Laser Interferometric Searches for Ultralight Dark Matter
激光干渉測量法捜索超軽暗物質

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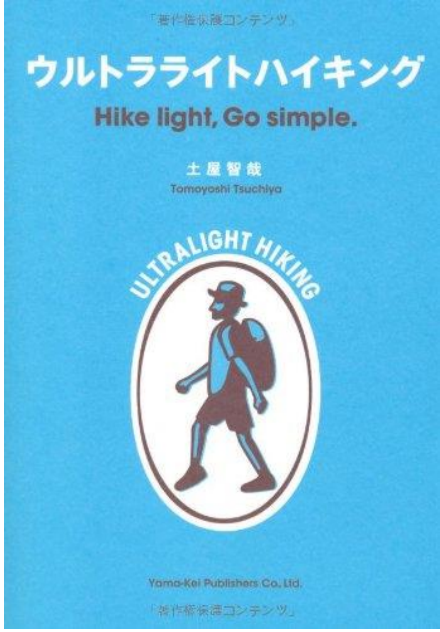
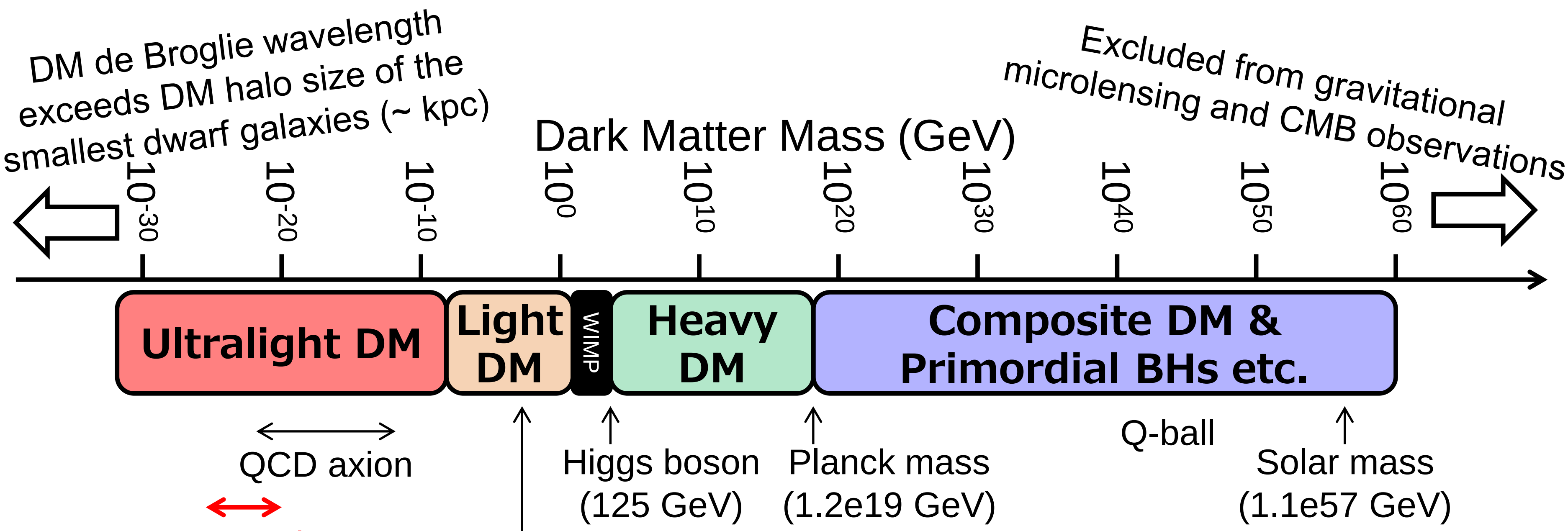


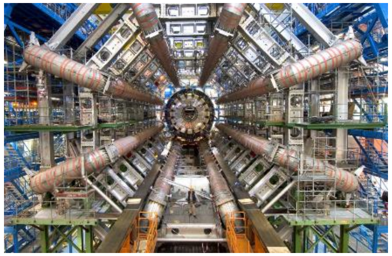
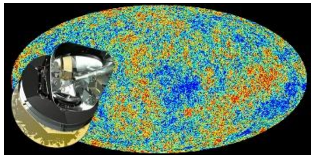
- Background
  - Dark matter models
  - Core-cusp problem
- Review of recent proposals
  - Variation of fine-structure constant and particle masses
    Scalar dark matter (dilaton etc.)
  - $U(1)_B$ or $U(1)_{B-L}$ gauge bosons
    Vector dark matter (dark photon etc.)
- Prospected sensitivity of KAGRA
  - Sensitivity of auxiliary length signals
  - Sensitivity for different DM models
- Summary

Dark Matter Models

- ~90 orders of magnitude
- Ultralight DMs behave as classical wave fields

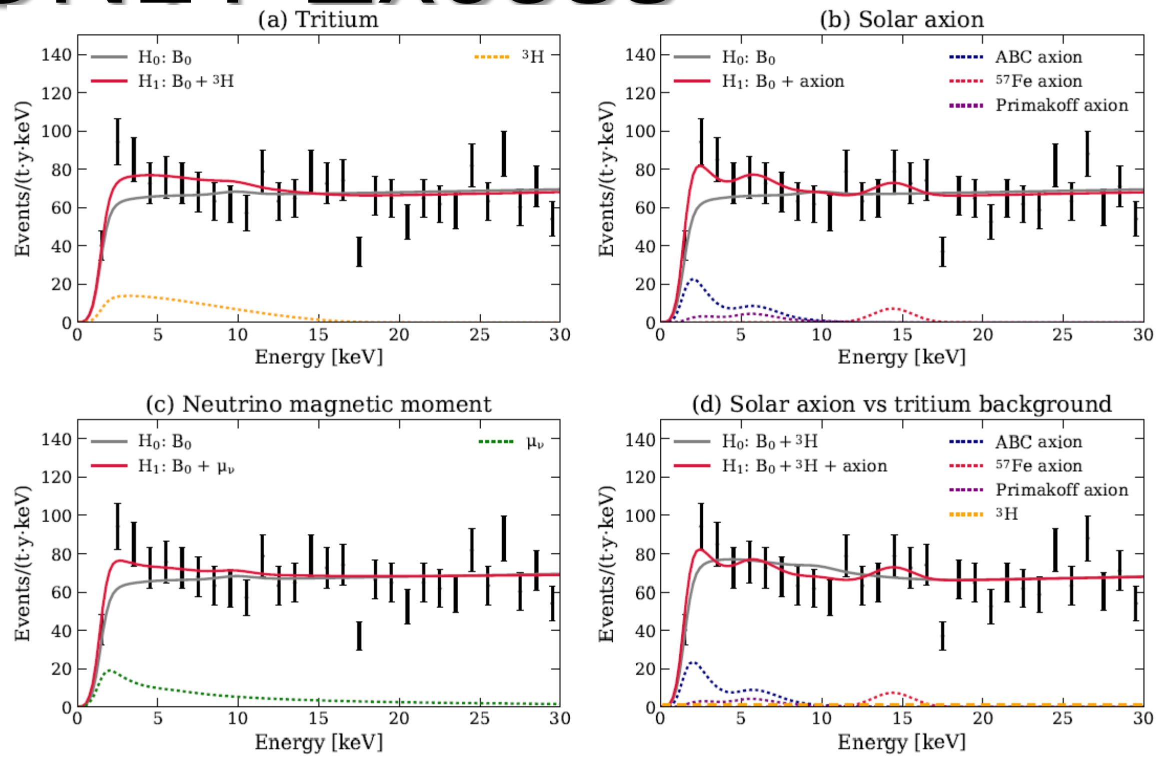





XENON1T Excess

- Solar axions
  - dark matter axion cannot be observed by XENON1T
  - XENON1T is sensitive to m_a< 100 eV, but cannot determine mass unless we assume QCD axion
  - in strong tension with stellar cooling constraints (axion-electron coupling g_{ae})
  - if QCD axion, m_a is around 0.1-60 eV



arXiv:2006.09721

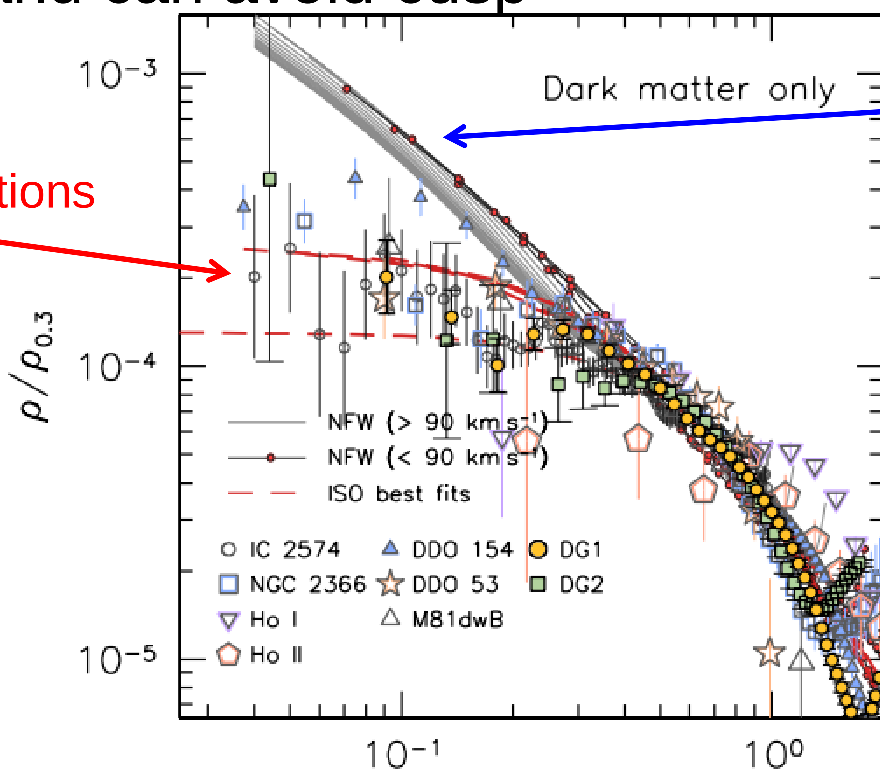
- Bosonic dark matter
  - XENON1T didn't find signal at m_a = 1-210 keV region
  - Placed world leading limits on ALP-electron coupling and vector dark matter kinetic mixing

Core-Cusp Problem

- Dark matter density profiles between observations and cosmological N-body simulations to not match
- Ultralight dark matter at ~10^{-22} eV has de Broglie wavelength of about the size of galaxy core (dwarf galaxies), and can avoid cusp

Core:
Inferred profile from rotation curve observations

There are also more recent observations which seems like cusp, or something between core and cusp (diversity problem).



$R/R_{0.3}$

Cusp:
From simulations (including DM only)

There are also arguments that simulations including baryons can create core (baryon feedback).

Ultralight DM is not the only solution.
Self-interacting DM is another candidate.

S-H Oh+, [AJ **142**, 24 (2011)]

Review

Recent Proposals for ULDM Search

- **$U(1)_B$ or $U(1)_{B-L}$ gauge bosons**
  - P. W. Graham+, PRD **93**, 075029 (2016)
  - ③ ➡ - A. Pierce+, PRL **121**, 061102 (2018)
  - ④ ➡ - D. Carney+, arXiv:1908.04797

  vector

- **Variation of fine-structure constant and particle masses**
  - Y. V. Stadnik & V. V. Flambaum, PRL **114**, 161301 (2015)
  - Y. V. Stadnik & V. V. Flambaum, PRA **93**, 063630 (2016)
  - ① ➡ - A. A. Geraci+, PRL **123**, 031304 (2019)
  - ② ➡ - H. Grote & Y. V. Stadnik, PRR **1**, 033187 (2019)
  - [- S. Morisaki & T. Suyama, PRD **100**, 123512 (2019)]

  scalar

- **Axion-like particles**
  - W. DeRocco & A. Hook, PRD **98**, 035021 (2018)
  - I. Obata, T. Fujita, YM, PRL **121**, 161301 (2018)
  - H. Liu+, PRD **100**, 023548 (2019)
  - K. Nagano, T. Fujita, YM, I. Obata, PRL **123**, 111301 (2019)
  - D. Martynov & H. Miao, PRD **101**, 095034 (2020)

  pseudoscalar

Not exhaustive.
The ones which require magnetic fields are not listed.

Geraci+ (2019)

- Searching for Ultralight Dark Matter with Optical Cavities

PHYSICAL REVIEW LETTERS **123,** 031304 (2019)

Searching for Ultralight Dark Matter with Optical Cavities

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(Received 1 August 2018; revised manuscript received 16 February 2019; published 17 July 2019)

We discuss the use of optical cavities as tools to search for dark matter (DM) composed of virialized ultralight fields (VULFs). Such fields could lead to oscillating fundamental constants, resulting in oscillations of the length of rigid bodies. We propose searching for these effects via differential strain measurement of rigid and suspended-mirror cavities. We estimate that more than 2 orders of magnitude of unexplored phase space for VULF DM couplings can be probed at VULF Compton frequencies in the audible range of 0.1–10 kHz.

DOI: 10.1103/PhysRevLett.123.031304

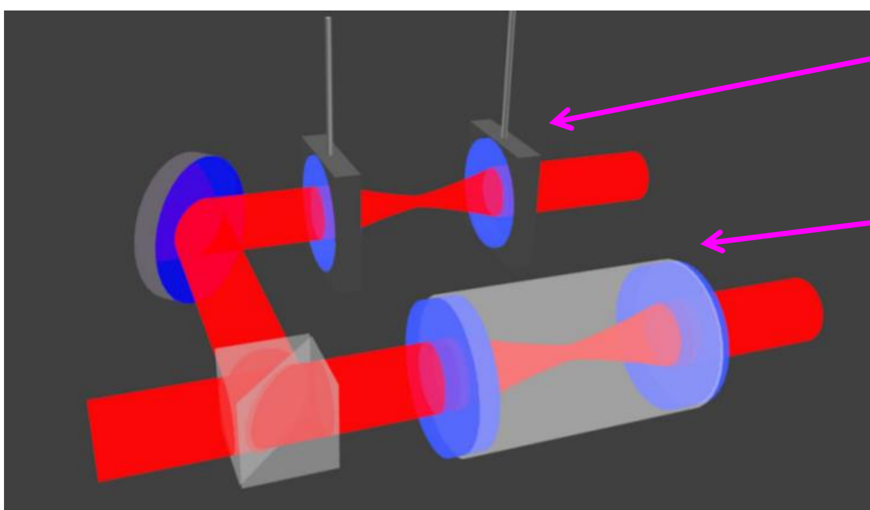
PRL **123**, 031304 (2019)

Geraci+ (2019): Principles

- Dilatonlike scalar DM drives oscillations of the electron mass m_e and fine structure constant α
- Which drives oscillations in the Bohr radius $a_0 = \hbar/(\alpha m_\mathrm{e} c)$
- Which changes the size of atoms and chemical bonds
- Time-varying strain in solid materials

$$h = -\frac{\delta\alpha}{\alpha_0} - \frac{\delta m_\mathrm{e}}{m_{\mathrm{e},0}}$$

- Compare the length between suspended cavity and rigid cavity



PRL **123**, 031304 (2019)

Geraci+ (2019): Calculations

- Scalar field (if coherence time > measurement time)

$$\phi(t,\mathbf{r}) = \frac{\hbar}{m_\phi c}\sqrt{2\rho_{\rm DM}}\cos\left(2\pi f_\phi t - \mathbf{k}_\phi \mathbf{r} + \cdots\right)$$

Local DM density — $\rho_{\rm DM} = m_\phi^2 \phi_0^2/2$ [same idea with axion]

$f_\phi = m_\phi c^2/(2\pi\hbar)$

$k_\phi = m_\phi v/\hbar$ — Local DM velocity

- Oscillations in the electron mass and fine structure constant

$$\frac{\delta m_{\rm e}(t,\mathbf{r})}{m_{\rm e,0}} = d_{m_{\rm e}}\sqrt{4\pi\hbar c}E_{\rm pl}^{-1}\phi(t,\mathbf{r})$$

$$\frac{\delta \alpha(t,\mathbf{r})}{\alpha_0} = d_{\rm e}\sqrt{4\pi\hbar c}E_{\rm pl}^{-1}\phi(t,\mathbf{r})$$

$d_{m_{\rm e}}$, $d_{\rm e}$: dimension less dilaton coupling constant

Planck energy: $E_{\rm pl} \equiv \sqrt{\hbar c^5/G}$

- Strain sensitivity [as usual]

$$S_{hh} = S_{xx}/L^2$$

L: Cavity length

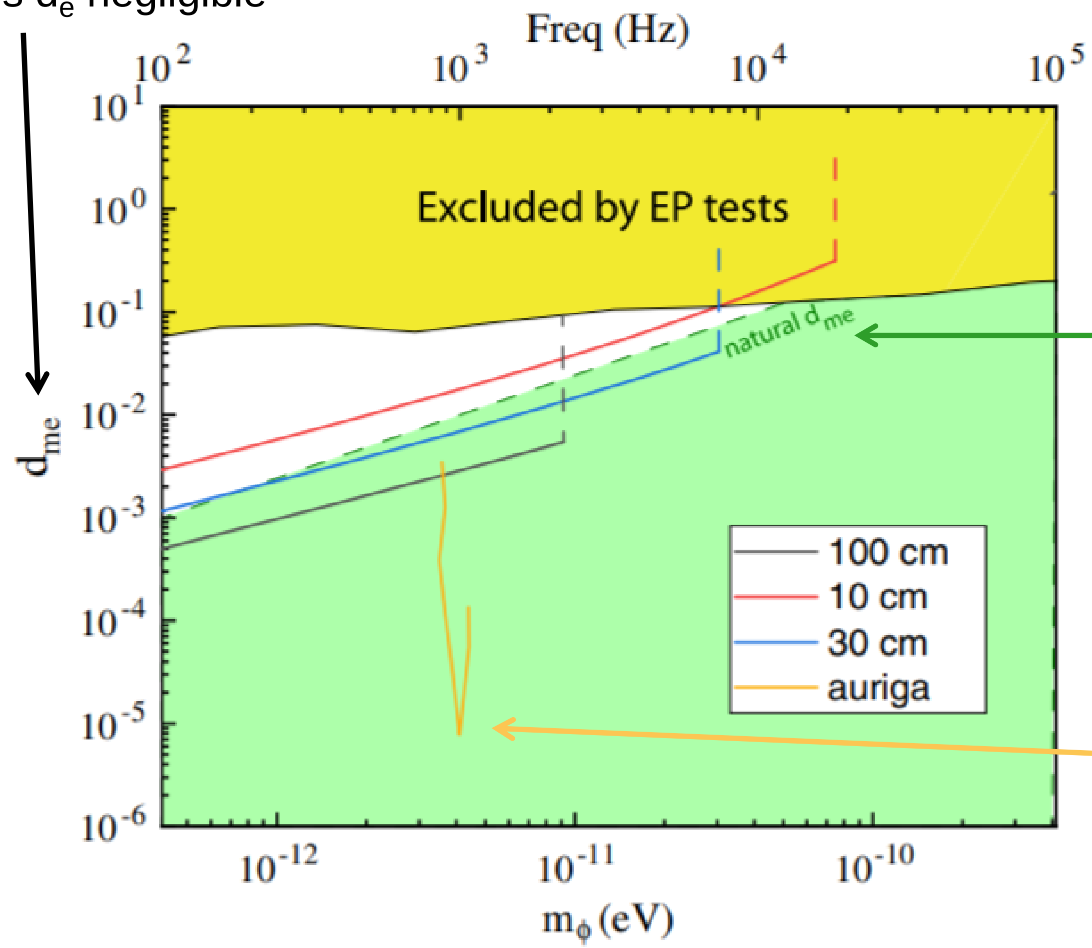
- $T^{-1/2}$ up to coherence time, $T^{-1/4}$ thereafter [as usual]

Geraci+ (2019): Sensitivity

- 1 mW input, finesse 10^4, cavity length 10, 30, 100 cm
- Room temperature fused silica spacer, 10^7 sec integration

[feasible parameters!]

Actually $|d_{me}+d_e|$ but assumed is d_e negligible



Thermal noise at the floor level can be achieved by changing the temperature to shift the resonant frequency (DM signals can be differentiated)

Theoretically well motivated region: Natural coupling for an electron Yukawa modulus with a 10 TeV cutoff (standard model is believed to be correct up to 10 TeV) [???]

Resonant bar GW detector AURIGA also sensitive but narrow band
See PRL 116, 031102 (2016)

Grote&Stadnik (2019)

- Novel signatures of dark matter in laser-interferometric gravitational-wave detectors

PHYSICAL REVIEW RESEARCH **1**, 033187 (2019)

Novel signatures of dark matter in laser-interferometric gravitational-wave detectors

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(Received 1 July 2019; published 19 December 2019)

Dark matter may induce apparent temporal variations in the physical "constants", including the electromagnetic fine-structure constant and fermion masses. In particular, a coherently oscillating classical dark-matter field may induce apparent oscillations of physical constants in time, while the passage of macroscopic dark-matter objects (such as topological defects) may induce apparent transient variations in the physical constants. In this paper, we point out several new signatures of the aforementioned types of dark matter that can arise due to the geometric asymmetry created by the beam-splitter in a two-arm laser interferometer. These new signatures include dark-matter-induced time-varying size changes of a freely suspended beam-splitter and associated time-varying shifts of the main reflecting surface of the beam-splitter that splits and recombines the laser beam, as well as time-varying refractive-index changes in the freely suspended beam-splitter and time-varying size changes of freely suspended arm mirrors. We demonstrate that existing ground-based experiments already have sufficient sensitivity using existing data to probe extensive regions of the unconstrained parameter space in models involving oscillating scalar dark-matter fields and domain walls composed of scalar fields. In the case of oscillating dark-matter fields, Michelson interferometers—in particular, the GEO 600 detector—are especially sensitive. The sensitivity of Fabry-Perot-Michelson interferometers, including LIGO, VIRGO, and KAGRA, to oscillating dark-matter fields can be significantly increased by making the thicknesses of the freely suspended Fabry-Perot arm mirrors different in the two arms. Not-too-distantly separated laser interferometers can benefit from cross-correlation measurements in searches for effects of spatially coherent dark-matter fields. In addition to broadband searches for oscillating dark-matter fields, we also discuss how small-scale Michelson interferometers, such as the Fermilab holometer, could be used to perform resonant narrowband searches for oscillating dark-matter fields with enhanced sensitivity to dark matter. Finally, we discuss the possibility of using future space-based detectors, such as LISA, to search for dark matter via time-varying size changes of and time-varying forces exerted on freely floating test masses.

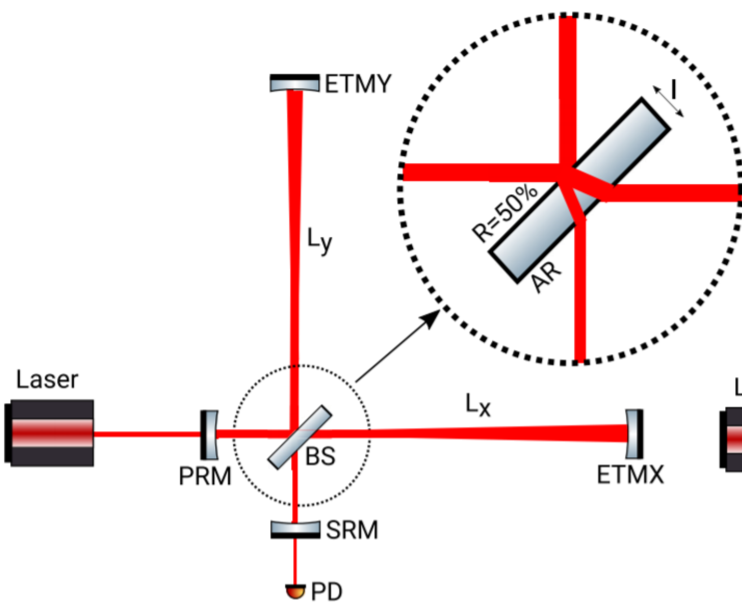
DOI: 10.1103/PhysRevResearch.1.033187

Grote&Stadnik (2019): Principles

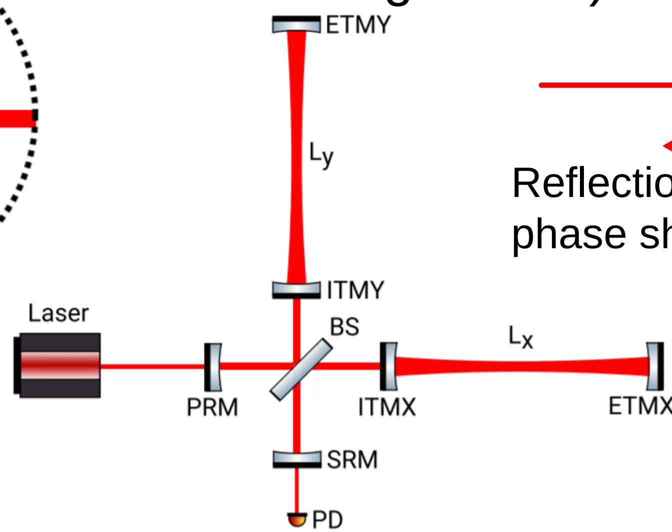
- Temporal variations in the fine structure constant and fermion mass creates
  - time-varying size changes
  - time-varying shifts of the reflecting surface
  - time-varying refractive index changes

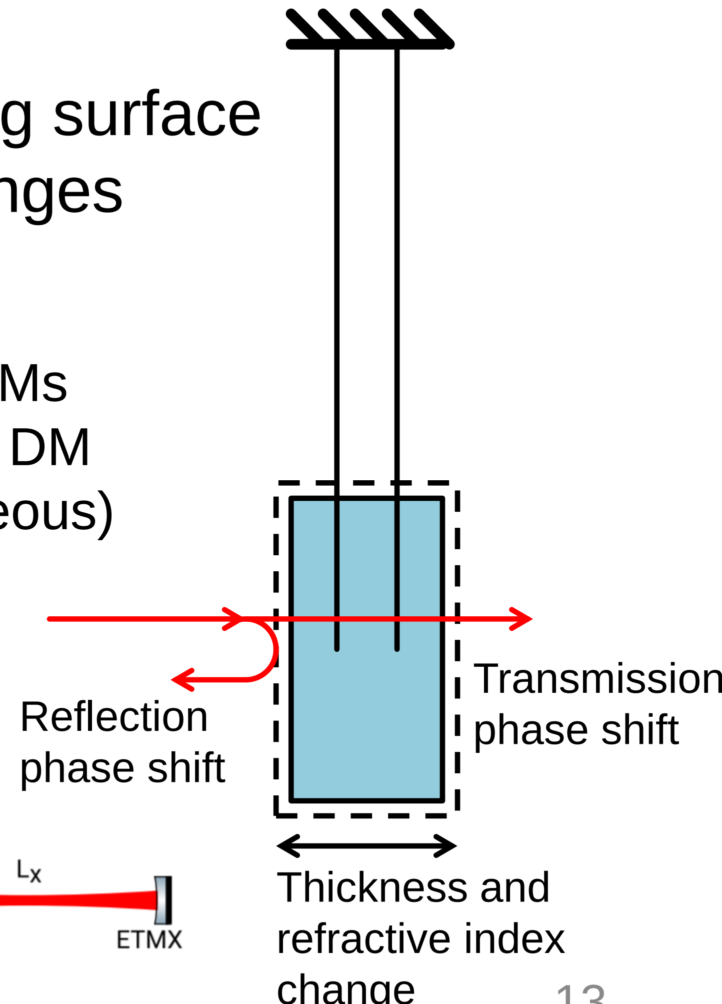
  of beam splitter and arm mirrors

GEO600: BS matters



LVK: Sensitive if ITMs are asymmetric (or DM field is inhomogeneous)





Grote&Stadnik (2019): Calculations

- Oscillations in the electron mass and fine structure constant

$$\frac{\delta m_{\mathrm{e}}}{m_{\mathrm{e}}} = \frac{1}{\Lambda_f}\phi$$

Coupling to fermion field [GeV]

$$\frac{\delta \alpha}{\alpha} = \frac{1}{\Lambda_\gamma}\phi$$

Coupling to electromagnetic field [GeV]

- Mirror thickness change

Mirror resonant frequency

Mirror Q

$$\frac{\delta l}{l} = \left(-\frac{\delta \alpha}{\alpha} - \frac{\delta m_{\mathrm{e}}}{m_{\mathrm{e}}}\right) \frac{1}{\sqrt{([1-(f/f_0)]^2 + [f/(f_0 Q_{\mathrm{mech}})]^2)}}$$

- Mirror refractive index change

[Material with large dn/dλ?]

$$\frac{\delta n}{n} = \frac{\Omega}{n}\frac{\partial n}{\partial \Omega}\left(-2\frac{\delta \alpha}{\alpha} - \frac{\delta m_{\mathrm{e}}}{m_{\mathrm{e}}}\right) \simeq 5 \times 10^{-3}\left(-2\frac{\delta \alpha}{\alpha} - \frac{\delta m_{\mathrm{e}}}{m_{\mathrm{e}}}\right)$$

Laser frequency

For fused silica at 1μm

PRR **1**, 033187 (2019)

Grote&Stadnik (2019): Calculations

- In the case of Michelson interferometer (GEO600)

$$\delta(L_\mathrm{x}-L_\mathrm{y}) = \sqrt{2}n_\mathrm{BS}l_\mathrm{BS}\left(\frac{\delta l_\mathrm{BS}}{l_\mathrm{BS}}+\frac{\delta n_\mathrm{BS}}{n_\mathrm{BS}}\right)$$

$$\simeq \sqrt{2}n_\mathrm{BS}l_\mathrm{BS}\left(-\frac{\delta\alpha}{\alpha}-\frac{\delta m_\mathrm{e}}{m_\mathrm{e}}\right)$$

BS thickness

If $f \ll f_{0,BS}$, δl/l term dominates

[I think this is incorrect; see next page]

- In the case of Fabry-Perot-Michelson interferometer (LVK)

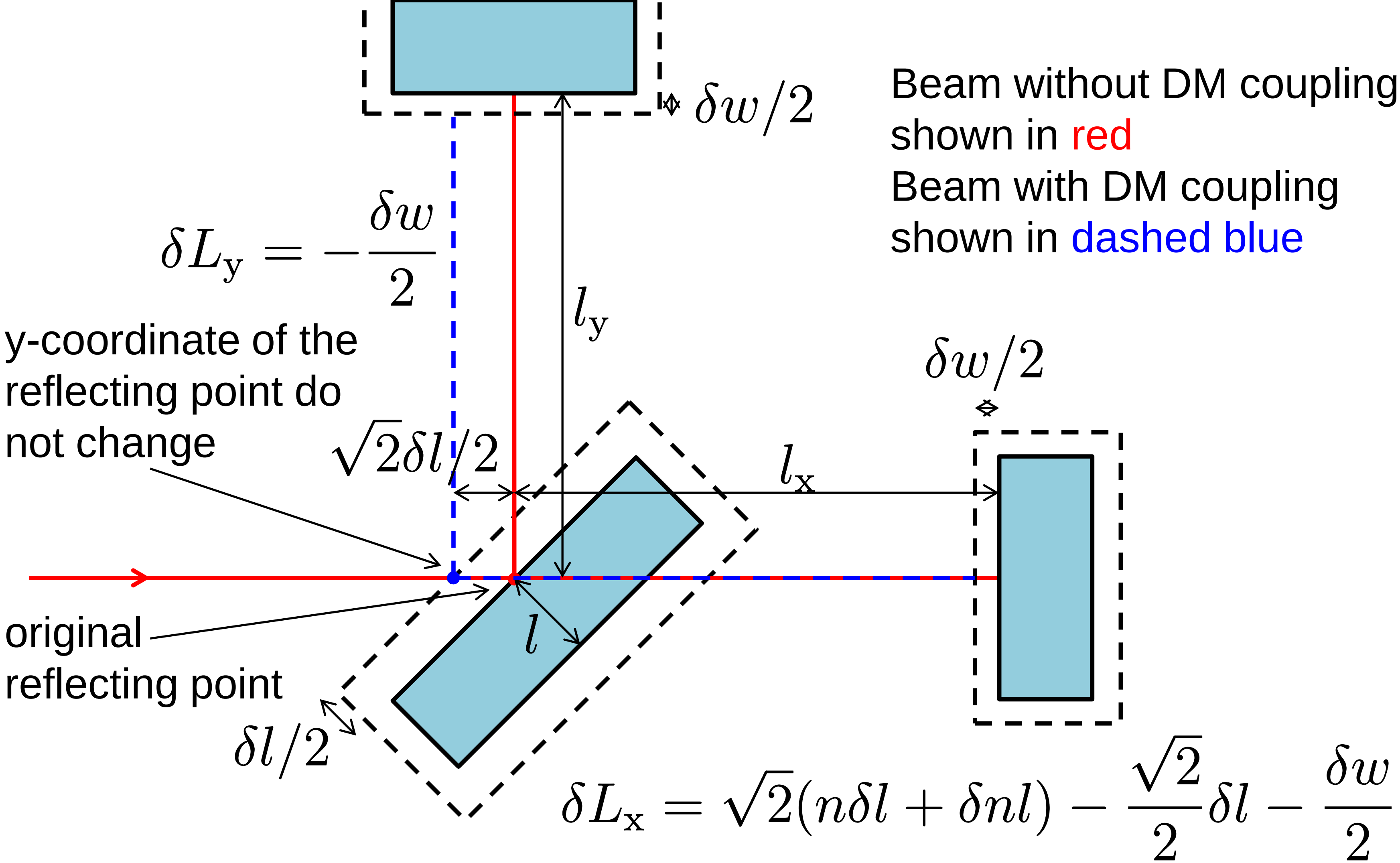
$$\delta(L_\mathrm{x}-L_\mathrm{y}) \simeq \left[\frac{\sqrt{2}n_\mathrm{BS}l_\mathrm{BS}}{N_\mathrm{eff}}-\Delta l_\mathrm{TM}\right]\left(-\frac{\delta\alpha}{\alpha}-\frac{\delta m_\mathrm{e}}{m_\mathrm{e}}\right)$$

Effective round-trip time (note that there's SRM)

TM thickness difference between arms

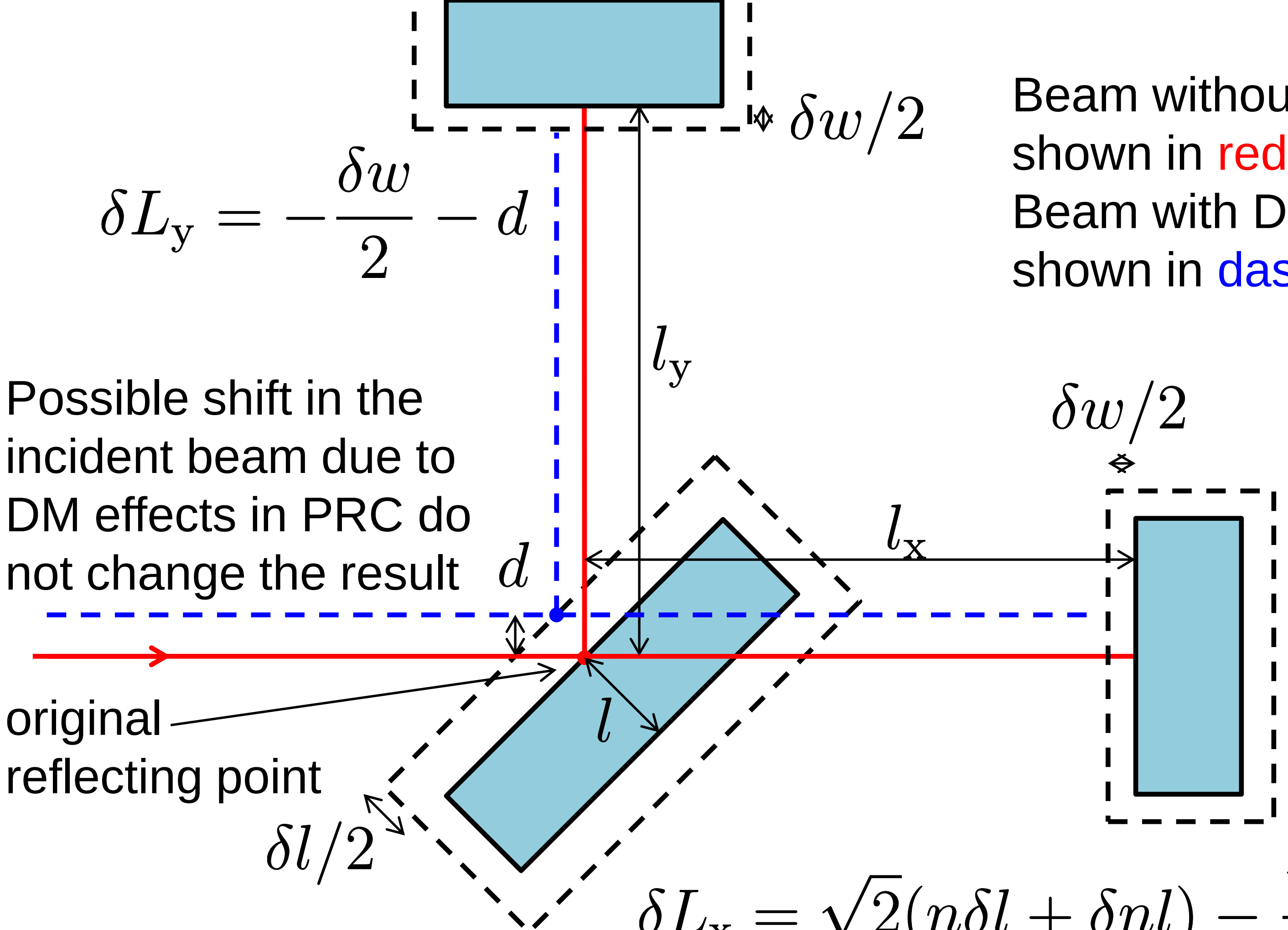
- $T^{-1/2}$ up to coherence time, $T^{-1/4}$ thereafter [as usual]

[Paper says always $T^{-1/2}$ if cross-correlation analysis, but I'm not sure if it is correct]



$$\delta(L_{\mathrm{x}} - L_{\mathrm{y}}) = \sqrt{2}(n\delta l + \delta n l) - \frac{\sqrt{2}}{2}\delta l$$

Beam without DM coupling shown in red
Beam with DM coupling shown in dashed blue



$$\delta L_{\mathrm{y}} = -\frac{\delta w}{2} - d$$

$$\delta L_{\mathrm{x}} = \sqrt{2}(n\delta l + \delta n l) - \frac{\sqrt{2}}{2}\delta l - \frac{\delta w}{2} - d$$

$$\delta(L_{\mathrm{x}} - L_{\mathrm{y}}) = \sqrt{2}(n\delta l + \delta n l) - \frac{\sqrt{2}}{2}\delta l$$

Grote&Stadnik (2019): Sensitivity

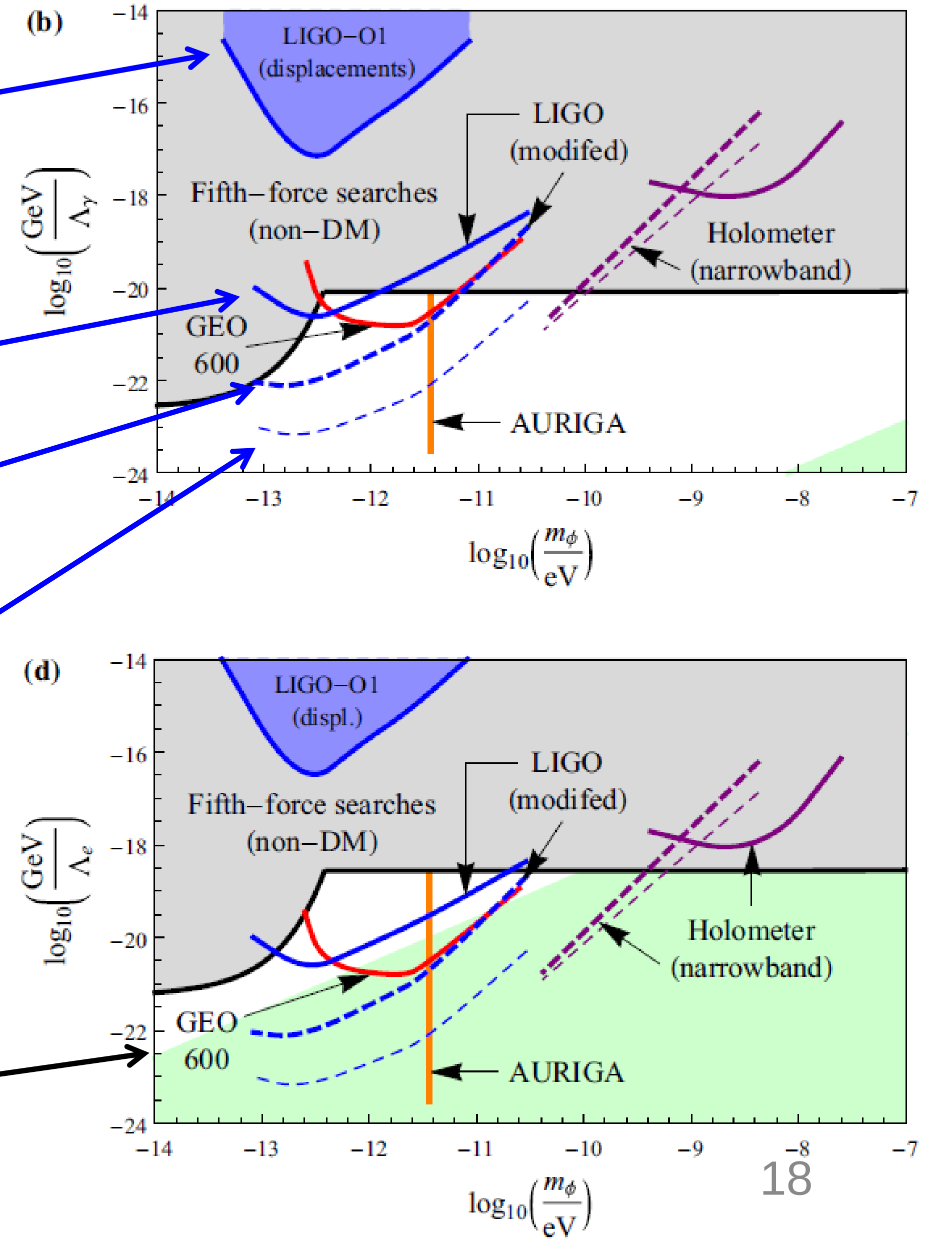
- 10^8 sec integration

H-K Guo+, Communications Physics 2, 155 (2019)
Taken from dark photon DM search [how to convert to scalar DM search???]

Advanced LIGO design
(Δl_{TM} = 80 um; BS effect dominates)

Advanced LIGO modified
($\Delta l_{TM} / l_{TM}$ = 10%; TM effect dominates)

Cross-correlation with modified aLIGOs



The region in pale green represents the region of parameter space that is technically natural for a new-physics cutoff scale of Λ ~ 10 TeV

Pierce+ (2018)

- Searching for Dark Photon Dark Matter with Gravitational-Wave Detectors

PHYSICAL REVIEW LETTERS **121**, 061102 (2018)

Searching for Dark Photon Dark Matter with Gravitational-Wave Detectors

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(Received 7 February 2018; revised manuscript received 2 May 2018; published 8 August 2018)

If dark matter stems from the background of a very light gauge boson, this gauge boson could exert forces on test masses in gravitational wave detectors, resulting in displacements with a characteristic frequency set by the gauge boson mass. We outline a novel search strategy for such dark matter, assuming the dark photon is the gauge boson of $U(1)_B$ or $U(1)_{B-L}$. We show that both ground-based and future space-based gravitational wave detectors have the capability to make a 5σ discovery in unexplored parameter regimes.

DOI: 10.1103/PhysRevLett.121.061102

PRL **121**, 061102 (2018)

Pierce+ (2018): Principles

- Dark photon: gauge boson of U(1) extension of the standard model
- Could couple to baryon number: B
- Could couple to baryon number minus lepton number: B-L
- Dark photon field:

Dark photon mass

$$\mathbf{A}(t,\mathbf{r}) = \mathbf{A_0}\sin\left(m_\mathrm{A}t - \mathbf{k}_\mathrm{A}\mathbf{r}\right)$$

- Acceleration on a mirror

Charge (B or B-L)
q/M is ~ 1/GeV for B, ~1/2 /GeV for B-L

$$\mathbf{a}(t,\mathbf{r}) = \epsilon e \frac{q_{D,i}}{M_i} m_\mathrm{A}\mathbf{A_0}\cos\left(m_\mathrm{A}t - \mathbf{k}_\mathrm{A}\mathbf{r_i}\right)$$

Dimension less dark photon coupling strength (normalized to EM coupling)

Mirror mass

This term is basically same for all the mirrors (for 100 Hz, m_A=4e-13 eV and $2\pi/k_A$=3e9 m)

- Even if mirrors have same q/M, signal remains due to DM propagation

PRL **121**, 061102 (2018)

Pierce+ (2018): Calculations

- DARM strain if all the mirrors have same q/M

$$R \equiv \frac{\Delta L}{L} = C\frac{q_D}{M}\epsilon e|\mathbf{A_0}|v$$

Local DM velocity

$$= C\frac{q_D}{M}\epsilon e\frac{\hbar}{c^4\sqrt{\varepsilon_0}}\frac{\sqrt{2\rho_{\rm DM}}}{m_{\rm A}}v$$

[√ε should be √(4πε) ??]

Geometric factor for averaging over the direction of DM propagation, dark photon polarization, orientation of GW detector arms (√2/3 for LVK) [For PRCL and MICH ?]

- Analogy to stochastic GW search

[different approach from previous papers]

overlap reduction function

observing time [no discussion on coherence time; I think it is imprinted in Δf]

$$\mathrm{SNR} = \frac{\gamma(|f|)h_0^2\sqrt{T}}{2\sqrt{S_{hh,1}(f)S_{hh,2}(f)\Delta f}}$$

2 for 2σ, ~7 for 5σ

Δf/f ~ 1e-6

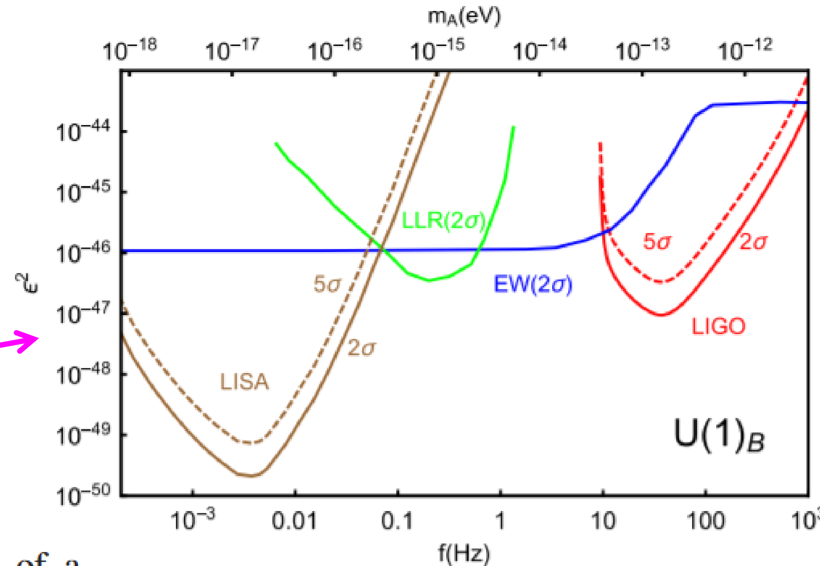
detector strain sensitivity

- Coupling ϵ can be determined with $R = h_0/2$

PRL **121**, 061102 (2018)

Pierce+ (2018): Sensitivity

- Two LIGO detectors or two LISA detectors
- T=2 years of correlation analysis



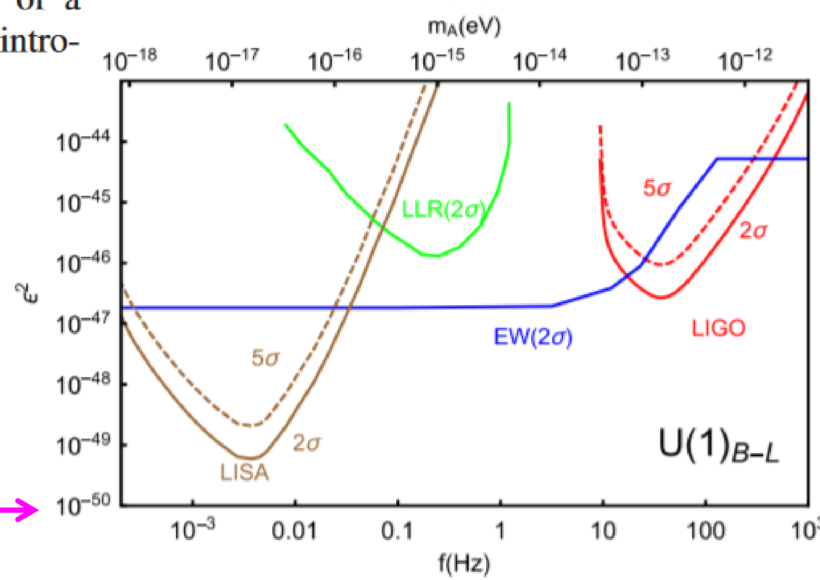
Factor of ~2 stronger limit for B compared with B-L due to larger charge

[44] The weak gravity conjecture requires the existence of a particle with $\epsilon q > m/M_{pl}$. This can be satisfied by introducing a $\mathcal{O}$(keV) particle with $\epsilon \sim 10^{-25}$.

m/Mpl = keV / 1e19 GeV
~ 1e-25

gravity should be the weakest force

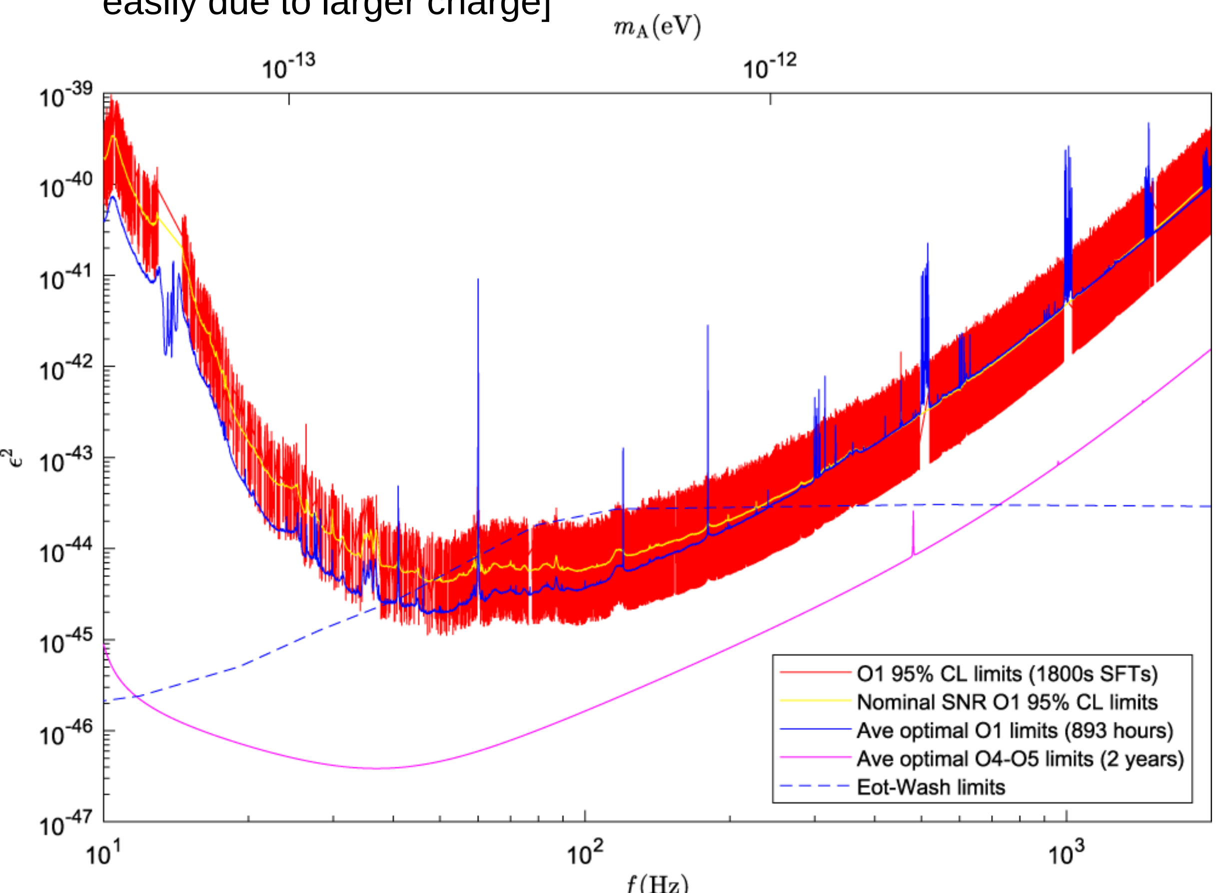
Weak gravity conjecture level



Real Search with aLIGO O1 Data

- Huai-Ke Guo+, [Communications Physics 2, 155 (2019)]
- Done by the same group with similar data analysis method
- Done only for $U(1)_B$ coupling

[probably because it can beat EP tests more easily due to larger charge]



COMMUNICATIONS PHYSICS

ARTICLE

https://doi.org/10.1038/s42005-019-0255-0 OPEN

Searching for dark photon dark matter in LIGO O1 data

Huai-Ke Guo[1], Keith Riles[2], Feng-Wei Yang[3,4*] & Yue Zhao[4]

Dark matter exists in our Universe, but its nature remains mysterious. The remarkable sensitivity of the Laser Interferometer Gravitational-Wave Observatory (LIGO) may be able to solve this mystery. A good dark matter candidate is the ultralight dark photon. Because of its interaction with ordinary matter, it induces displacements on LIGO mirrors that can lead to an observable signal. In a study that bridges gravitational wave science and particle physics, we perform a direct dark matter search using data from LIGO's first (O1) data run, as opposed to an indirect search for dark matter via its production of gravitational waves. We demonstrate an achieved sensitivity on squared coupling as $\sim 4\times 10^{-45}$, in a $U(1)_B$ dark photon dark matter mass band around $m_A \sim 4\times 10^{-13}$ eV. Substantially improved search sensitivity is expected during the coming years of continued data taking by LIGO and other gravitational wave detectors in a growing global network.

[arXiv:1908.04797](https://arxiv.org/abs/1908.04797)

Carney+ (2019)

- Ultralight dark matter detection with mechanical quantum sensors

FERMILAB-PUB-19-364-T

Ultralight dark matter detection with mechanical quantum sensors

Daniel Carney[a,b], Anson Hook[c], Zhen Liu[c], Jacob M. Taylor[a], and Yue Zhao[d]

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[b] *Fermi National Accelerator Laboratory, Batavia, IL, USA*

[c] *Maryland Center for Fundamanetal Physics, University of Maryland, College Park, MD USA and*

[d] *Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA*

(Dated: August 15, 2019)

We consider the use of quantum-limited mechanical force sensors to detect ultralight (sub-meV) dark matter candidates which are weakly coupled to the standard model. We emphasize the scalable nature of an array of sensors, which can be used to reject many backgrounds, and leads to sensitivities scaling at least as fast as $\sqrt{N_{\mathrm{det}}}$. We show that for some ultralight dark matter candidates, a pair of milligram-scale, mechanical sensors operating at the standard quantum limit already has detection reach competitive with other quantum acceleration sensors.

arXiv:1908.04797

Carney+ (2019): Principle

- Vector B-L dark matter produces force

$$F = g_{\mathrm{B-L}} N_{\mathrm{B-L}} F_0 \sin(m_{\mathrm{A}} t + \delta_\tau)$$

Dimension less coupling constant

B-L charge

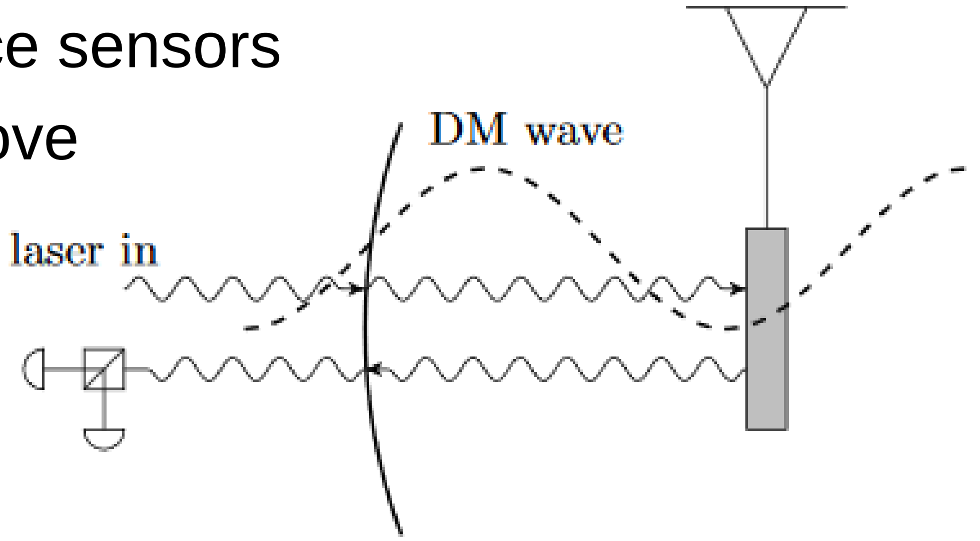
$$F_0 \simeq \sqrt{\rho_{\mathrm{DM}}} \simeq 10^{-15}\,\mathrm{N}$$

[√(2ρ) ??]

$$N_{\mathrm{B-L}} \simeq \frac{M}{2m_{\mathrm{neutron}}}$$

Mirror mass

- Detect it with quantum force sensors
- Array of sensors can improve sensitivity by $\sqrt{N_{\mathrm{det}}}$



- Assume only one mirror is suspended

Carney+ (2019): Calculations

- Sensitivity to the coupling will be

[I think factor of 2 is consistently missing in Eq. (11) and Eq. (17)]

$$g_{\mathrm{B-L}} < \sqrt{\frac{S_{FF}(\omega)}{N_{\mathrm{B-L}}^2 F_0^2 N_{\mathrm{det}} T_{\mathrm{tot}}}}$$

Force sensitivity

$$\sqrt{S_{FF}} = \omega^2 M \sqrt{S_{xx}}$$

$$= \sqrt{\frac{S_{xx}}{N_{\mathrm{det}} T_{\mathrm{tot}}}} \frac{m_{\mathrm{neutron}} \omega^2}{r_{\mathrm{neutron}} F_0}$$

Neutron ratio (~1/2)

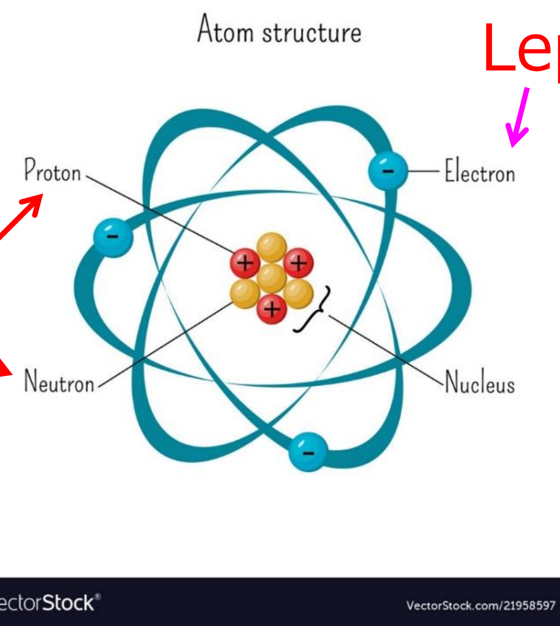
- Effective integration time [as usual]

$$T_{\mathrm{tot}} = T_{\mathrm{int}} \ \ (\mathrm{if}\ T_{\mathrm{int}} < \tau_{\mathrm{coh}})$$

$$T_{\mathrm{tot}} = \sqrt{T_{\mathrm{int}} \tau_{\mathrm{coh}}} \ \ (\mathrm{if}\ T_{\mathrm{int}} > \tau_{\mathrm{coh}})$$

Lepton

Baryon

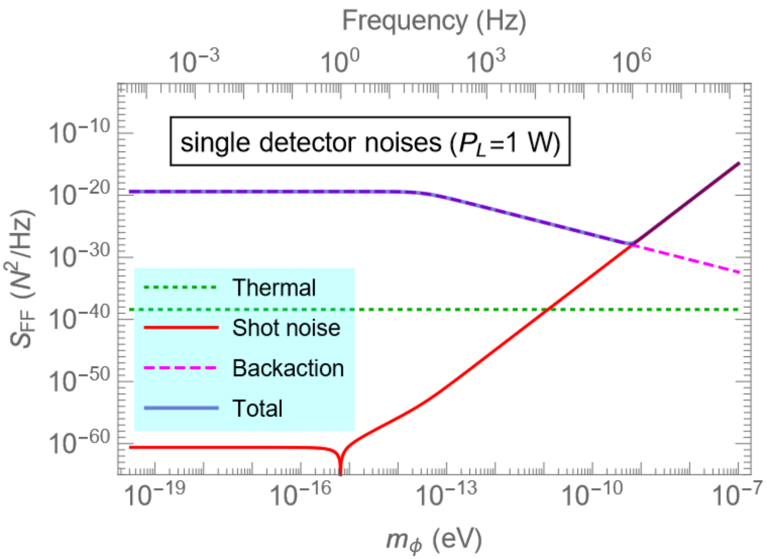


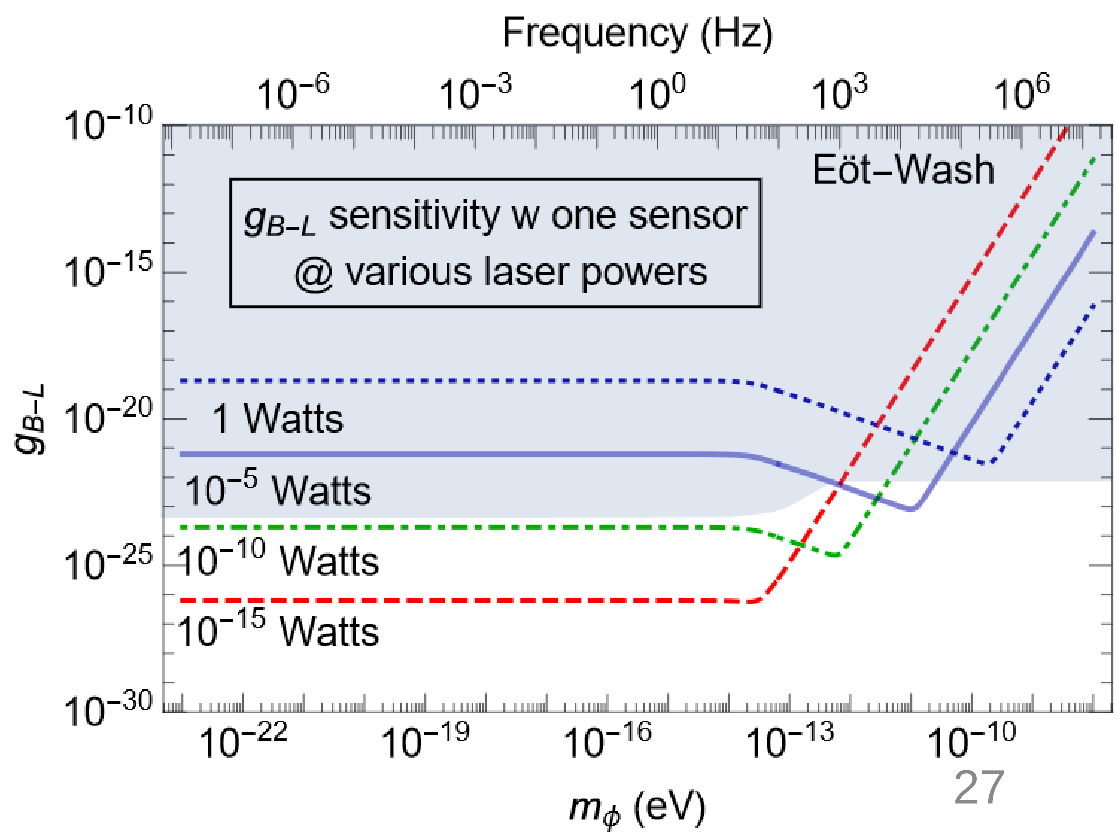
B-L = (Proton)+(Neutron)-(Electron)
= (Neutron) for neutral atoms

Carney+ (2019): Sensitivity

- 1 mg, mechanical frequency of 1 Hz, at 10 mK
- Input laser power changed from 1 W to 1e-15 W (scan to broaden the sensitivity)
- 1 cm cavity (long cavity is not necessary)

Force sensitivity
[finesse is too high…]

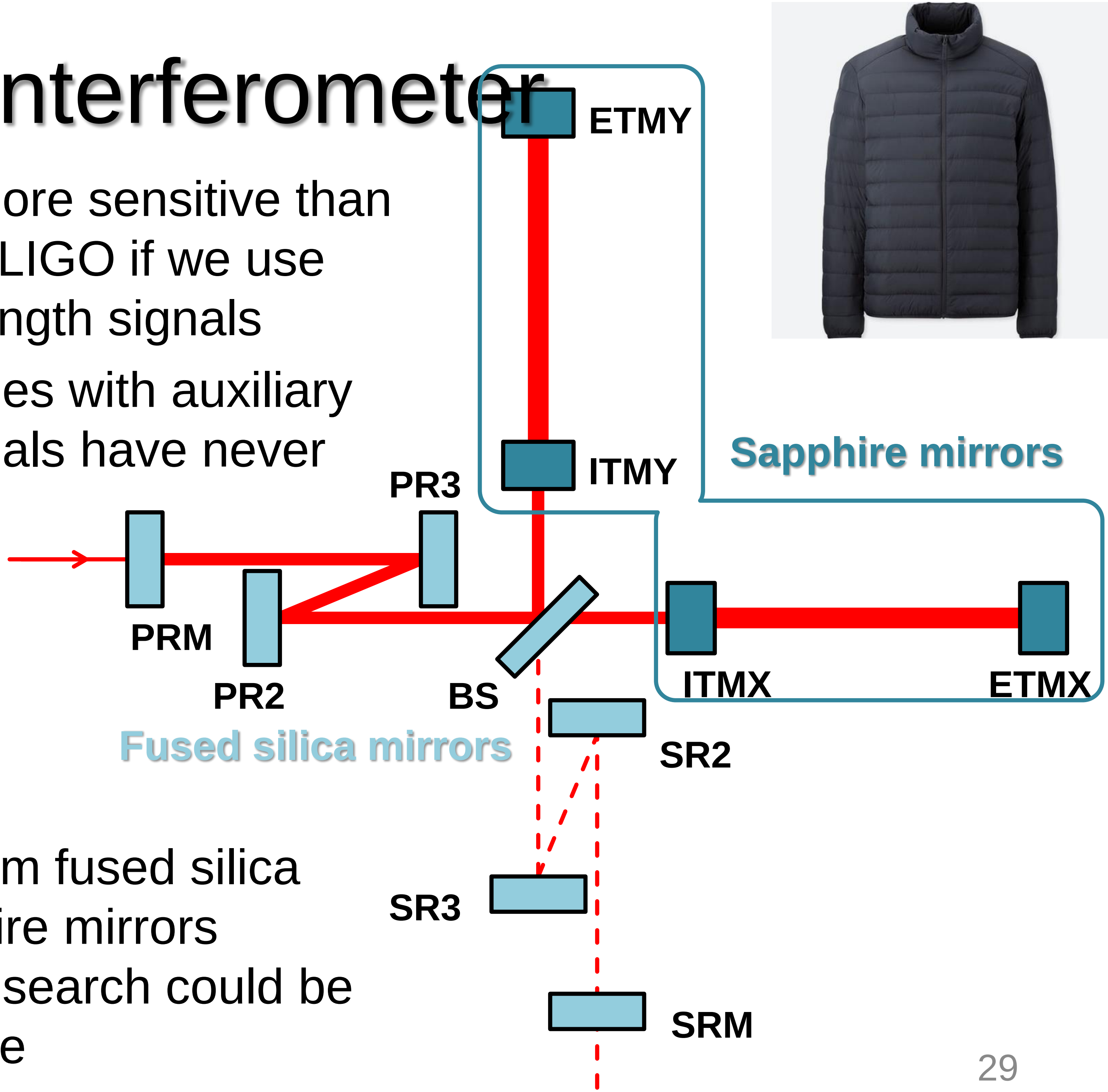




KAGRA Sensitivity

KAGRA Interferometer

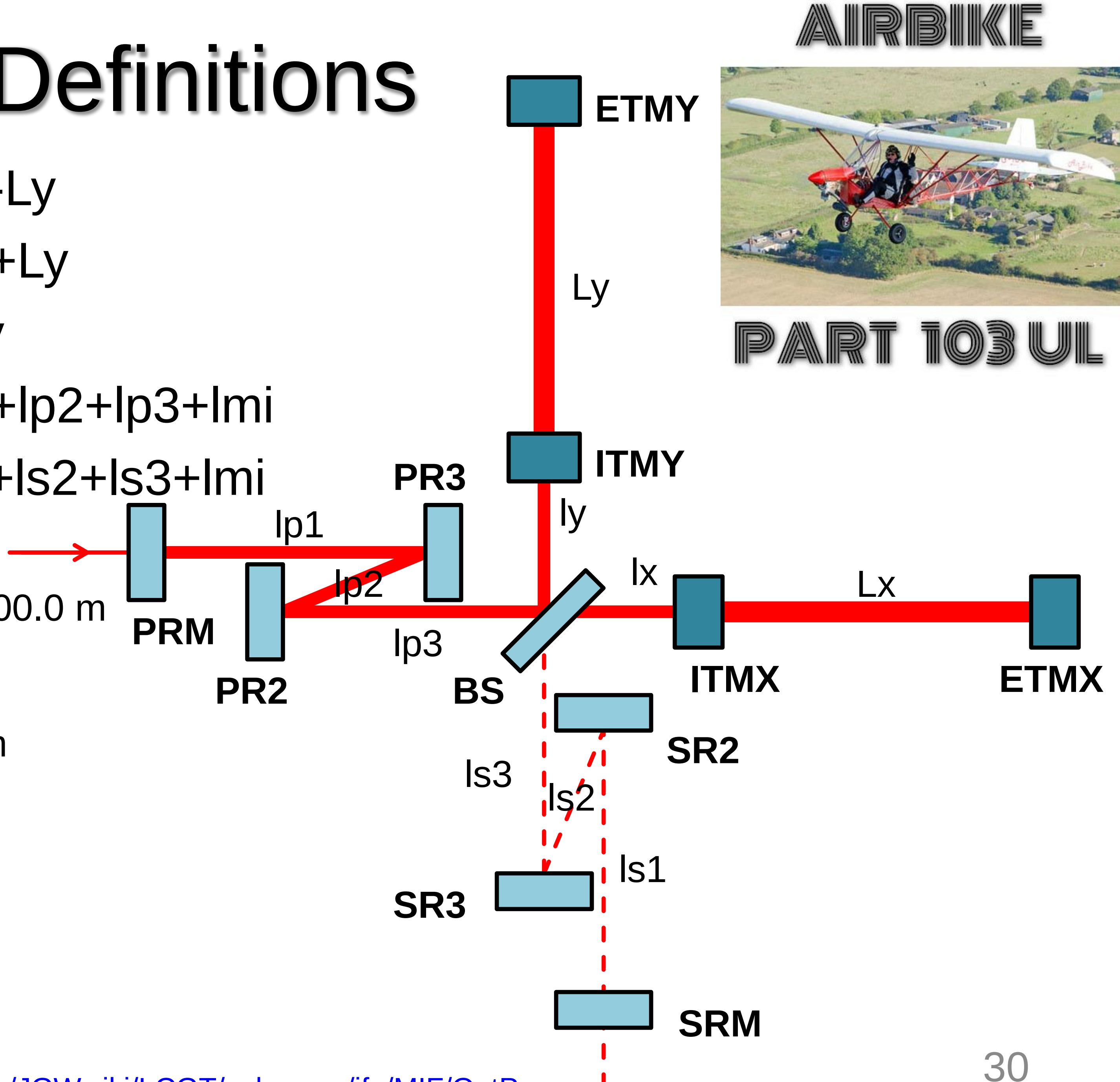
- Possibly more sensitive than Advanced LIGO if we use auxiliary length signals
- DM searches with auxiliary length signals have never been done



- Consist from fused silica and sapphire mirrors
  → unique search could be possible

Length Definitions

- DARM: Lx-Ly
- CARM: Lx+Ly
- MICH: lx-ly
- PRCL: lp1+lp2+lp3+lmi
- SRCL: ls1+ls2+ls3+lmi

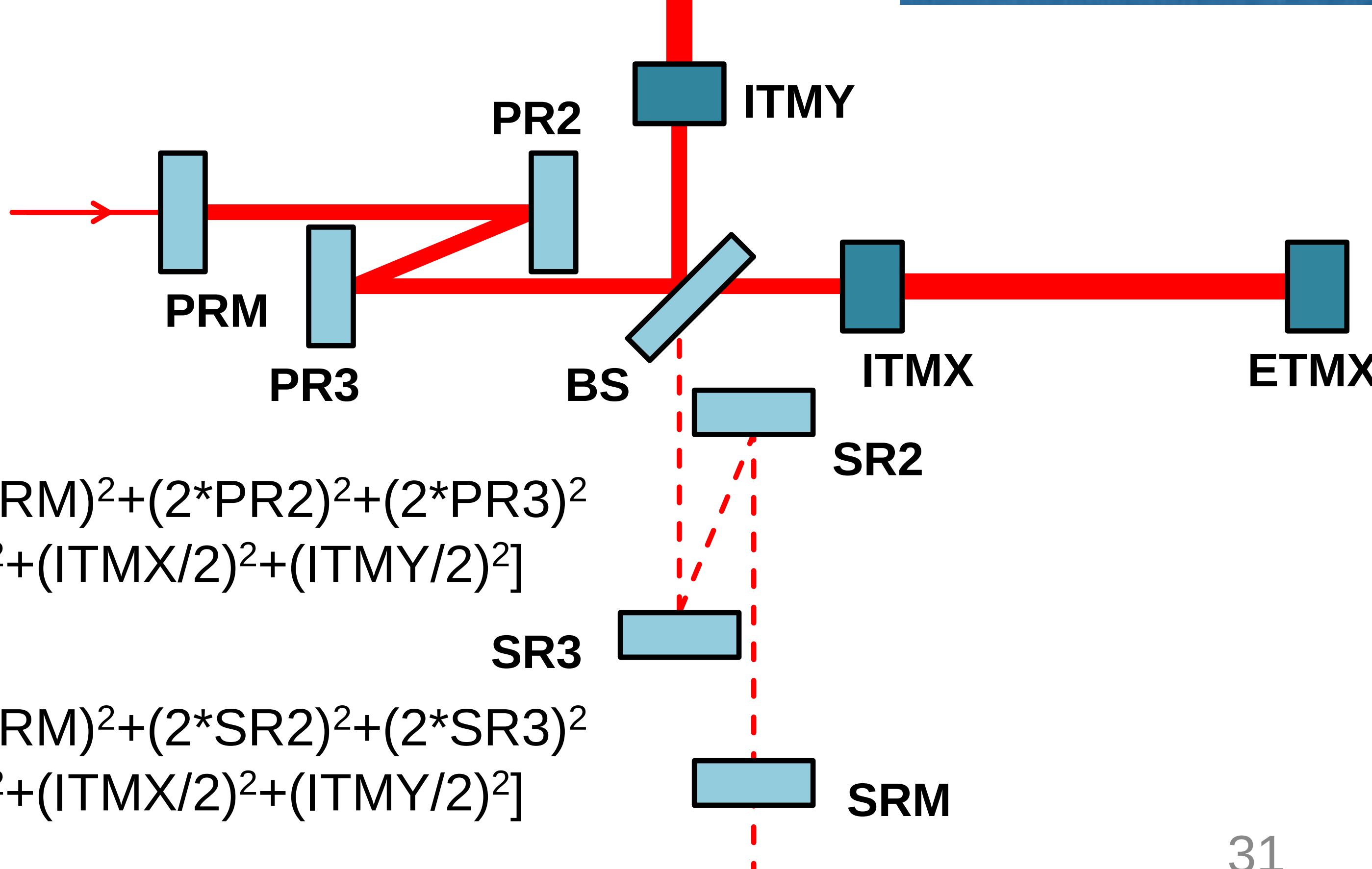


Lx = Ly = Larm = 3000.0 m
Lx = 26.6649 m
ly = 23.3351 m
lmi = (lx+ly)/2 = 25 m
lp1 = 14.7615 m
lp2 = 11.0661 m
lp3 = 15.7638 m
ls1 = 14.7412 m
ls2 = 11.1115 m
ls2 = 15.7386 m

http://gwwiki.icrr.u-tokyo.ac.jp/JGWwiki/LCGT/subgroup/ifo/MIF/OptParam

Sensitivity

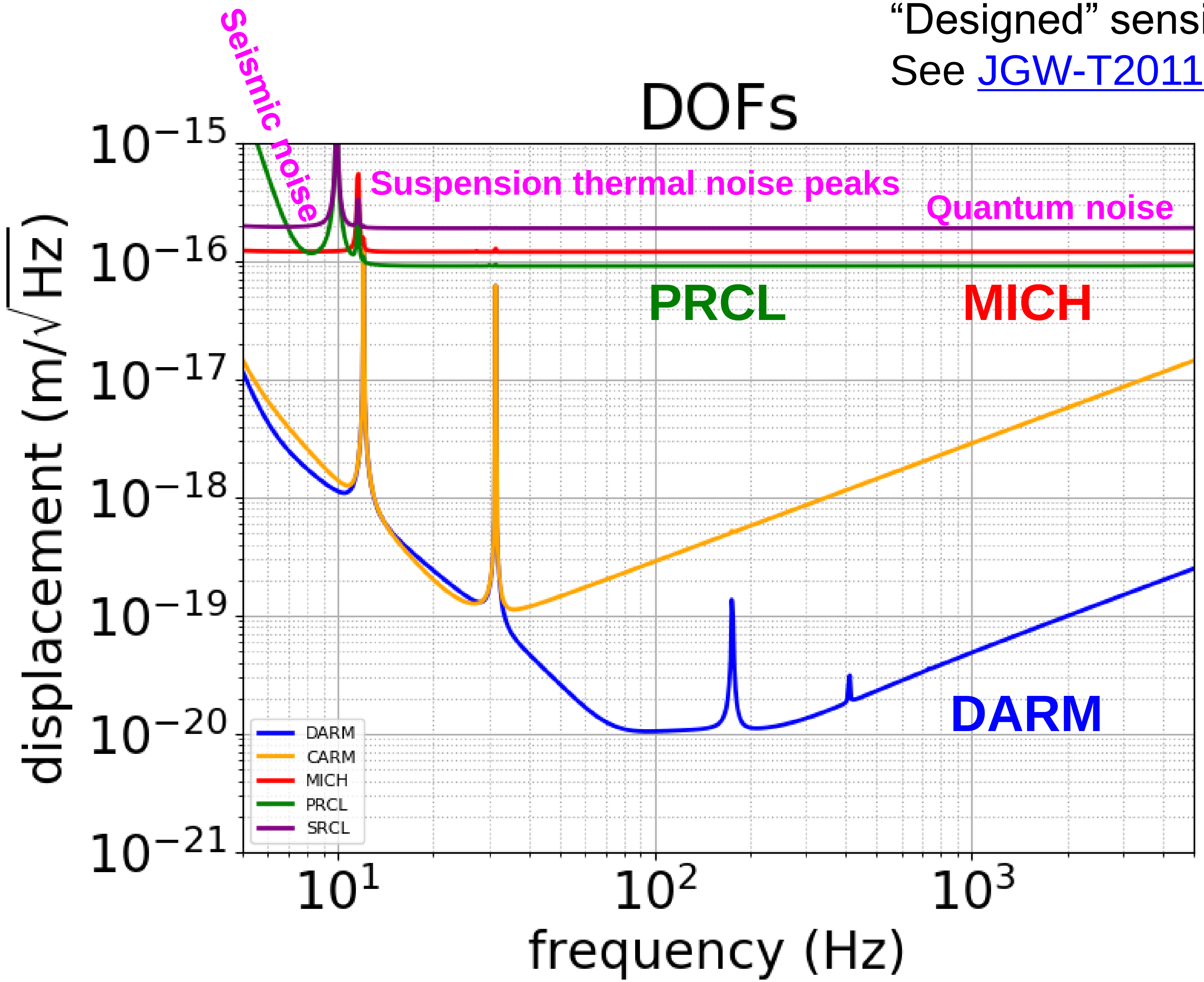
- DARM: √[(ITMX)^2+(ETMX)^2+ (ITMY)^2+(ETMY)^2]
- CARM: √[(ITMX)^2+(ETMX)^2+ (ITMY)^2+(ETMY)^2]
- MICH: √[(√2*BS)^2+(ITMX)^2+(ITMY)^2]



- PRCL: √[(PRM)^2+(2*PR2)^2+(2*PR3)^2 +(√2/2*BS)^2+(ITMX/2)^2+(ITMY/2)^2]
- SRCL: √[(SRM)^2+(2*SR2)^2+(2*SR3)^2 +(√2/2*BS)^2+(ITMX/2)^2+(ITMY/2)^2]

Auxiliary Displacement Sensitivity

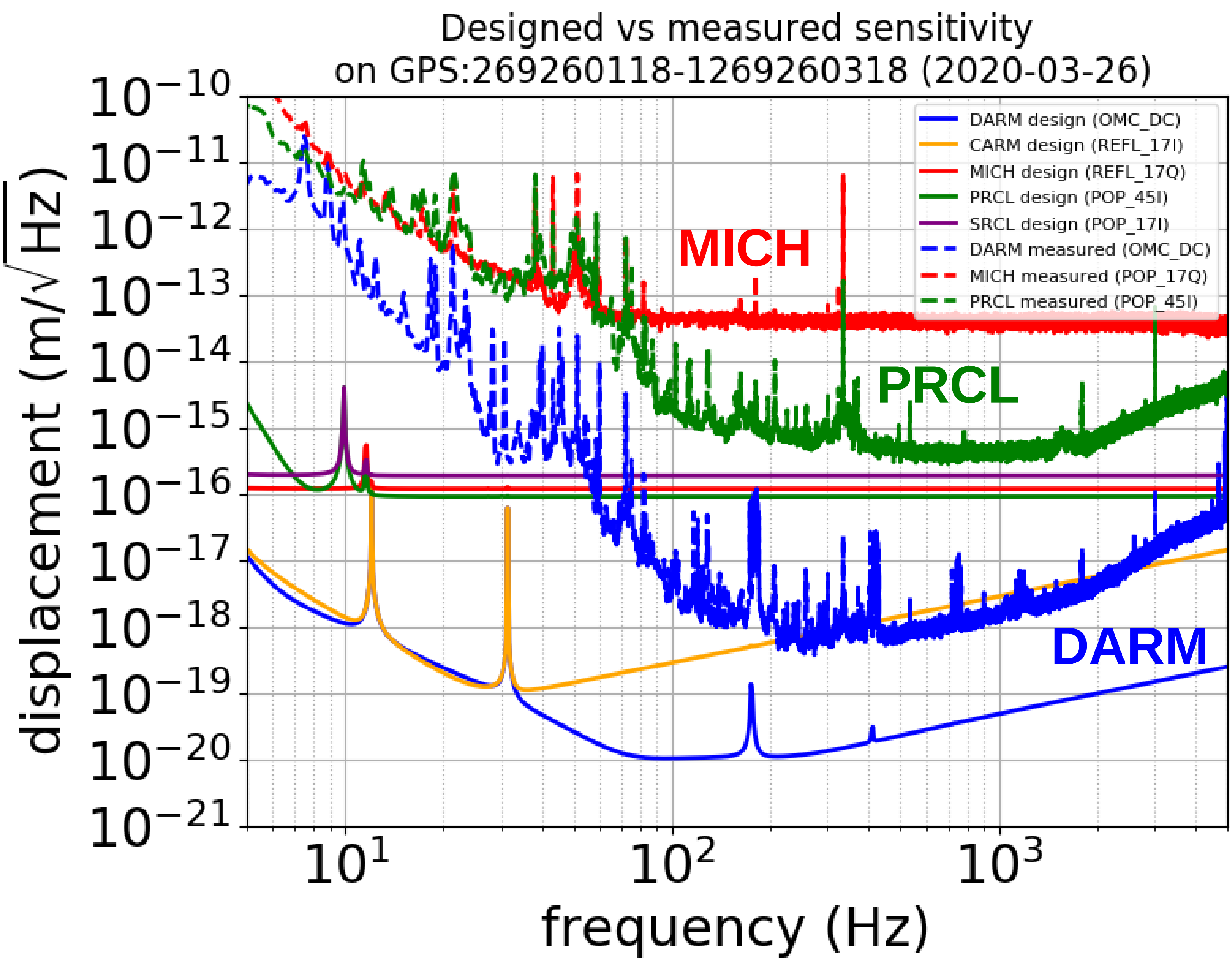
"Designed" sensitivity
See JGW-T2011755 for details



NOTE: frequency noise and intensity noise not considered for CARM

Mar 26, 2020 Sensitivity

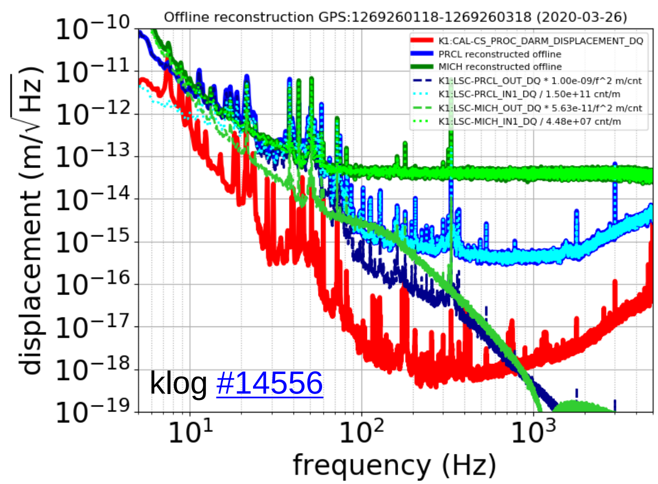
Current DARM best sensitivity

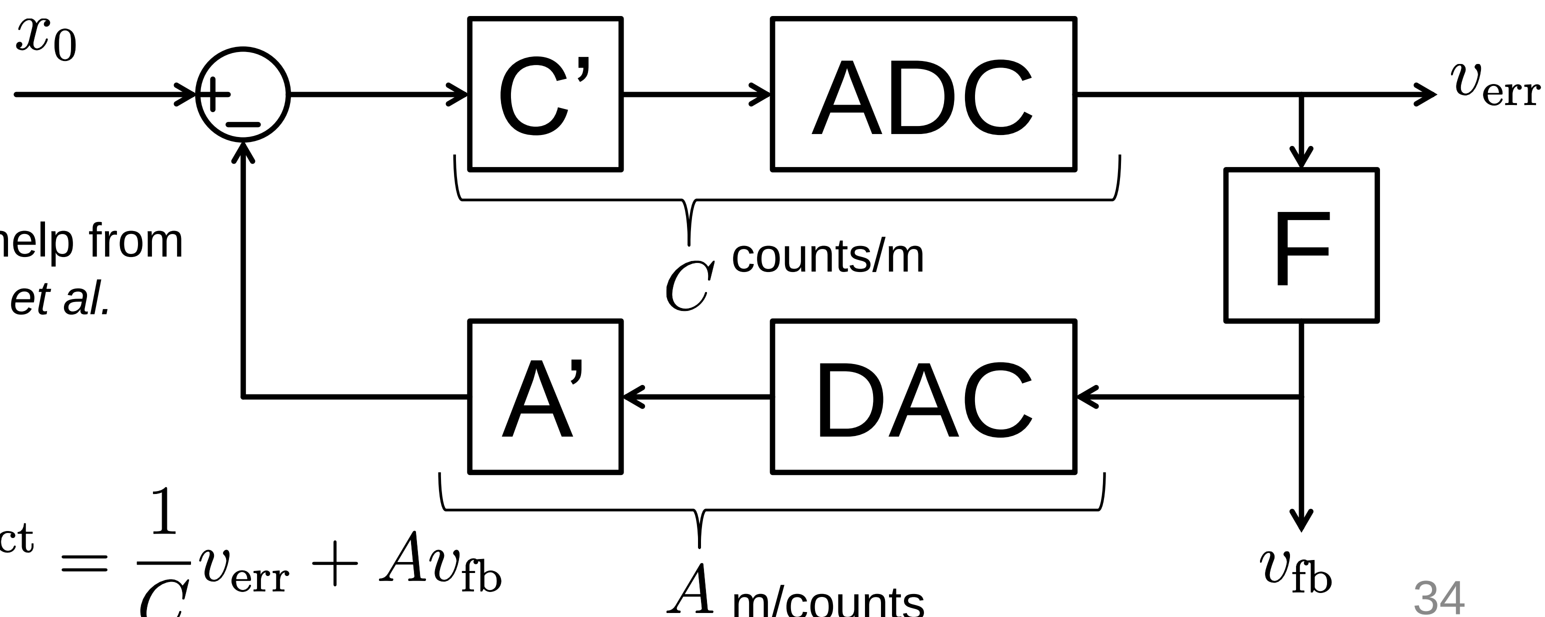


MICH and PRCL calibrated offline (see klog #14556)

Offline Reconstruction

- MICH and PRCL was not calibrated online during O3GK (April 7 to April 21, 2020)
- Offline reconstruction was done using the calibration factor measured on April 21
- More serious calibration necessary





With a lot of help from T. Yamamoto *et al.*

$$x_0^{\mathrm{reconstruct}} = \frac{1}{C} v_{\mathrm{err}} + A v_{\mathrm{fb}}$$

Scalar Dark Matter: Calculations

- Effective averaging time

$$T_{\mathrm{tot}} = T_{\mathrm{int}} \;(\mathrm{if}\, T_{\mathrm{int}} < \tau_{\mathrm{coh}}), \quad T_{\mathrm{tot}} = \sqrt{T_{\mathrm{int}}\tau_{\mathrm{coh}}} \;(\mathrm{if}\, T_{\mathrm{int}} > \tau_{\mathrm{coh}})$$

- Minimum detectable displacement in amplitude with SNR=1

$$\delta x_{\mathrm{min}} = \frac{2}{\sqrt{T_{\mathrm{tot}}}}\sqrt{S_{xx}}$$

[Need to check this factor of 2; I think this is correct]

Displacement sensitivity

- Displacement from DM coupling

$$\delta x = \delta x_0 \left(-\frac{\delta\alpha}{\alpha} - \frac{\delta m_{\mathrm{e}}}{m_{\mathrm{e}}}\right)$$

$$\rho_{\mathrm{DM}} = m_\phi^2 \phi_0^2/2$$

$$= \delta x_0(-d_{\mathrm{e}} - d_{m_{\mathrm{e}}})\sqrt{4\pi\hbar c}E_{\mathrm{pl}}^{-1}\phi_0 \cos\omega_\phi t$$

PRL **123**, 031304 (2019) case

$$= \delta x_0 \left(-\frac{1}{\Lambda_\gamma} - \frac{1}{\Lambda_{\mathrm{e}}}\right)\phi_0 \cos\omega_\phi t$$

PRR **1**, 033187 (2019) case

Scalar Dark Matter: Calculations

- Assuming all the mirrors are placed in homogeneous DM
- DARM

$$\delta x_0 = \frac{\sqrt{2}(n_{\rm BS} - 1/2) l_{\rm BS}}{N_{\rm eff}} - \Delta l_{\rm TM}$$

Thickness difference [(ITMX+ETMX)-(ITMY+ETMY)]/2

~80 um for aLIGO
~0.09 mm for KAGRA (JGW-P2011476)

[I think this Neff should be checked more carefully]

- MICH

$$\delta x_0 = \sqrt{2}(n_{\rm BS} - 1/2) l_{\rm BS} + \Delta(n_{\rm TM} l_{\rm TM}) - \Delta l_{\rm TM}/2$$

Thickness difference (ITMX – ITMY)

~-0.21 mm for KAGRA (JGW-P2011476)

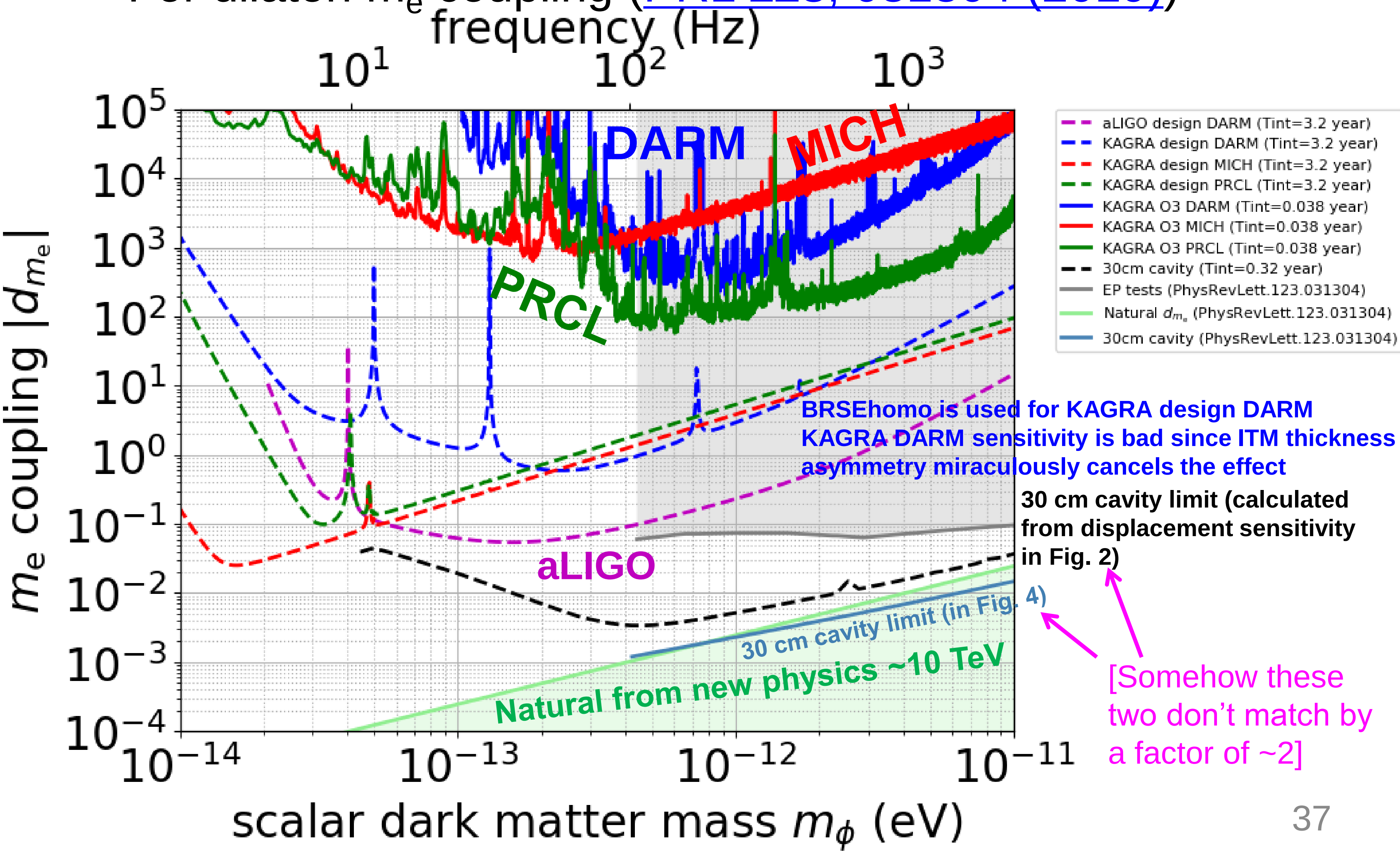
- PRCL

$$\delta x_0 = \frac{1}{2}\left(\sqrt{2}(n_{\rm BS} - 1/2) l_{\rm BS} + 2(n_{\rm TM} - 1/2) l_{\rm TM}\right) - l_{\rm PRM}/2 - l_{\rm PR2} - l_{\rm PR3}$$

- MICH and PRCL can be more sensitive, since more mirrors are involved and the effect is not cancelled

Scalar Dark Matter: Sensitivity

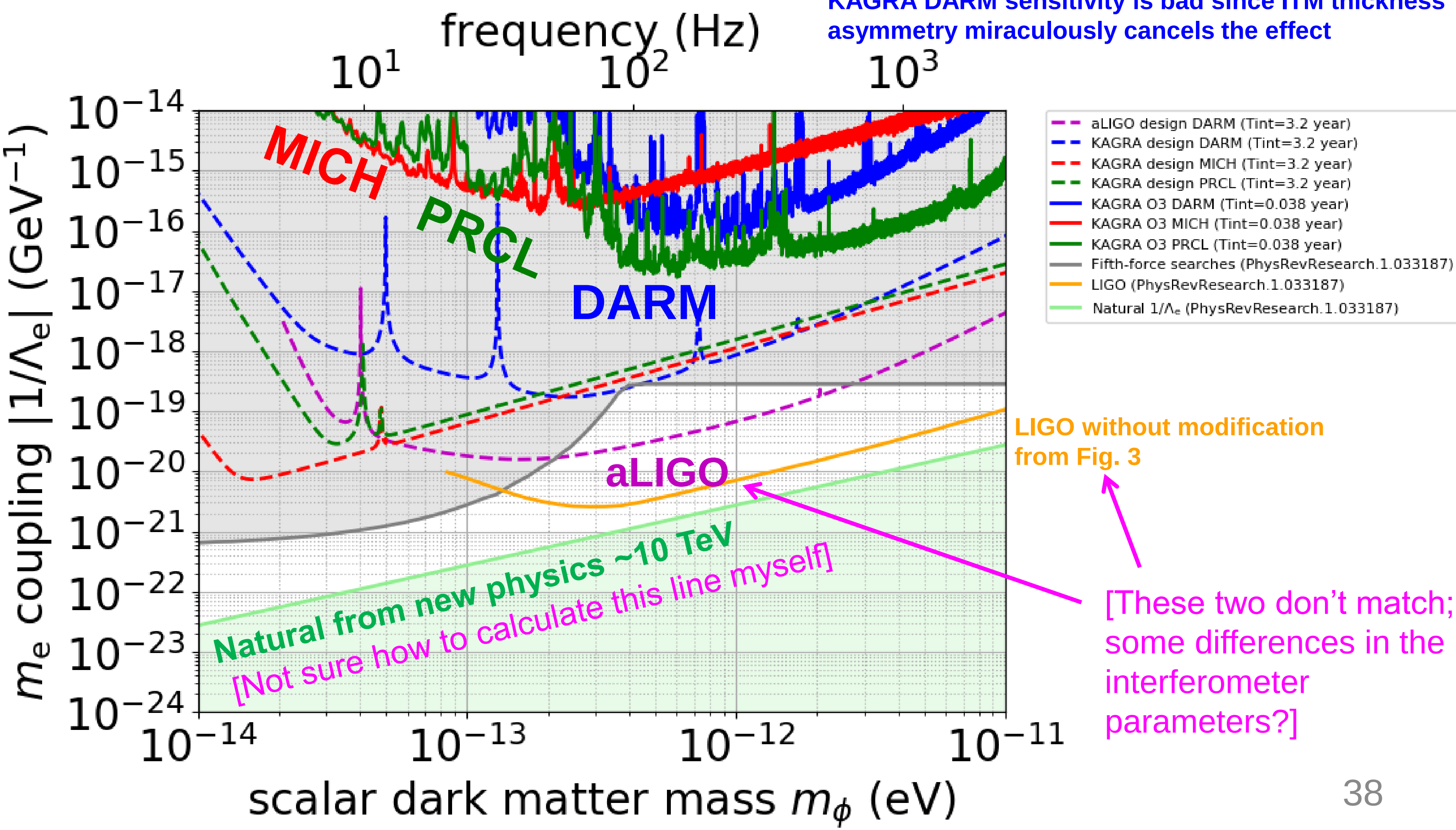
- For dilaton m_e coupling (PRL **123**, 031304 (2019))



Scalar Dark Matter: Sensitivity

- For m_e coupling (PRR **1**, 033187 (2019))

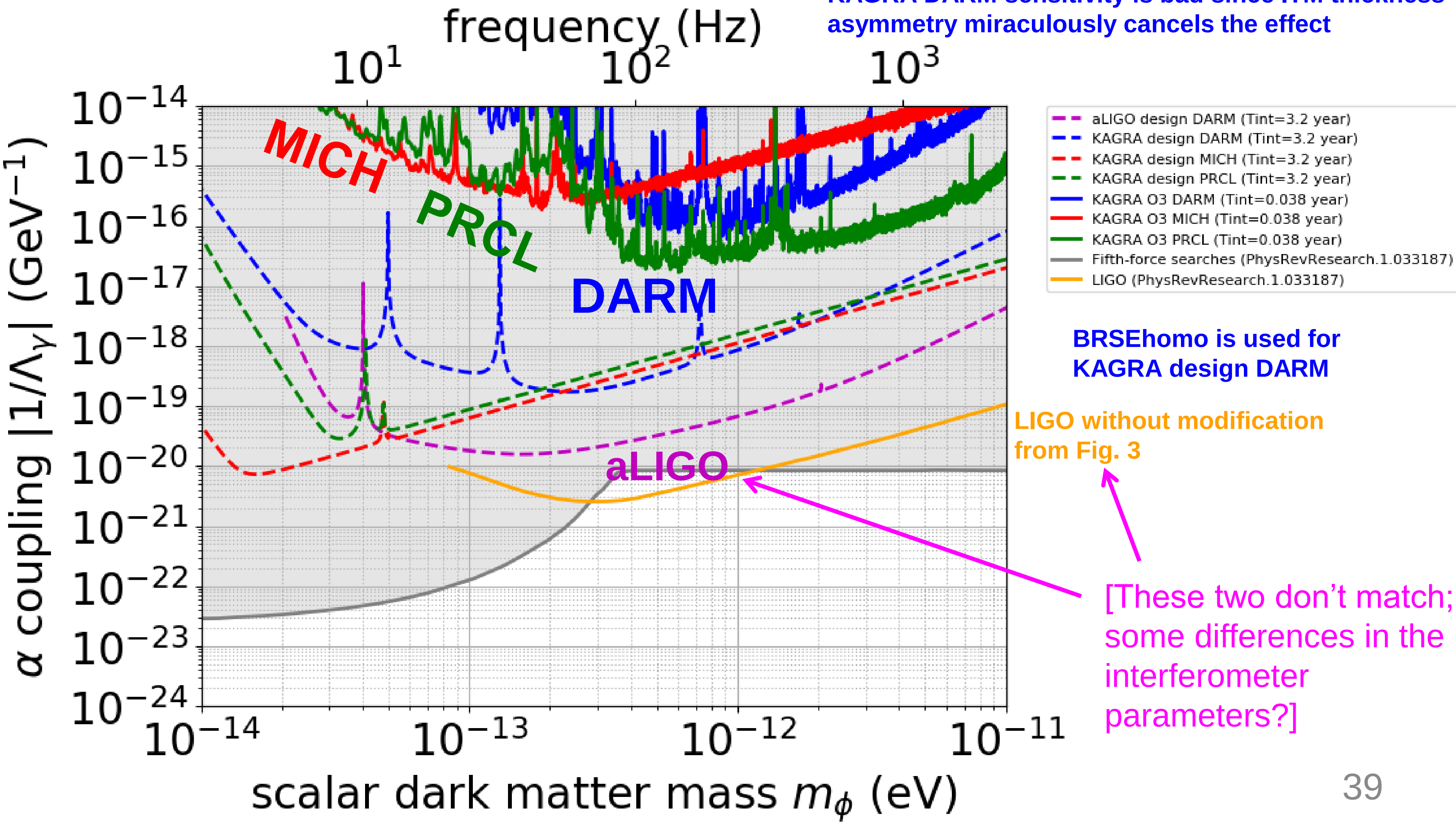
BRSEhomo is used for KAGRA design DARM
KAGRA DARM sensitivity is bad since ITM thickness asymmetry miraculously cancels the effect



Scalar Dark Matter: Sensitivity

- For α coupling (PRR **1**, 033187 (2019))

BRSEhomo is used for KAGRA design DARM
KAGRA DARM sensitivity is bad since ITM thickness asymmetry miraculously cancels the effect



BRSEhomo is used for KAGRA design DARM

LIGO without modification from Fig. 3

[These two don't match; some differences in the interferometer parameters?]

Vector Dark Matter: Calculations

- Effective averaging time (following arXiv:1908.04797)

$$T_{\rm tot} = T_{\rm int}\ ({\rm if}\ T_{\rm int} < \tau_{\rm coh}), \quad T_{\rm tot} = \sqrt{T_{\rm int}\tau_{\rm coh}}\ ({\rm if}\ T_{\rm int} > \tau_{\rm coh})$$

- Minimum detectable displacement in amplitude with SNR=1

$$\delta x_{\rm min} = \frac{2}{\sqrt{T_{\rm tot}}}\sqrt{S_{xx}}$$

[Need to check this factor of 2]

Displacement sensitivity

- Acceleration to mirror

$$|\mathbf{a}| = \epsilon e \frac{q_{\rm B-L}}{M} m_{\rm A} A_0 = \epsilon e \frac{r_{\rm neutron}}{m_{\rm neutron}}\sqrt{2\rho_{\rm DM}}$$

PRL **121**, 061102 (2018) case

$$|\mathbf{a}| = |\mathbf{F}|/M = g_{\rm B-L}\frac{N_{\rm B-L}}{M}F_0 = g_{\rm B-L}\frac{r_{\rm neutron}}{m_{\rm neutron}}\sqrt{\rho_{\rm DM}}$$

arXiv:1908.04797 case

[Simply $\epsilon = g_{\rm B-L}$ if F_0=1e-15 N?
(both are dimensionless)]

$$\rho_{\rm DM} = m_{\rm A}^2 A_0^2/2$$

Vector Dark Matter: Calculations

- Relative displacement depends on the geometry
- DARM (all same mirrors)

For small kL

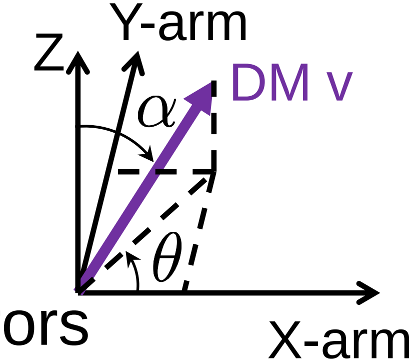
$$\delta x_{\rm DARM} = |a_{{\rm TM},x}\cos\theta - a_{{\rm TM},y}\sin\theta| \left(\frac{|k_{\rm A}|L_{\rm arm}\sin\alpha}{m_{\rm A}^2}\right)$$

average →

$$\sqrt{\langle \delta x_{\rm DARM}^2\rangle} = \frac{\sqrt{2}}{3}\frac{|a_{\rm TM}||k_{\rm A}|L_{\rm arm}}{m_{\rm A}^2}$$

[I didn't confirm if this averaging is correct]

PRL **121**, 061102 (2018) Eq. (A3)



- Acceleration difference between different mirrors

$$a_1\cos(m_{\rm A}t) - a_2\cos(m_{\rm A}t + k_{\rm A}L)$$

$$\simeq \sqrt{(a_1-a_2)^2 - a_1a_2(k_{\rm A}L)^2}$$

This term is ~10 orders of magnitude larger for fused silica and sapphire B-L, if L~100 m

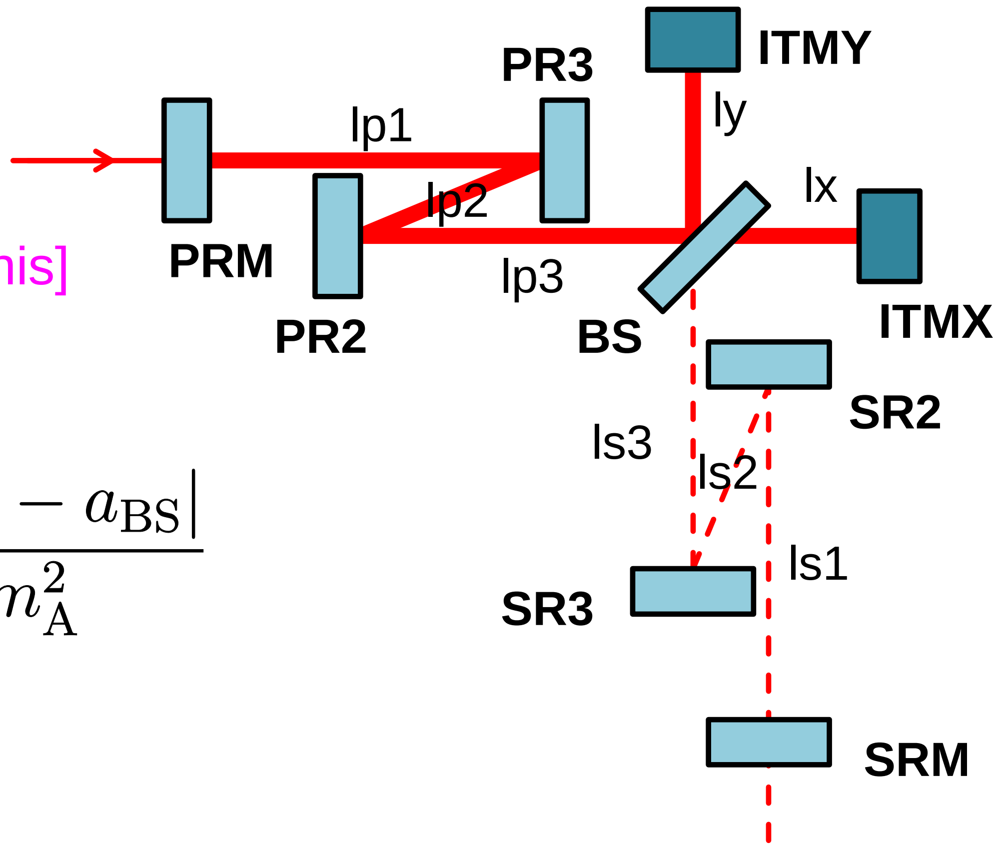
Only this term remains for mirrors with same charge (kL=6e-6 for 100 Hz, L=3 km)

$$a_{\rm TM} : a_{\rm BS} \simeq 0.51 : 0.5$$

For B-L (for B, all mirrors are the same)

Vector Dark Matter: Calculations

- For central part, kL term can be negligible



[I need someone to check this]

- MICH

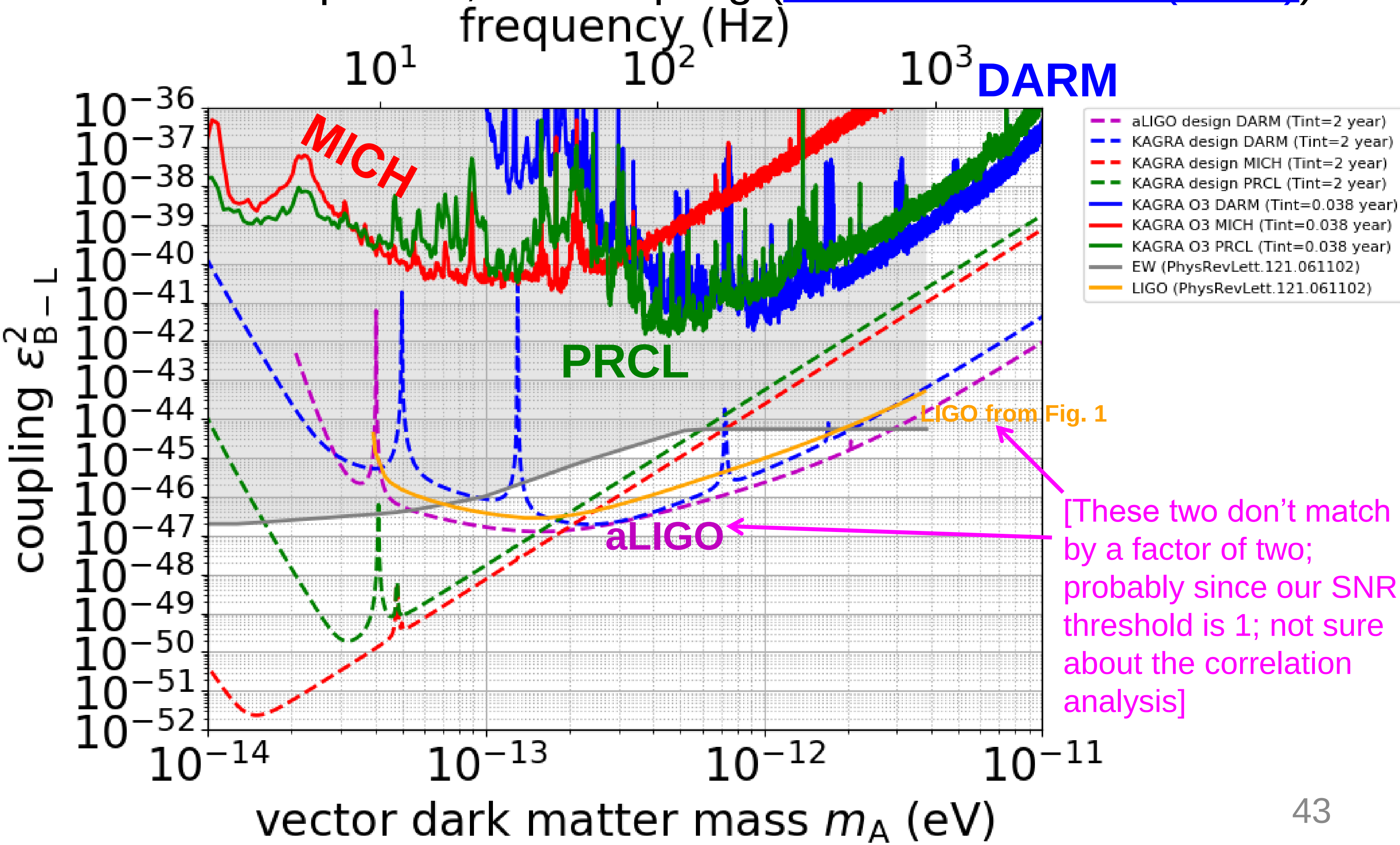
$$\sqrt{\langle \delta x^2_{\mathrm{MICH}} \rangle} = \frac{\sqrt{2}}{3} \frac{|a_{\mathrm{TM}} - a_{\mathrm{BS}}|}{m^2_{\mathrm{A}}}$$

- PRCL

$$\sqrt{\langle \delta x^2_{\mathrm{PRCL}} \rangle} = \frac{1}{3} \frac{\frac{1}{2}\sqrt{(a_{\mathrm{TM}} + a_{\mathrm{BS}} - 2a_{\mathrm{PRM}})^2 + (a_{\mathrm{TM}} - a_{\mathrm{BS}})^2}}{m^2_{\mathrm{A}}}$$

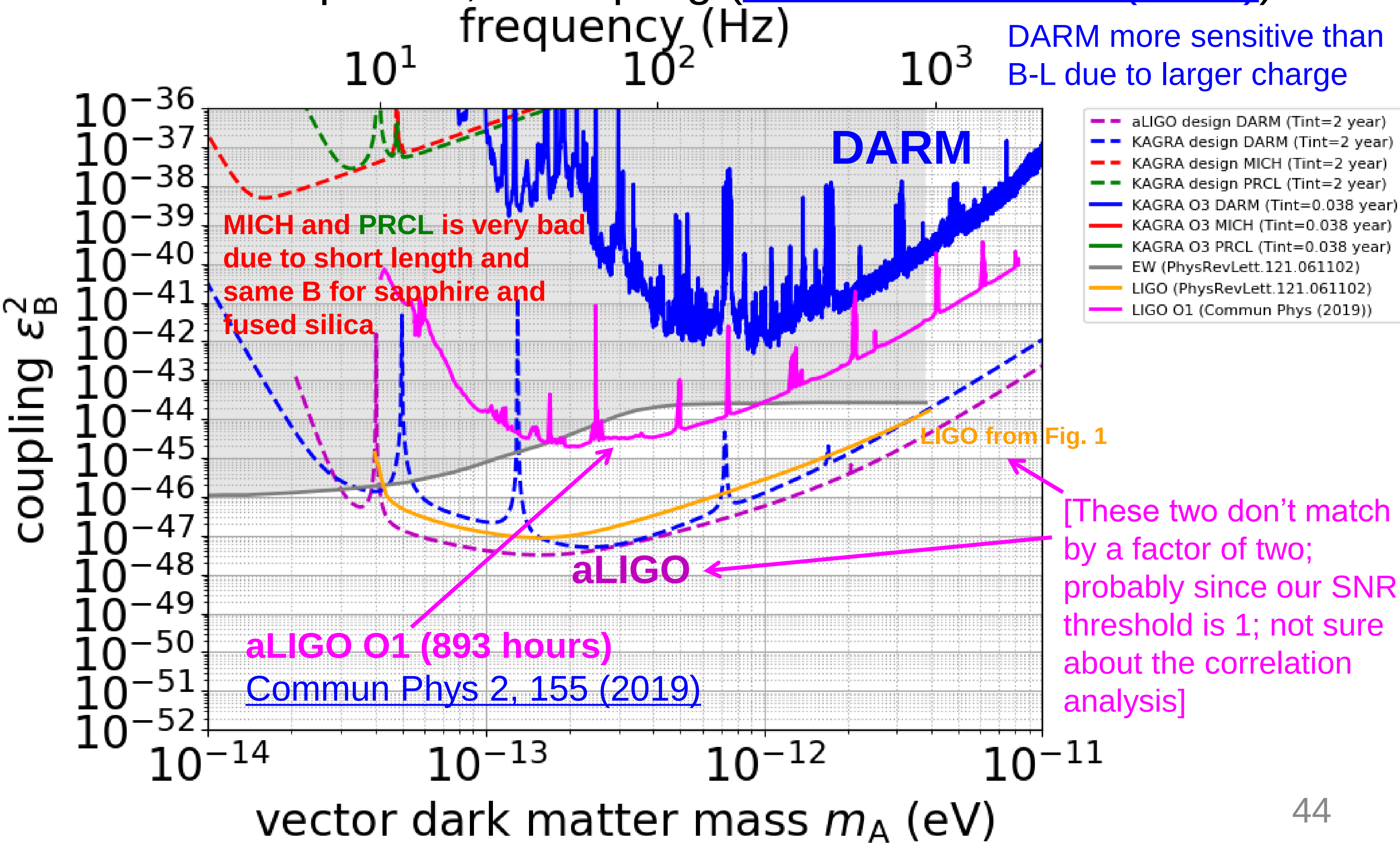
Vector Dark Matter: Sensitivity

- For dark photon, B-L coupling (PRL **121**, 061102 (2018))



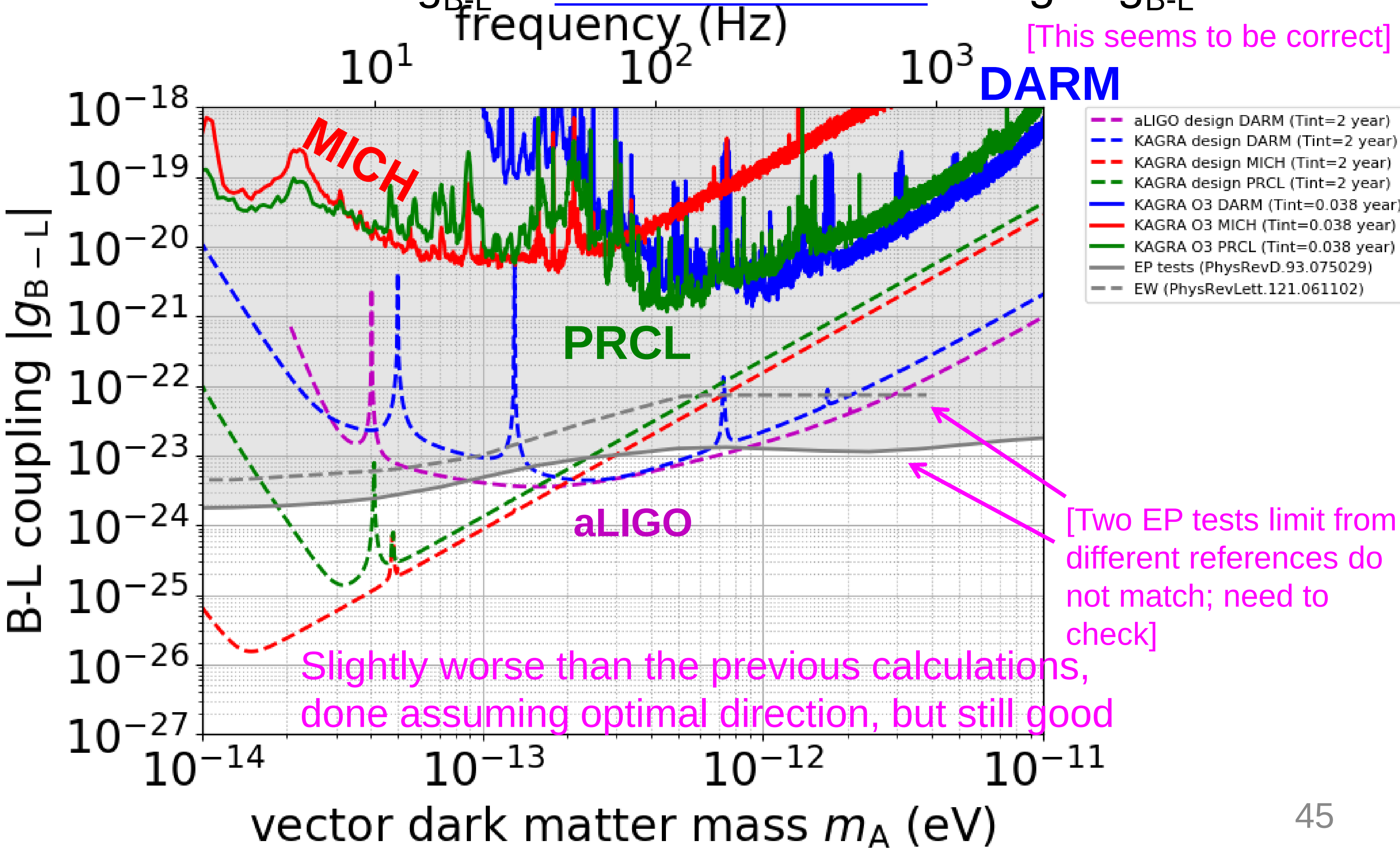
Vector Dark Matter: Sensitivity

- For dark photon, B coupling ([PRL **121**, 061102 (2018)](#))



Vector Dark Matter: Sensitivity

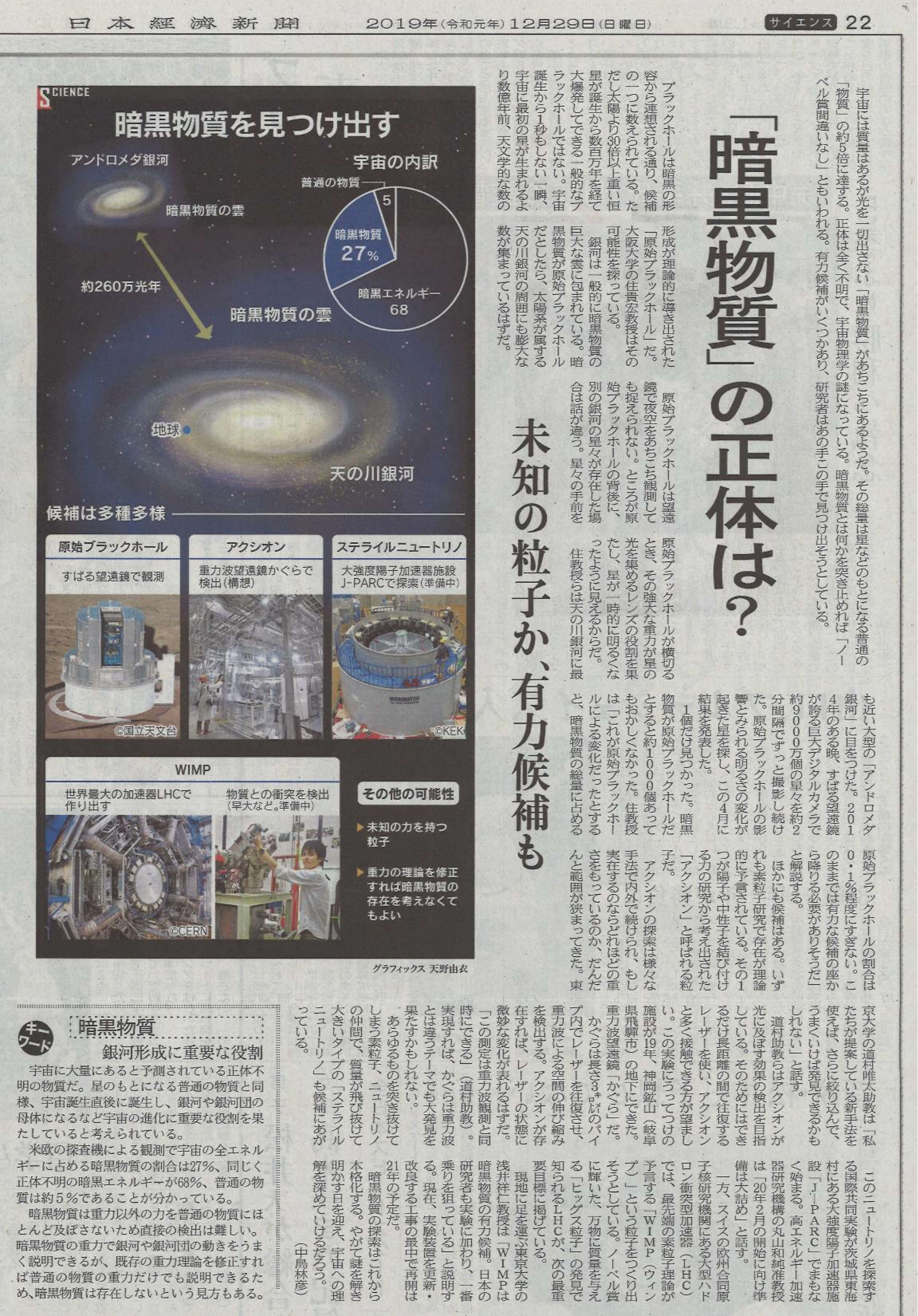
- Converted to g_{B-L} in [arXiv:1908.04797](https://arxiv.org/abs/1908.04797) using $\varepsilon = g_{B-L}$



Thoughts

- **For scalar dark matter search**
  - sensitivity improvement at low frequencies is possible with auxiliary signals, but it seems like it is not feasible to beat EP tests
  - Table-top experiments would be better
  - Physics target from "~10 TeV"
- **For vector dark matter search**
  - considered DM vector "correctly"
  - KAGRA can do unique search with auxiliary signals
  - Large-scale experiments have advantages at low frequencies due to serious vibration isolation (we must achieve the low frequency sensitivity target!!)
  - Physics target from weak gravity conjecture

- Diverse DM models and parameter space; many people discussing almost same ideas with different parameters
- More thinking necessary on data analysis, cross-correlation analysis
  - $T^{-1/2}$ or still $T^{-1/4}$
- Investigations on EP tests also necessary



日本経済新聞　2019年（令和元年）12月29日（日曜日）　サイエンス　22

「暗黒物質」の正体は？

未知の粒子か、有力候補も

宇宙には質量はあるが光を一切出さない「暗黒物質」があちこちにあるようだ。その総量は星などのもとになる普通の「物質」の約5倍に達する。正体は全く不明で、宇宙物理学の謎になっている。暗黒物質とは何かを突き止めれば「ノーベル賞間違いなし」ともいわれる。有力候補がいくつかあり、研究者はあの手この手で見つけ出そうとしている。

ブラックホールは暗黒の形容から連想される通り、候補の一つに数えられている。ただし太陽より30倍以上重い恒星が誕生から数百万年を経て大爆発してできる一般的なブラックホールではない。宇宙誕生から1秒もしない一瞬、宇宙に最初の星が生まれるより数億年前、天文学的な数の形成が理論的に導き出された「原始ブラックホール」だ。大阪大学の住貴宏教授はその可能性を探っている。

銀河は一般的に暗黒物質の巨大な雲に包まれている。暗黒物質が原始ブラックホールだとしたら、太陽系が属する天の川銀河の周囲にも膨大な数が集まっているはずだ。

原始ブラックホールは望遠鏡で夜空をあちこち観測しても捉えられない。ところが原始ブラックホールの背後に、別の銀河の星々が存在した場合は話が違う。星々の手前を原始ブラックホールが横切るとき、その強大な重力が星の光を集めるレンズの役割を果たし、星が一時的に明るくなったように見えるからだ。

住教授らは天の川銀河に最も近い大型の「アンドロメダ銀河」に目をつけた。2014年のある晩、すばる望遠鏡が誇る巨大デジタルカメラで約9000万個の星々を約2分間隔でずっと撮影し続けた。原始ブラックホールの影響とみられる明るさの変化が起きた星を探し、この4月に結果を発表した。

1個だけ見つかった。暗黒物質が原始ブラックホールだとすると約1000個あってもおかしくなかった。住教授は「これが原始ブラックホールによる変化だったとすると、暗黒物質の総量に占める原始ブラックホールの割合は0・1%程度にすぎない。このままでは有力な候補の座から降りる必要がありそうだ」と解説する。

ほかにも候補はある。いずれも素粒子研究で存在が理論的に予言されている。その1つが陽子や中性子を結び付ける力の研究から考え出された「アクシオン」と呼ばれる粒子だ。

アクシオンの探索は様々な手法で内外で続けられ、もし実在するのならどれほどの重さをもっているのか、だんだんと範囲が狭まってきた。東京大学の道村唯太助教は「私たちが提案している新手法を使えば、さらに絞り込んで、うまくいけば発見できるかもしれない」と話す。

道村助教らはアクシオンが光に及ぼす効果の検出を目指している。そのためにはできるだけ長距離の間で往復するレーザーを使い、アクシオンと多く接触できる方が望ましい。この実験にうってつけの施設が19年、神岡鉱山（岐阜県飛騨市）の地下にできた。重力波望遠鏡「かぐら」だ。

かぐらは長さ3キロメートルのパイプ内でレーザーを往復させ、重力波による空間の伸び縮みを検出する。アクシオンが存在すれば、レーザーの状態に微妙な変化が表れるはずだ。「この測定は重力波観測と同時にできる」（道村助教）。実現すれば、かぐらは重力波とは違うテーマでも大発見を果たすかもしれない。

あらゆるものを突き抜けてしまう素粒子、ニュートリノの仲間で、質量が飛び抜けて大きいタイプの「ステライルニュートリノ」も候補にあがっている。

このニュートリノを探索する国際共同実験が茨城県東海村にある大強度陽子加速器施設「J－PARC」でまもなく始まる。高エネルギー加速器研究機構の丸山和純准教授は「20年2月の開始に向け準備は大詰め」と話す。

一方、スイスの欧州合同原子核研究機関にある大型ハドロン衝突型加速器（LHC）では、最先端の素粒子理論が予言する「WIMP（ウィンプ）」という粒子をつくり出そうとしている。ノーベル賞に輝いた、万物に質量を与える「ヒッグス粒子」の発見で知られるLHCが、次の最重要目標に掲げている。

現地に足を運ぶ東京大学の浅井祥仁教授は「WIMPは暗黒物質の有力候補。日本の研究者も実験に加わり、一番乗りを狙っている」と説明する。現在、実験装置を更新・改良する工事の最中で再開は21年の予定だ。

暗黒物質の探索はこれから本格化する。やがて謎を解き明かす日を迎え、宇宙への理解を深めていけるだろう。

（中島林彦）

SCIENCE

暗黒物質を見つけ出す

アンドロメダ銀河
暗黒物質の雲
約260万光年
暗黒物質の雲
地球
天の川銀河

宇宙の内訳
普通の物質 5
暗黒物質 27%
暗黒エネルギー 68

候補は多種多様

原始ブラックホール
すばる望遠鏡で観測
©国立天文台

アクシオン
重力波望遠鏡かぐらで検出（構想）

ステライルニュートリノ
大強度陽子加速器施設J-PARCで探索（準備中）
©KEK

WIMP
世界最大の加速器LHCで作り出す
©CERN
物質との衝突を検出（早大など。準備中）

その他の可能性
▶未知の力を持つ粒子
▶重力の理論を修正すれば暗黒物質の存在を考えなくてもよい

グラフィックス 天野由衣

キーワード

暗黒物質

銀河形成に重要な役割

宇宙に大量にあると予測されている正体不明の物質だ。星のもとになる普通の物質と同様、宇宙誕生直後に誕生し、銀河や銀河団の母体になるなど宇宙の進化に重要な役割を果たしていると考えられている。

米欧の探査機による観測で宇宙の全エネルギーに占める暗黒物質の割合は27%、同じく正体不明の暗黒エネルギーが68%、普通の物質は約5%であることが分かっている。

暗黒物質は重力以外の力を普通の物質にほとんど及ぼさないため直接の検出は難しい。暗黒物質の重力で銀河や銀河団の動きをうまく説明できるが、既存の重力理論を修正すれば普通の物質の重力だけでも説明できるため、暗黒物質は存在しないという見方もある。

Summary

- Dark matter search is another way of probing gravitational physics
- Laser interferometers are attractive tools to search for ultralight dark matter
- Table-top experiments with new ideas can compete with large scale projects
- KAGRA can do unique searches because of the use of sapphire mirrors