Ultra-light dark matter detection with gravitational wave interferometers

F. Urban
CEICO, Institute of Physics of the Czech Academy of Sciences, Prague

Axions in Stockholm 2025, Nordita, Stockholm – Sweden
July 11, 2025

Co-funded by the European Union
MINISTRY OF EDUCATION, YOUTH AND SPORTS

:: outline ::

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- Dark Matter

:: outline ::

Dark Matter ...or modified gravity?

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Ultra-light dark matter primer

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When ULDM looks like GWs

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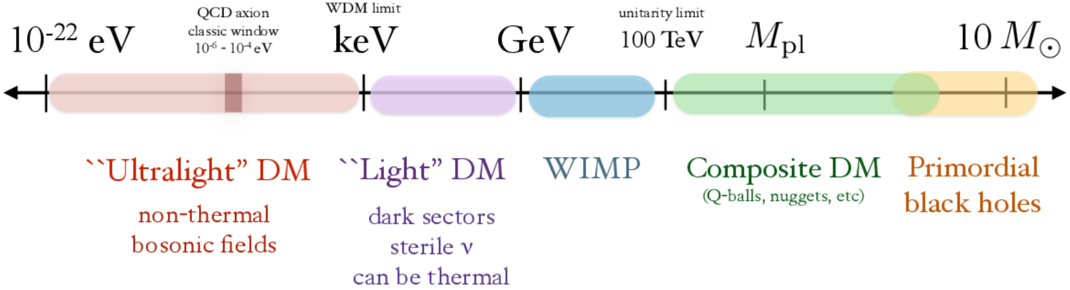
Detection strategies

with J M Armaleo, D López Nacir, P C Moreiro Delgado, O J Piccinni JCAP2021, in progress

dark matter

Mass scale of dark matter

(not to scale)



:: ultra-light ::

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Dynamics of the zero mode: $\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$

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6. This is true regardless of spin because anisotropies average out

:: variety ::

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AIs Blas+ arXiv2025 and LSDs Danieli, Moreiro Delgado and FU ongoing bigravity

:: bimetric theory ::

$S =$

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$$S = \int \mathrm{d}^4 x \Big[$$

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$$S = \int \mathrm{d}^4 x \Big[\sqrt{g}\, m_g^2 R(g)$$

- $R(g)$ is the **Ricci** for the metric $g_{\mu\nu}$, with strength m_g

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Massless field $G_{\mu\nu}$,

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Theory Hassan and Rosen 2012 ◇ DM Babichev+ w/FU 2016x2, Marzola, Raidal and FU 2017 *and many more*

:: Lorentz violation ::

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with coupling to the SM

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Theory Dubovsky 2004, Rubakov & Tinyakov 2008 ◇ in AIs Blas, Carlton & McCabe 2025

:: perturb ::

Each dark matter field wave is described by

$$\boxed{M_{ij}^a(t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m}\cos\left[m\left(1+\frac{v_a^2}{2}\right)t + \vec{k}_a\cdot\vec{x} + \Upsilon_a\right]\varepsilon_{ij}^a(\mathrm{r})}$$

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from which one finds the curvature perturbations

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This looks like a continuous gravitational wave

gravitational waves

:: continuouſ gravitational waveſ ::

:: continuous gravitational waves ::

Persistent, quasi-monochromatic

The coherence time is $t_{\mathrm{coh}} := 4\pi/mv^2 = 2/fv^2 \sim 10^6/f$

:: continuous gravitational waves ::

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  Ignore the gradients within $\lambda_{\mathrm{dB}} := 2\pi/mv = 1/fv \sim 10^3/f$

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Thanks to a longer integration time and $h_0 \propto T_{\mathrm{obs}}^{-1/2} \to T_{\mathrm{obs}}^{-1/4}\, T_{\mathrm{chunk}}^{-1/4}$

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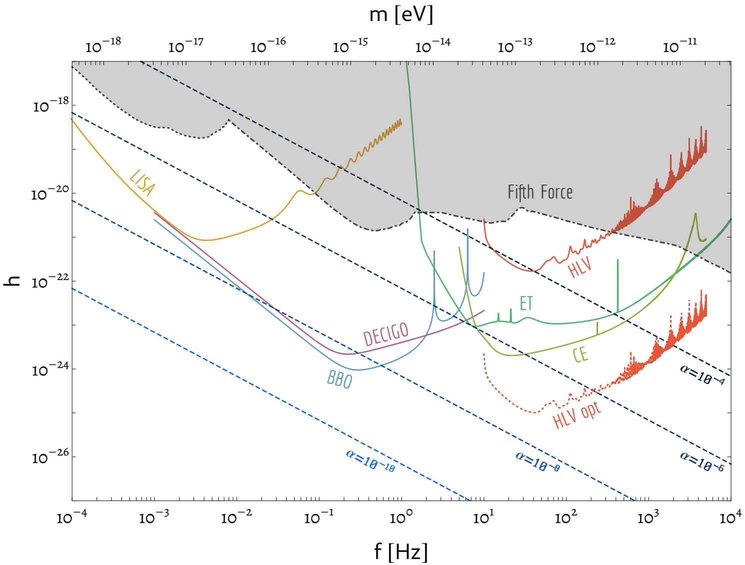
There are three new polarisations!

$$\boldsymbol{\varepsilon}^{(\pm 2)} = \frac{1}{2}\begin{pmatrix} 1 & \pm i & 0 \\ \pm i & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \boldsymbol{\varepsilon}^{(\pm 1)} = \frac{1}{2}\begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & \pm i \\ 1 & \pm i & 0 \end{pmatrix} \qquad \boldsymbol{\varepsilon}^{(0)} = \frac{1}{\sqrt{6}}\begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 2 \end{pmatrix}$$

results



m [eV]
10^{-18}
10^{-17}
10^{-16}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
h
LISA
Fifth Force
HLV
ET
DECIGO
CE
BBO
HLV opt
$\alpha=10^{-4}$
$\alpha=10^{-6}$
$\alpha=10^{-8}$
$\alpha=10^{-10}$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
f [Hz]

:: pipeline ::

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          - Count the peaks above a threshold $\theta_{\text{thr}} = 2.5$

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      - Make FFTs of the data with length given by v_{esc} (about 10^5 s)
        - Make the frequency/time peakmaps
          - Count the peaks above a threshold $\theta_{\mathrm{thr}} = 2.5$
            - Pick a detection critical ratio threshold

:: pipeline ::

- Generate a stack of 1000 ULDM waves
  - Add noises from LIGO/Virgo data
    - Build BSDs in 10 Hz frequency bands / 1 month long
      - Make FFTs of the data with length given by v_{esc} (about 10^5 s)
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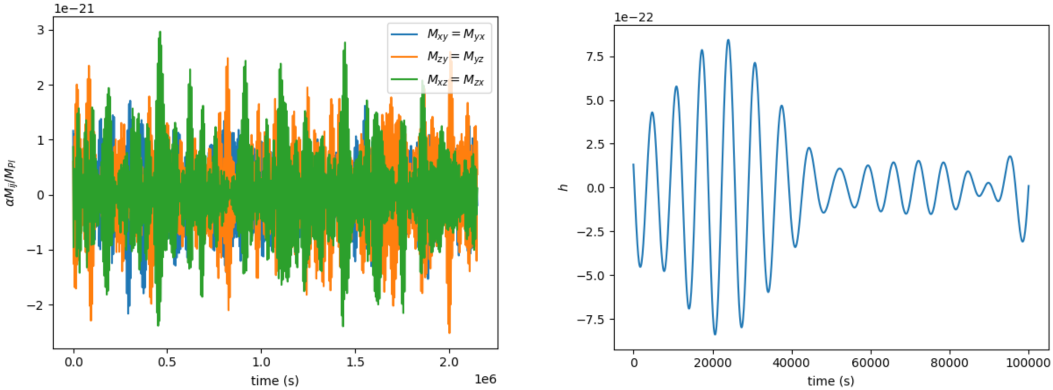
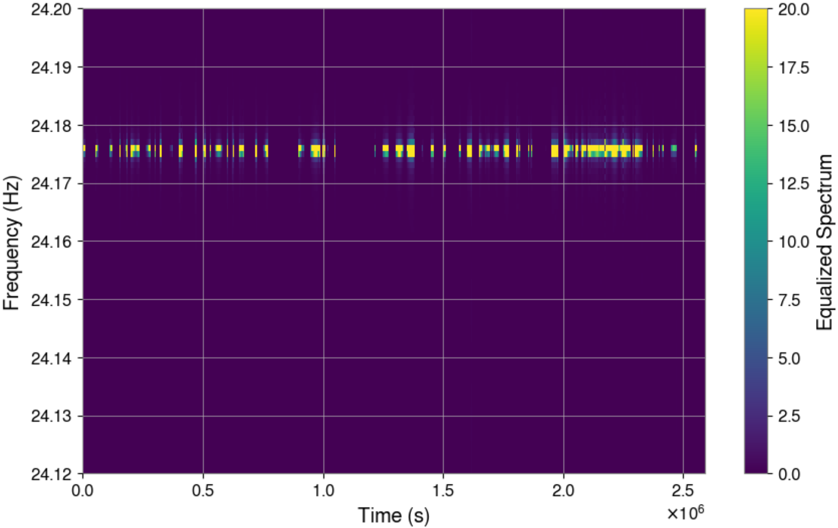
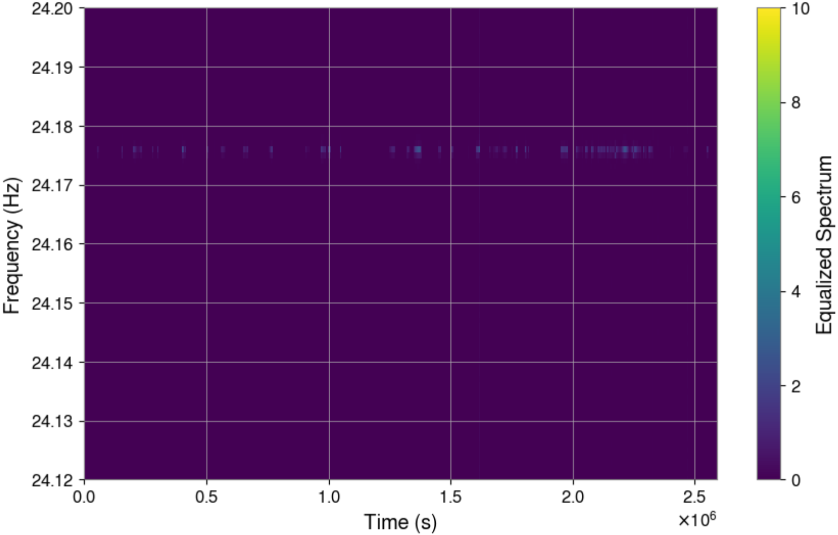
$$\boxed{h_{opt} \approx \frac{1.02}{N^{1/4}\theta_{thr}^{1/2}} \sqrt{\frac{S_n(f)}{T_{FFT,max}}} \left(\frac{p_0(1-p_0)}{p_1^2}\right)^{1/4} \sqrt{CR_{thr} - \sqrt{2}\mathrm{erfc}^{-1}(2\Gamma)}}$$

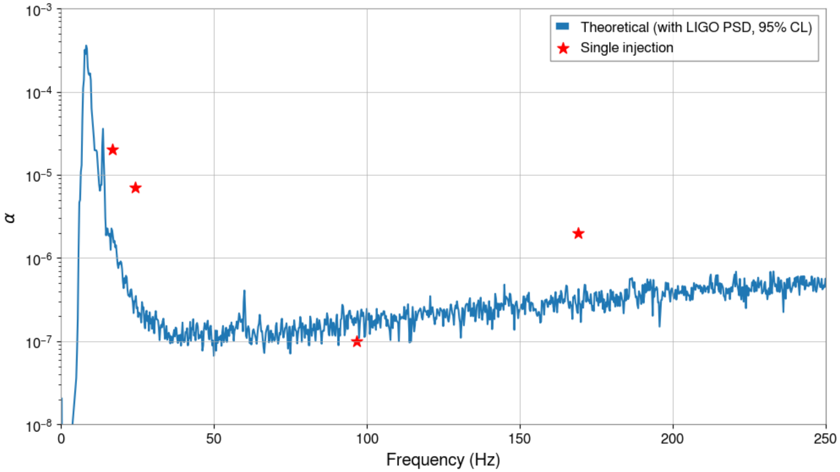


1e−21
$M_{xy} = M_{yx}$
$M_{zy} = M_{yz}$
$M_{xz} = M_{zx}$
$\alpha M_{ij}/M_{Pl}$
time (s)
1e6
1e−22
h
time (s)



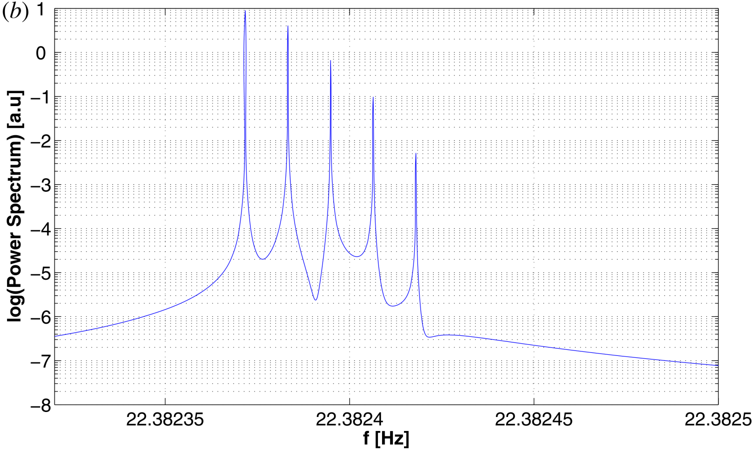
24.20
24.19
24.18
24.17
24.16
24.15
24.14
24.13
24.12
Frequency (Hz)
0.0
0.5
1.0
1.5
2.0
2.5
$\times 10^6$
Time (s)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
Equalized Spectrum


24.20
24.19
24.18
24.17
24.16
24.15
24.14
24.13
24.12
Frequency (Hz)
0.0
0.5
1.0
1.5
2.0
2.5
×10^6
Time (s)
10
8
6
4
2
0
Equalized Spectrum



Theoretical (with LIGO PSD, 95% CL)
Single injection
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
α
0
50
100
150
200
250
Frequency (Hz)

how to tell?


(b)
1
0
−1
−2
−3
−4
−5
−6
−7
−8
log(Power Spectrum) [a.u]
22.38235
22.3824
22.38245
22.3825
f [Hz]

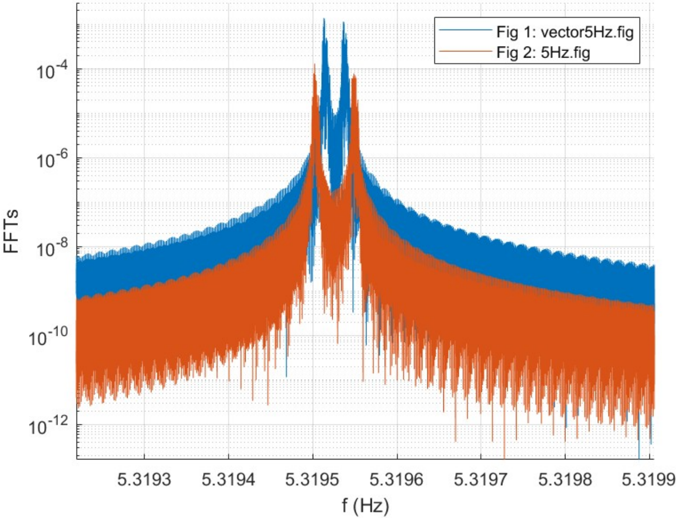


Fig 1: vector5Hz.fig
Fig 2: 5Hz.fig
FFTs
f (Hz)
10^-4
10^-6
10^-8
10^-10
10^-12
5.3193
5.3194
5.3195
5.3196
5.3197
5.3198
5.3199

∷ ſummary ∷

ſummary

Dark Matter remains a **mystery** in cosmology

:: ſummary ::

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Watch out for **actual data** analysis

with JM Armaleo, D López Nacir, P C Moreiro Delgado, O J Piccinni JCAP2021 and in progress

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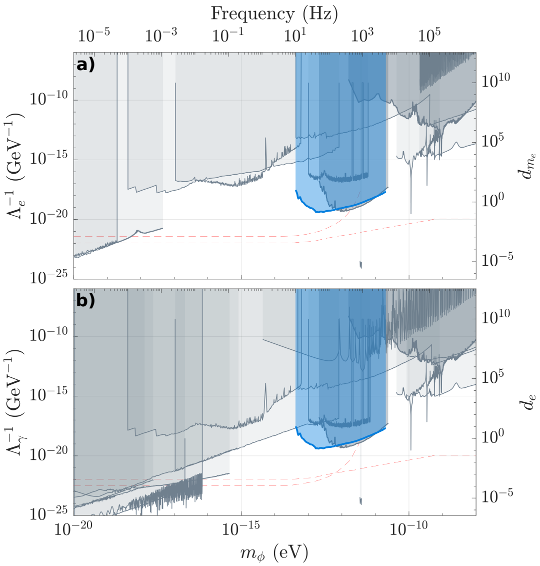
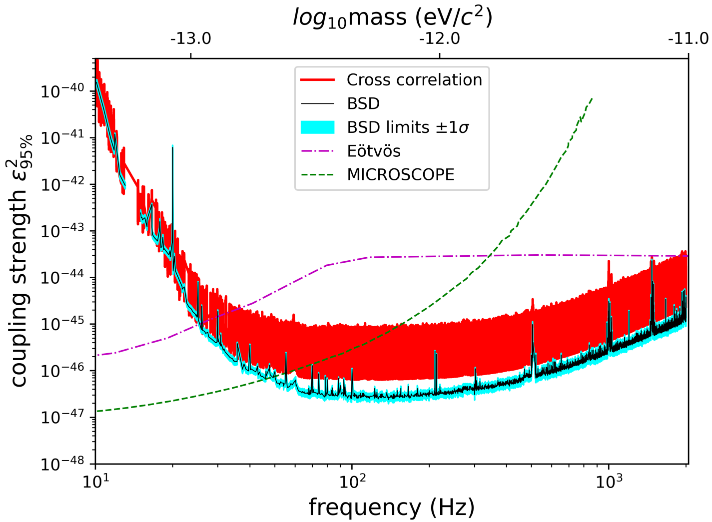
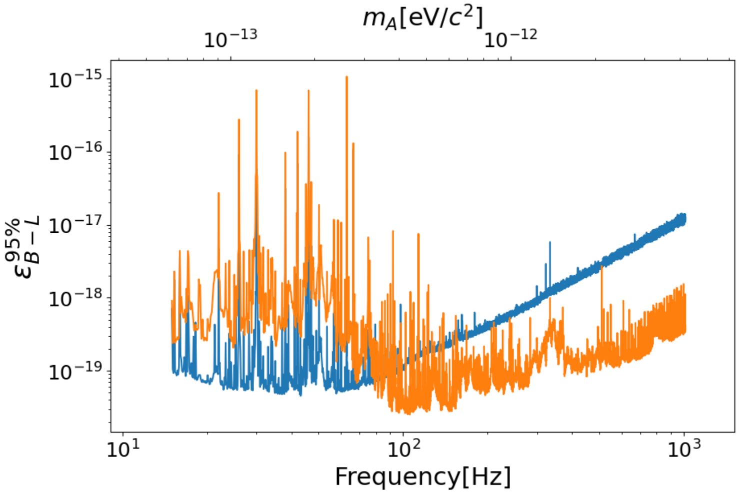


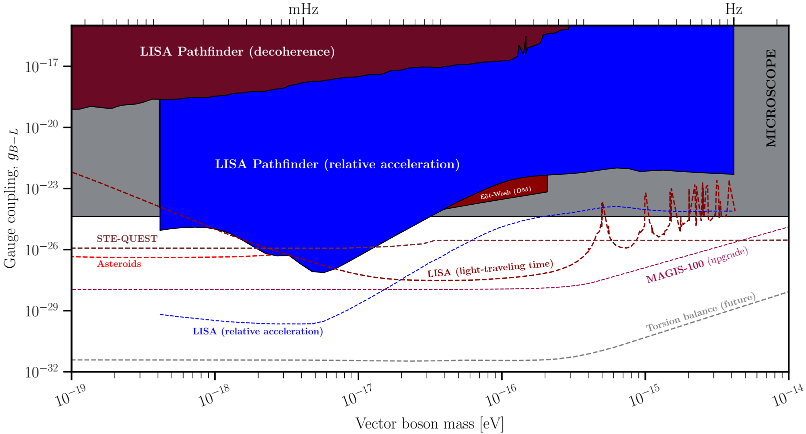
Frequency (Hz)
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
a)
b)
Λ_e^{-1} (GeV^{-1})
Λ_γ^{-1} (GeV^{-1})
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{10}
10^{5}
10^{0}
10^{-5}
d_{m_e}
d_e
10^{-20}
10^{-15}
10^{-10}
m_ϕ (eV)



log_{10}mass (eV/c^2)
-13.0
-12.0
-11.0
coupling strength $\varepsilon^2_{95\%}$
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^1
10^2
10^3
frequency (Hz)
Cross correlation
BSD
BSD limits ±1σ
Eötvös
MICROSCOPE



$m_A[\mathrm{eV}/c^2]$
10^{-13}
10^{-12}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\varepsilon^{95\%}_{B-L}$
10^{1}
10^{2}
10^{3}
Frequency[Hz]


mHz
Hz
LISA Pathfinder (decoherence)
LISA Pathfinder (relative acceleration)
MICROSCOPE
Eöt-Wash (DM)
STE-QUEST
Asteroids
LISA (light-traveling time)
MAGIS-100 (upgrade)
Torsion balance (future)
LISA (relative acceleration)
Gauge coupling, g_{B-L}
10^{-17}
10^{-20}
10^{-23}
10^{-26}
10^{-29}
10^{-32}
10^{-19}
10^{-18}
10^{-17}
10^{-16}
10^{-15}
10^{-14}
Vector boson mass [eV]