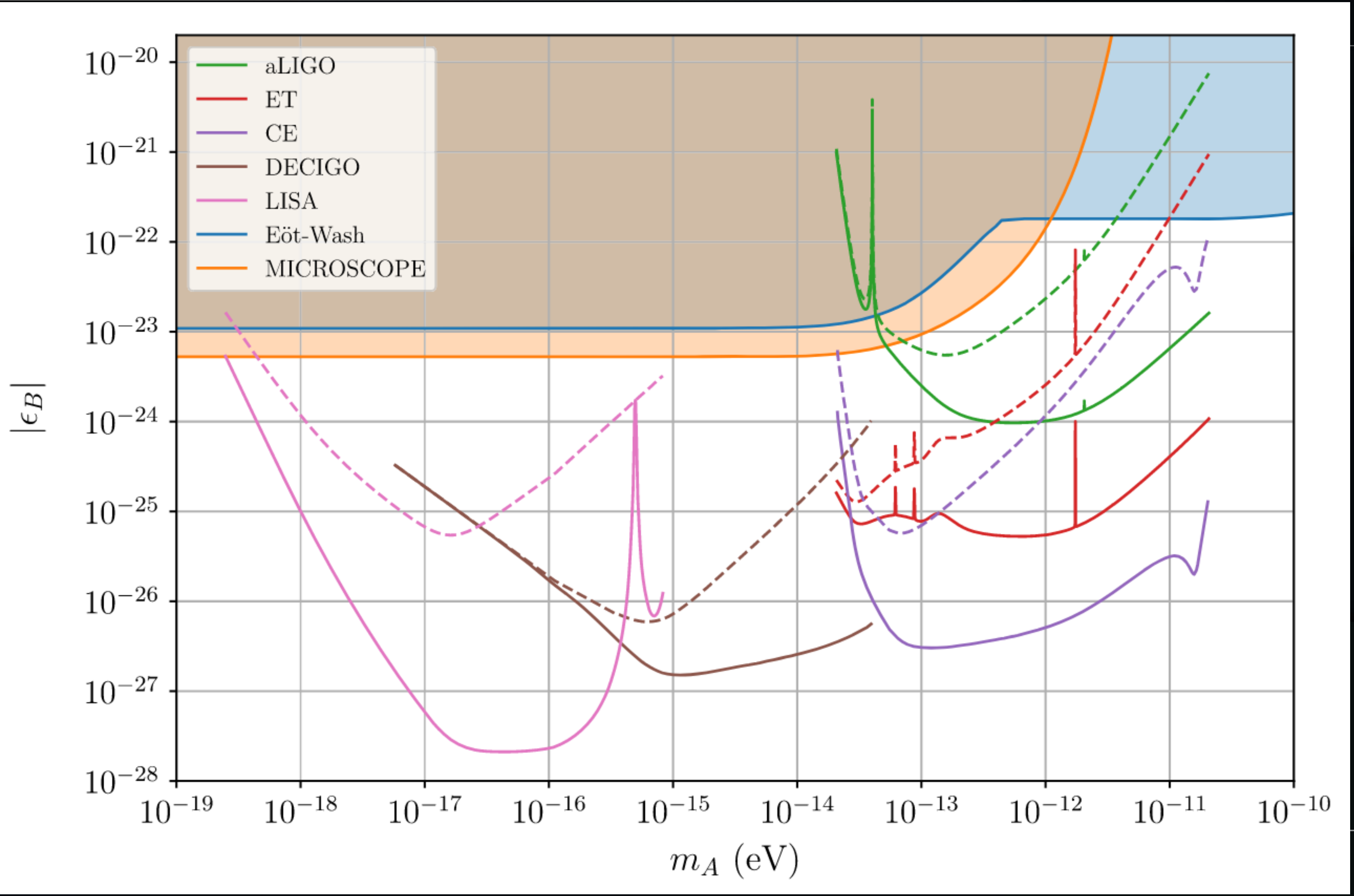
- O4 LIGO-Virgo-KAGRA collaboration paper (dark photons and scalar fields)
- KAGRA work on effects from different materials
- Future GW detectors / interferometers
  - LIGO-Virgo-KAGRA upgrades
  - Einstein Telescope / Cosmic Explorer
  - LISA and other space interferometers
  - Table-tops







Projected sensitivity for dark photon DM

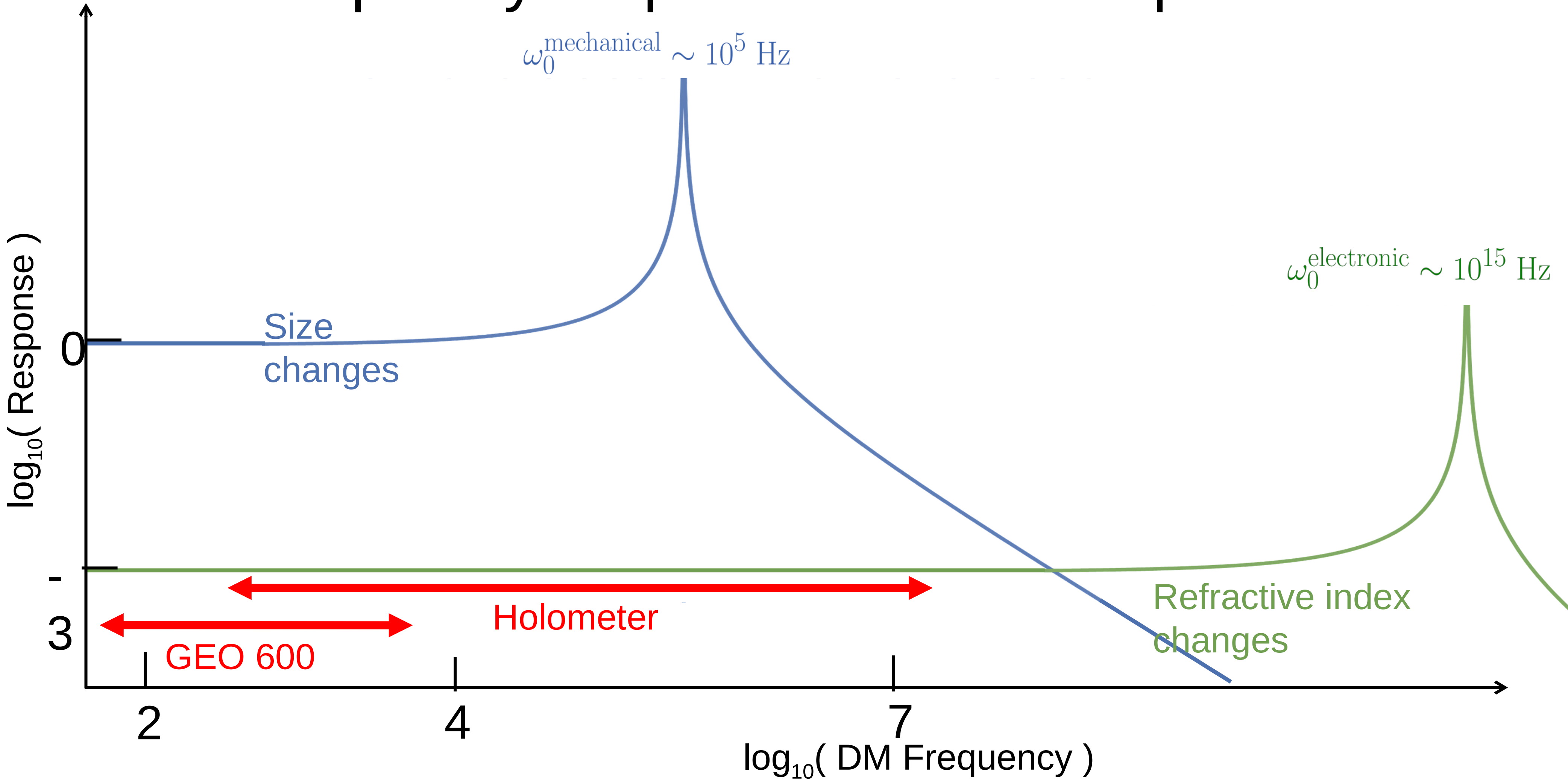


Morisaki et al.
PRD 103, 051702
(2021)

Summary

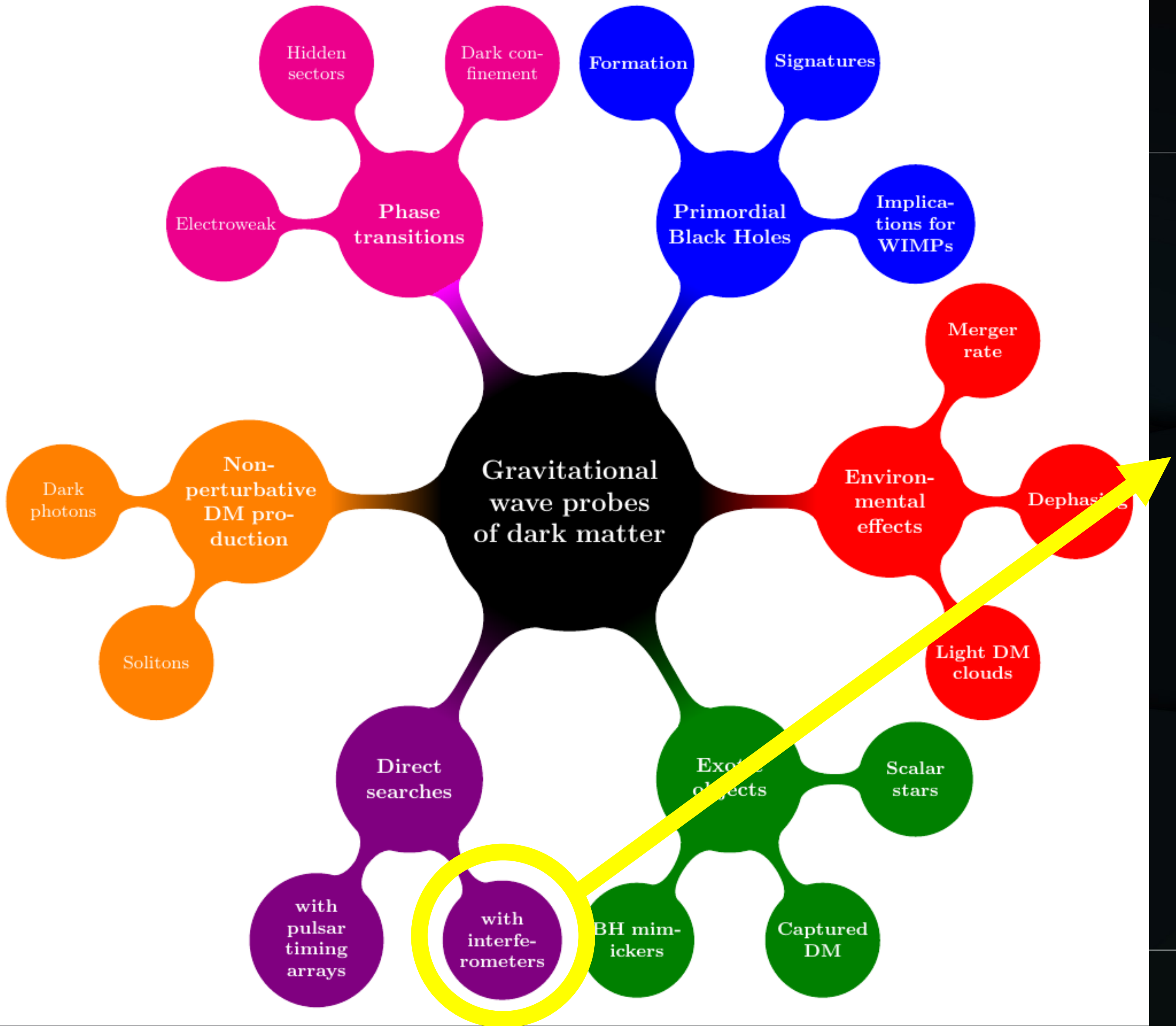
- Direct search for scalar field and dark photon DM with GW detectors (LIGO, Virgo, GEO) + Holometer
- Nothing found, but new upper limits set that beat existing experimental limits by up to several orders of magnitude
- Laser interferometers are a very sensitive tool. Sensitivity and size will increase in the future and other coupling mechanisms may be explored

Frequency response of a beamsplitter



Dark Matter and gravitational waves

- Mind map from:
- Bertone et al., SciPost Physics Core 3, 007 (2020)
- (arXiv:1907.10610)



Dark Matter and gravitational waves

- Scalar fields
- Dark photons
- Domain walls
- Clumpy DM
- ...