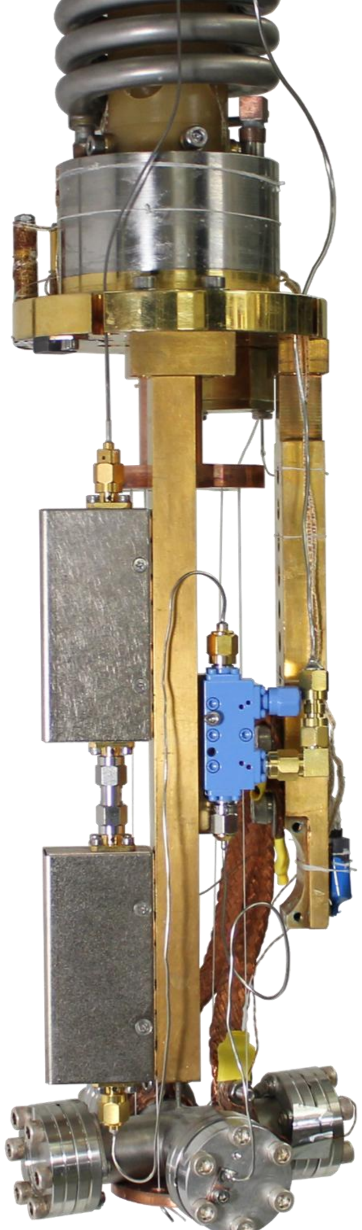


Listening to the Sound of Gravitational Waves and Dark Matter with Superfluid Helium

SNOLAB

Future Projects Workshop

Marvin Hirschel

John Davis Lab

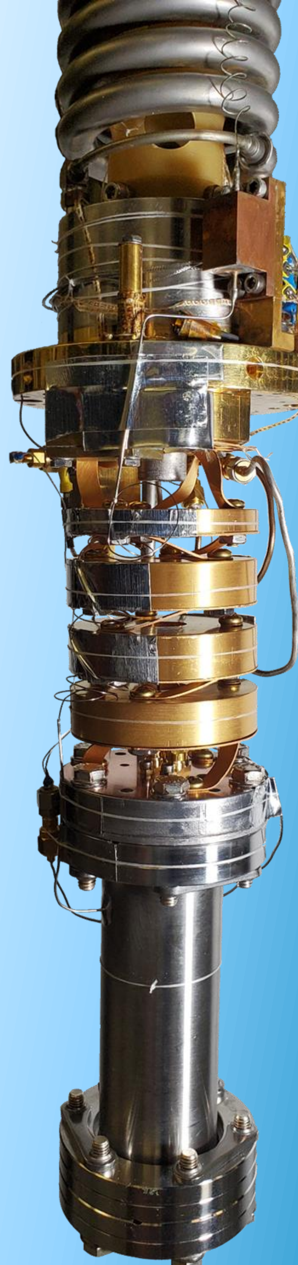
University of Alberta

UNIVERSITY OF ALBERTA

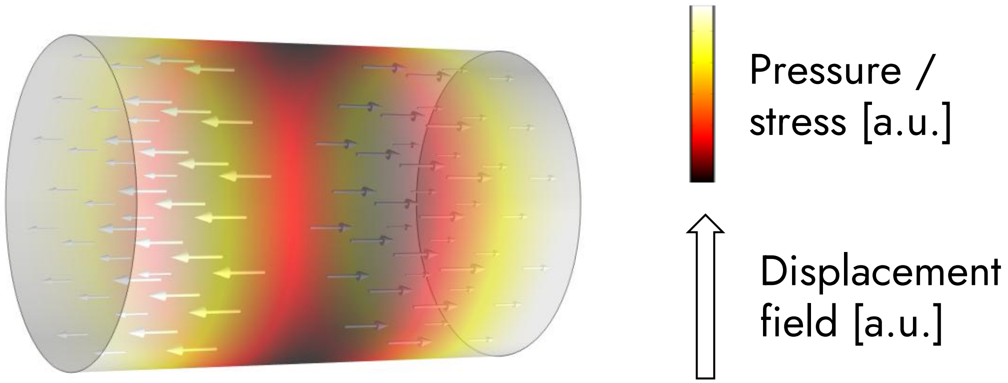
2 4.0026

HeLIOS

Helium UltraLIght Dark Matter Optomechanical Sensor



Resonant Mass Detectors

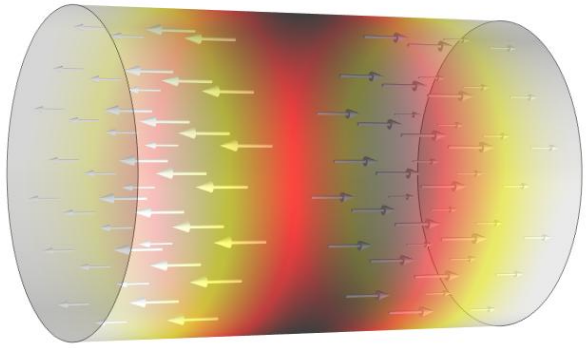


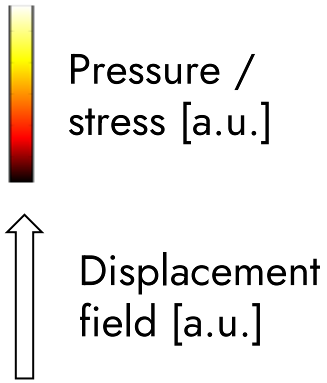
[1]

1960s: Weber Bar (Joseph Weber)

[1] S. Gottardo, *Substantia* 1, 61-67 (2017).

Resonant Mass Detectors





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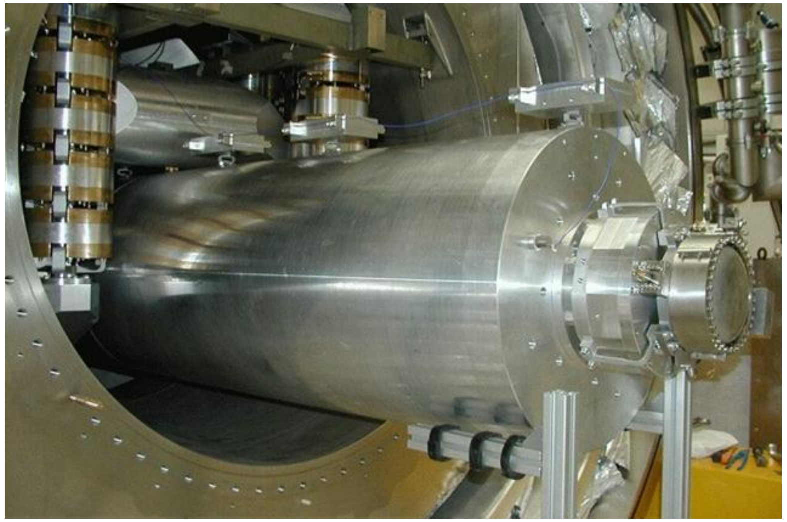
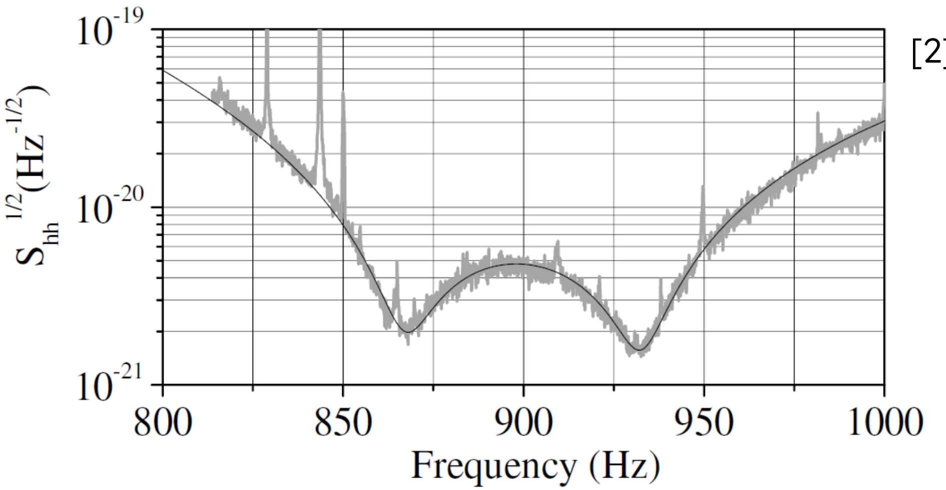


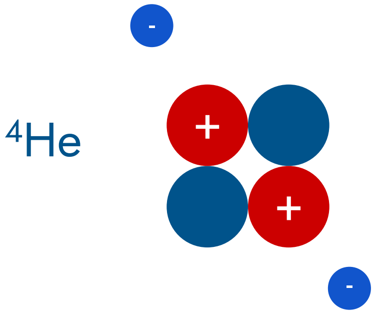


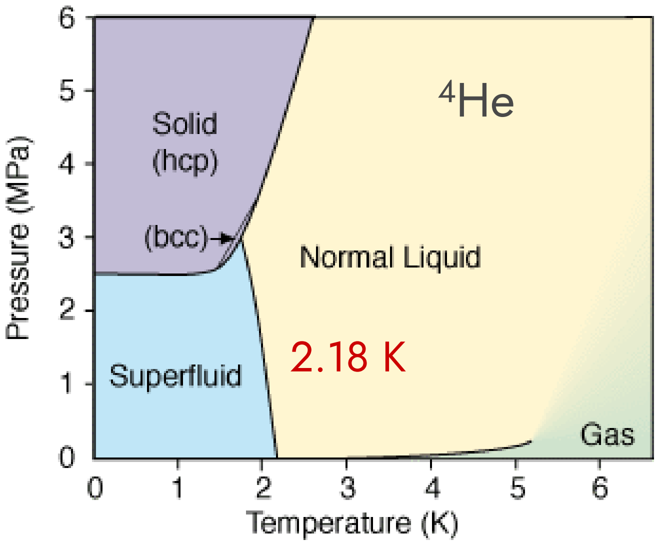
[2]

1997-2017: AURIGA

[1] S. Gottardo, *Substantia* 1, 61-67 (2017).
[2] L. Baggio, M. Bignotto, M. Bonaldi, et al., *PRL* 94, 241101 (2005).

Superfluid Helium as Ideal Acoustic Medium

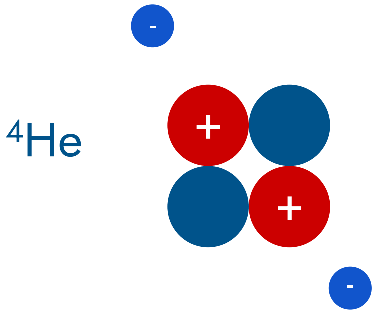


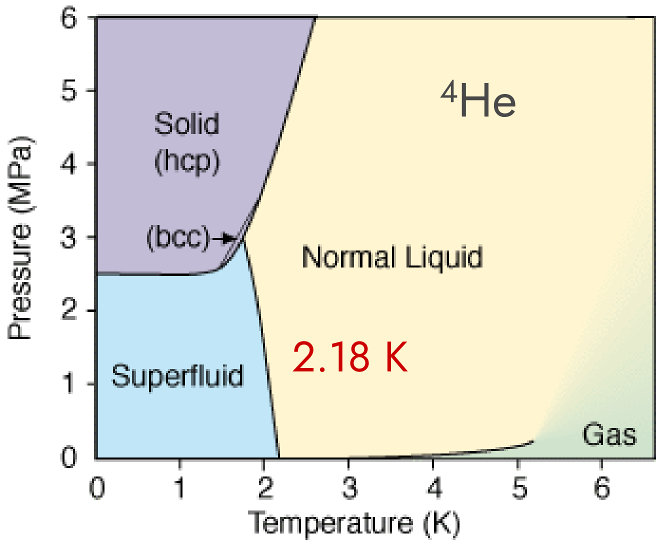


[1]

[1] Encyclopedia of Condensed Matter Physics 3, 51-67 (2024).

Superfluid Helium as Ideal Acoustic Medium





[1]

- ✓ He only liquid at LT
  - ➢ No impurities / defects (except ^{3}He)
  - ➢ Homogeneous & isotropic

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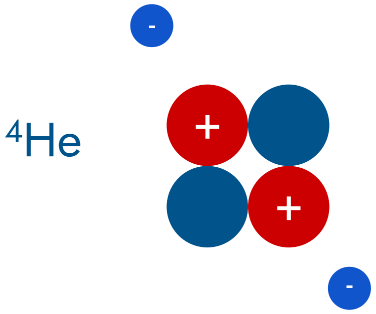
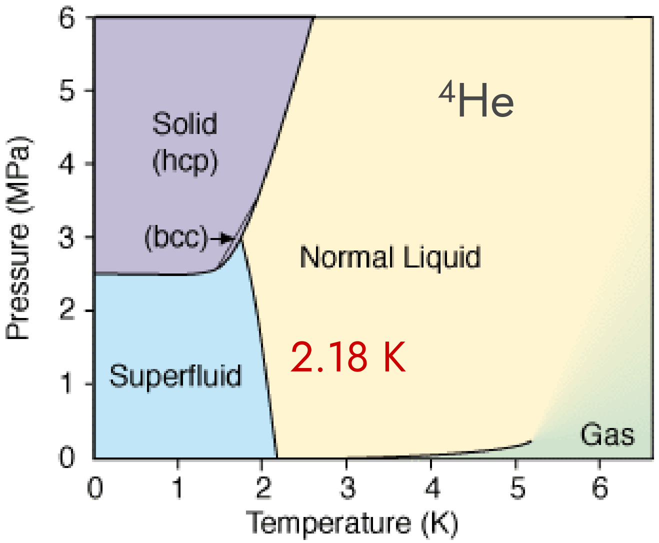
Superfluid Helium as Ideal Acoustic Medium





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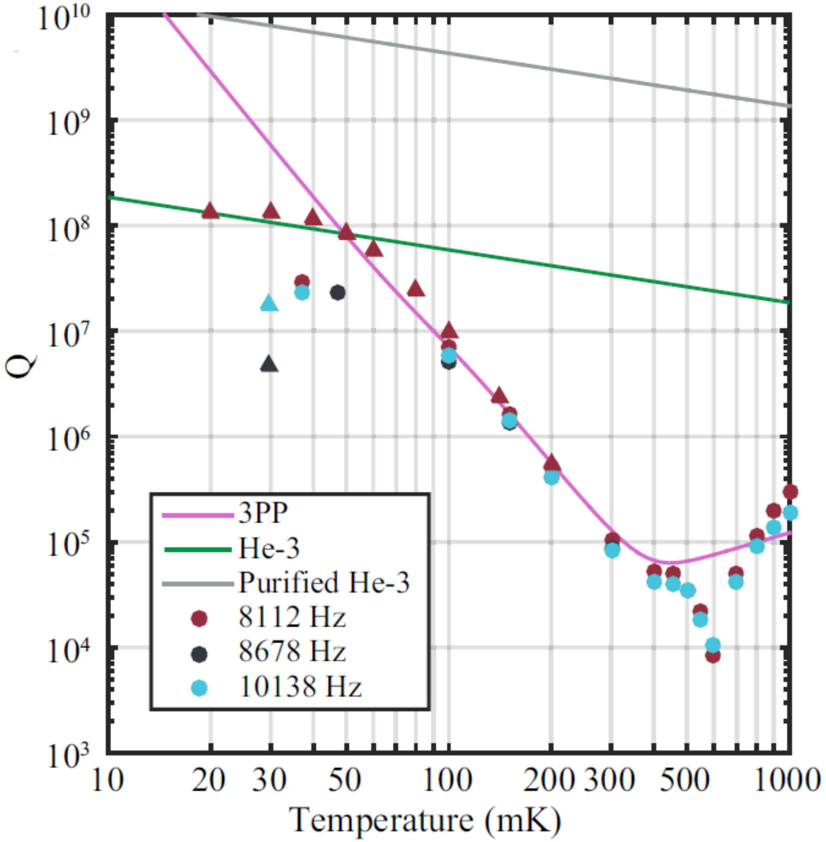

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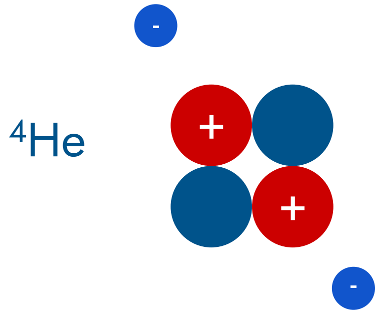
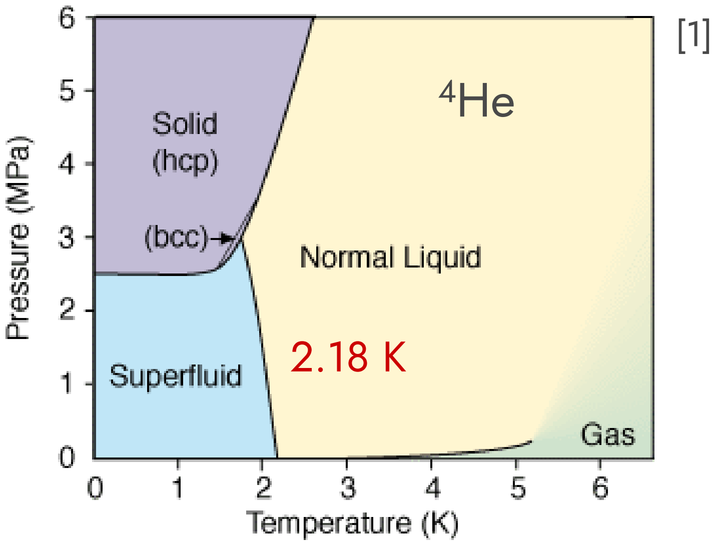
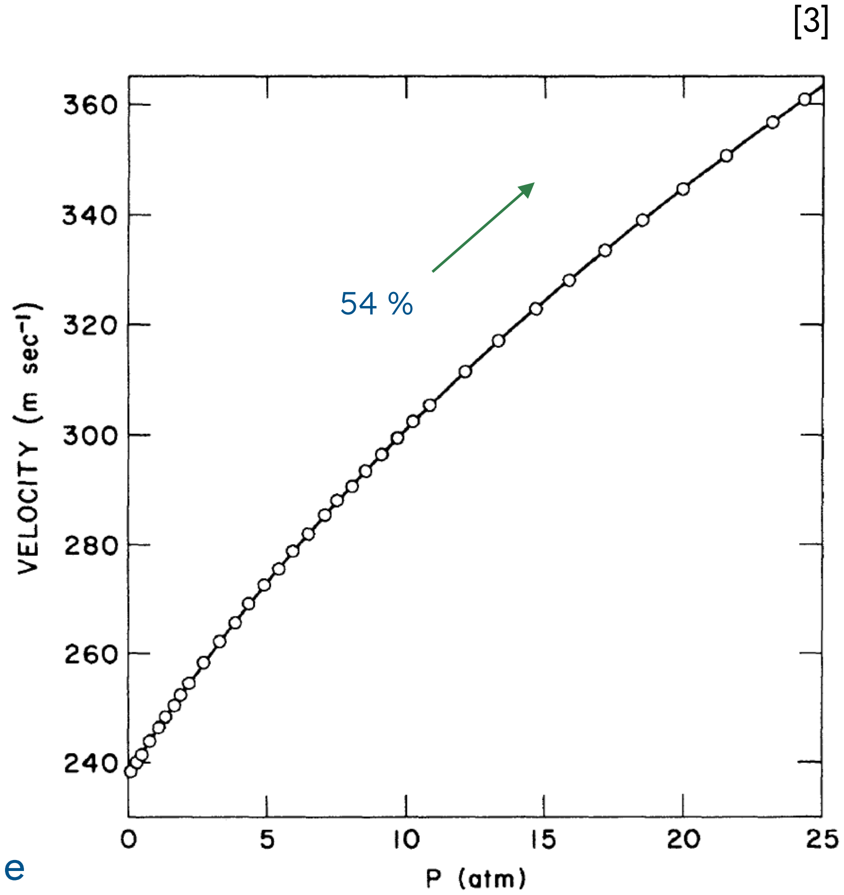
- ✓ He only liquid at LT
  - ➢ No impurities / defects (except ^{3}He)
  - ➢ Homogeneous & isotropic
- ✓ Zero viscosity
  - ➢ Low mechanical losses

[1] Encyclopedia of Condensed Matter Physics 3, 51-67 (2024).
[2] L. A. De Lorenzo & K. C. Schwab, *J. Low Temp. Phys.* 186, 233 (2016).

Superfluid Helium as Ideal Acoustic Medium



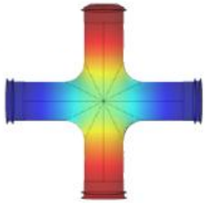


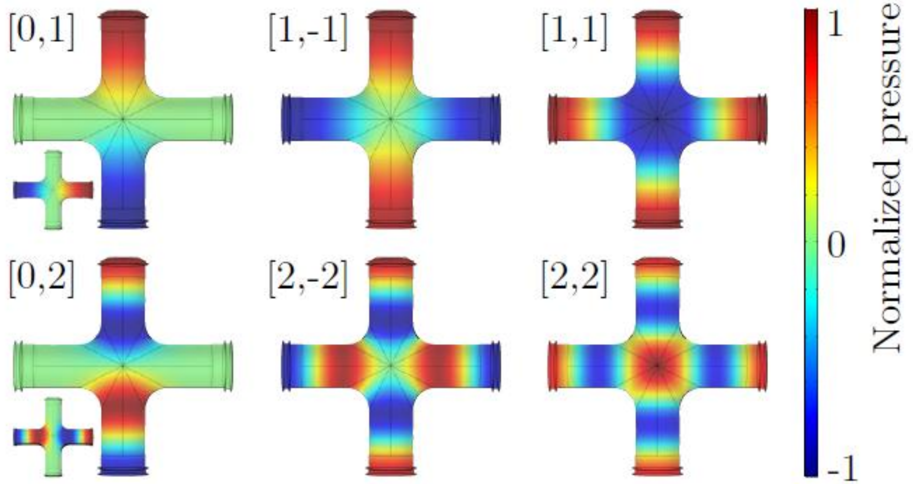


- ✓ He only liquid at LT
  - ➢ No impurities / defects (except ^{3}He)
  - ➢ Homogeneous & isotropic
- ✓ Zero viscosity
  - ➢ Low mechanical losses
- ✓ Can be pressurized
  - ➢ Acoustic frequency tunable

[1] Encyclopedia of Condensed Matter Physics 3, 51-67 (2024).
[3] B. M. Abraham, Y. Eckstein. J. B. Ketterson et al., PRA 1, 250 (1970).

Superfluid Gravitational Wave Detector





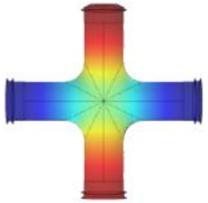
[1]

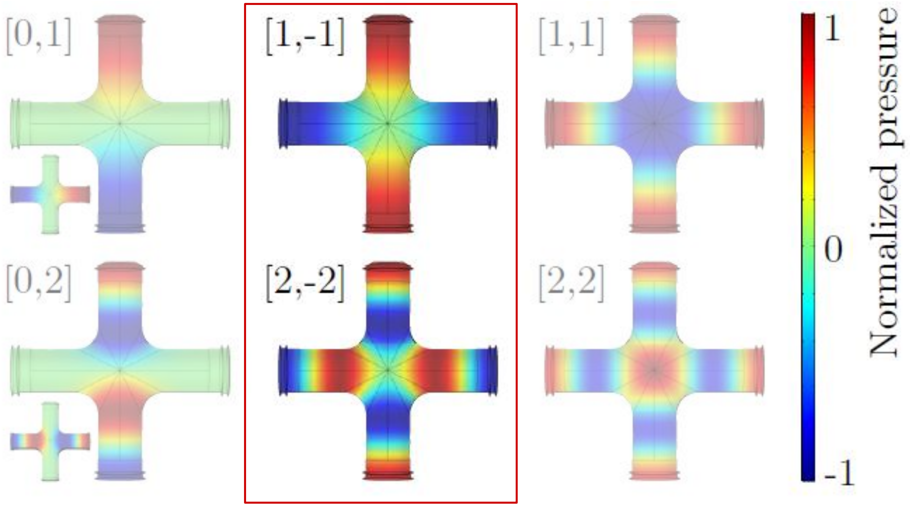
Mode	f_{m} [Hz]	μ/M	A_G/A
[0,1]	1618	0.16	0
[1,-1]	1769	0.19	0.47
[1,1]	3179	0.47	0.21
[0,2]	4692	0.26	0
[2,-2]	5253	0.21	0.27

Mode	f_{m} [Hz]	μ/M	A_G/A
[2,2]	6381	0.41	0.04
[3,-3]	8619	0.27	0.07
[4,-4]	11800	0.15	0.03
[5,-5]	14770	0.12	0.02

[1] V. Vadakkumbatt, M. Hirschel, J. Manley, T. J. Clark, S. Singh & J. P. Davis, PRD 104, 082001 (2021).

Superfluid Gravitational Wave Detector





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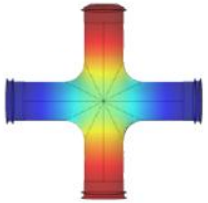

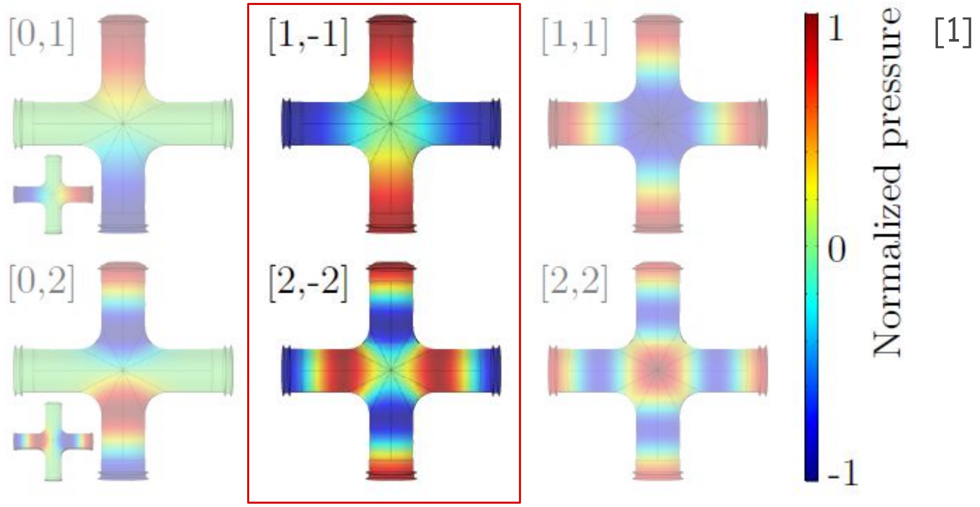

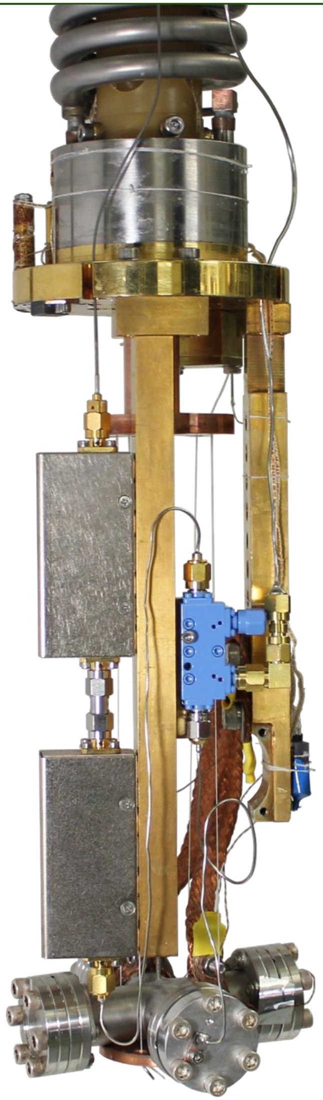

16 mK

30 ml

Mode	f_m [Hz]	μ/M	A_G/A
[0,1]	1618	0.16	0
[1,-1]	1769	0.19	0.47
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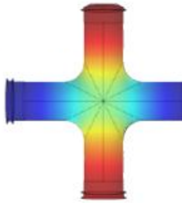

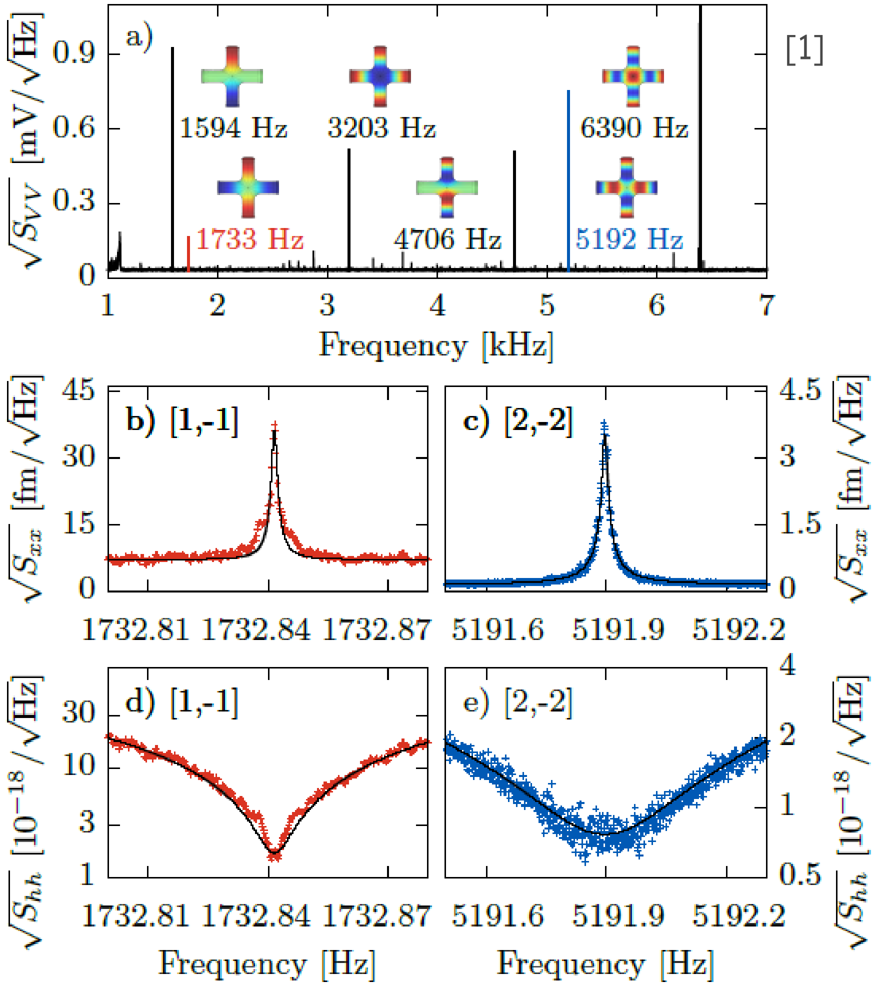

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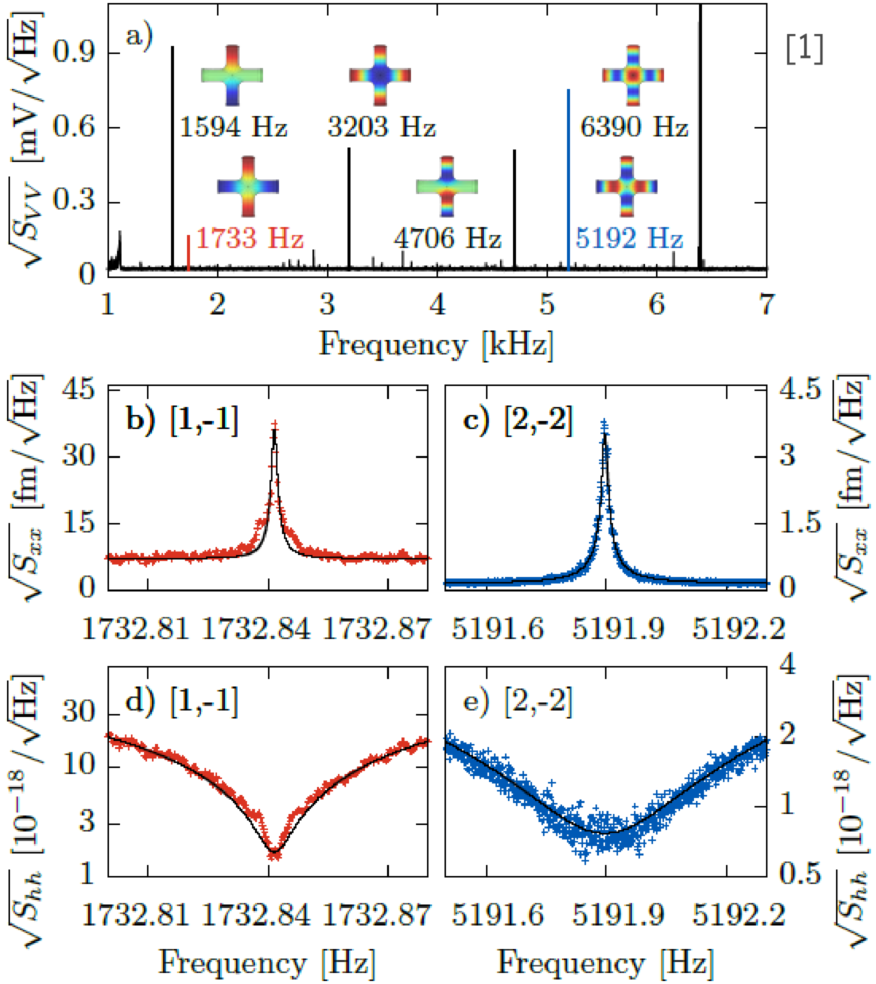

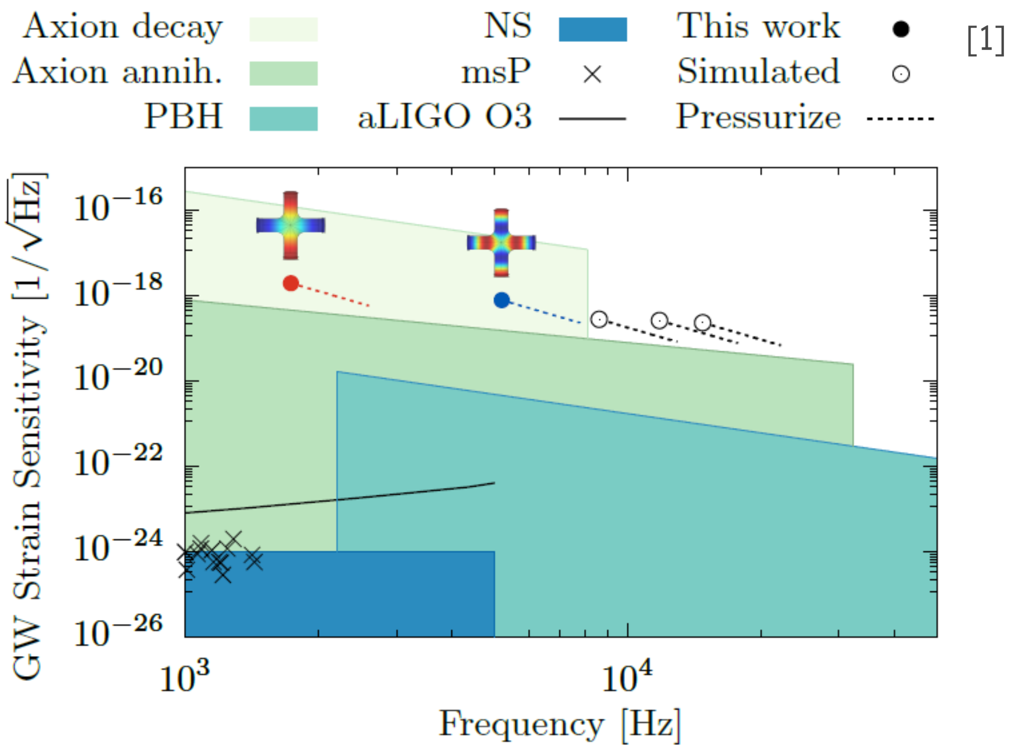

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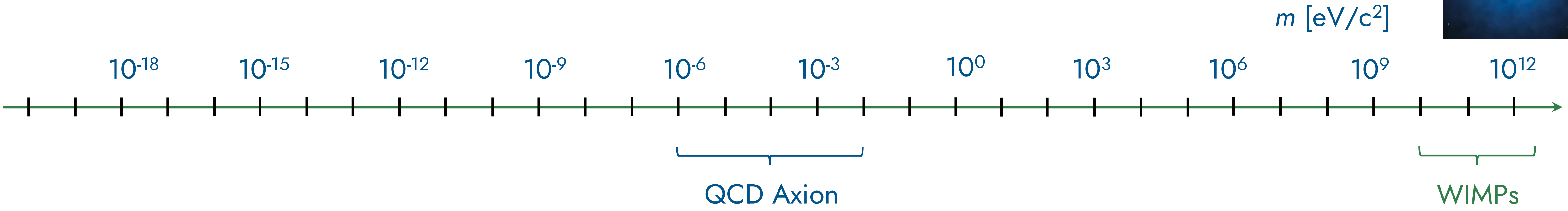
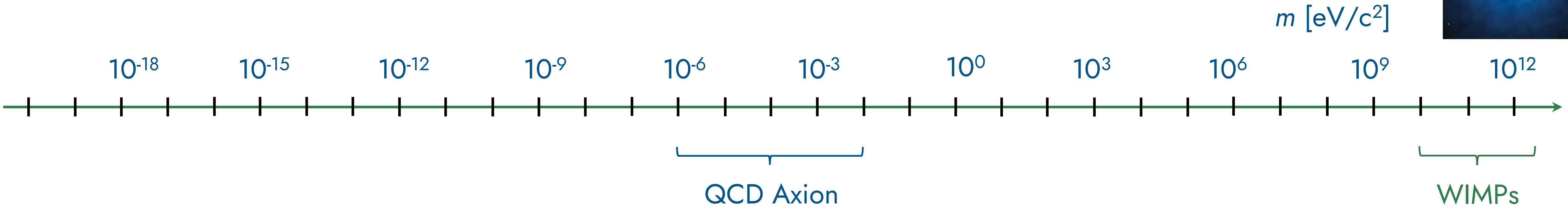
Ultralight Dark Matter (UDM)



Ultralight Dark Matter (UDM)



$$\varrho = 0.4 \ \mathrm{GeV/cm^3}$$

Ultralight Dark Matter (UDM)

m [eV/c^2]

10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12}

QCD Axion

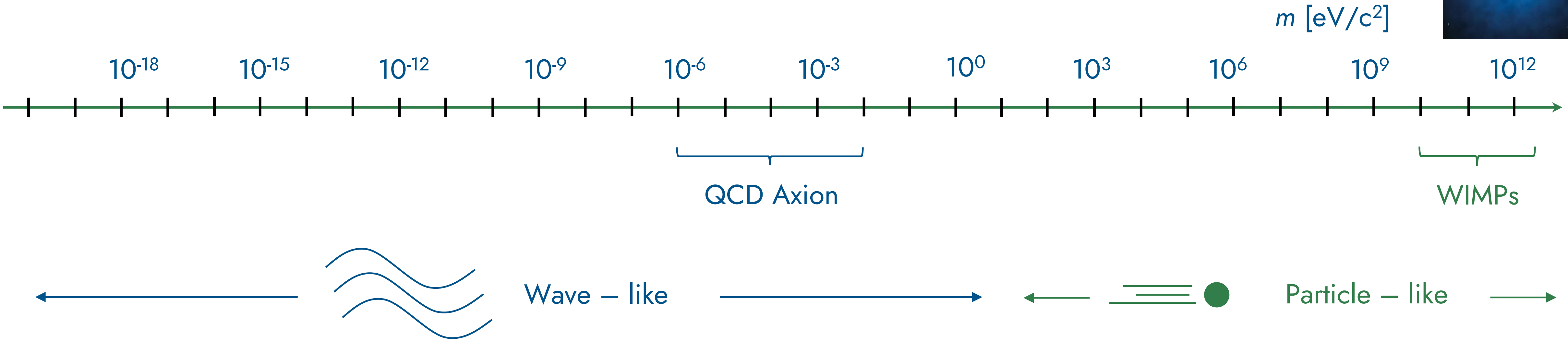
WIMPs

Wave – like

$\varrho = 0.4 \ \mathrm{GeV/cm^3}$

$n\lambda^3 > 1$

Ultralight Dark Matter (UDM)

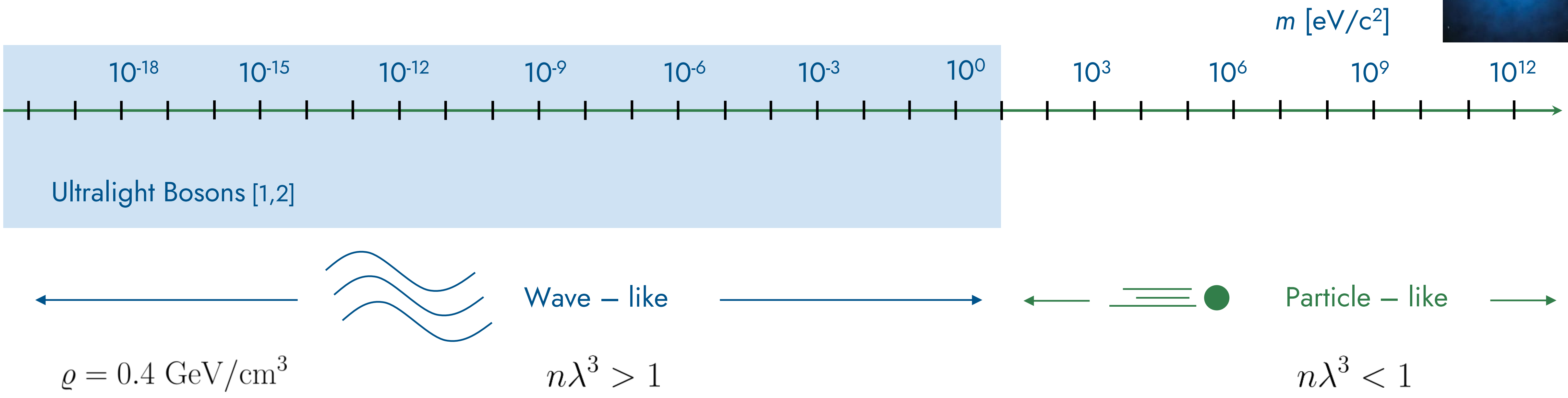


$\varrho = 0.4\ \mathrm{GeV/cm^3}$

$n\lambda^3 > 1$

$n\lambda^3 < 1$

Ultralight Dark Matter (UDM)



[1] Snowmass 2021 "New Horizons", D. Antypas et al., *arXiv*, 2203.14915 (2022).
[2] A. Derevianko, *PRA* 97, 042506 (2018).

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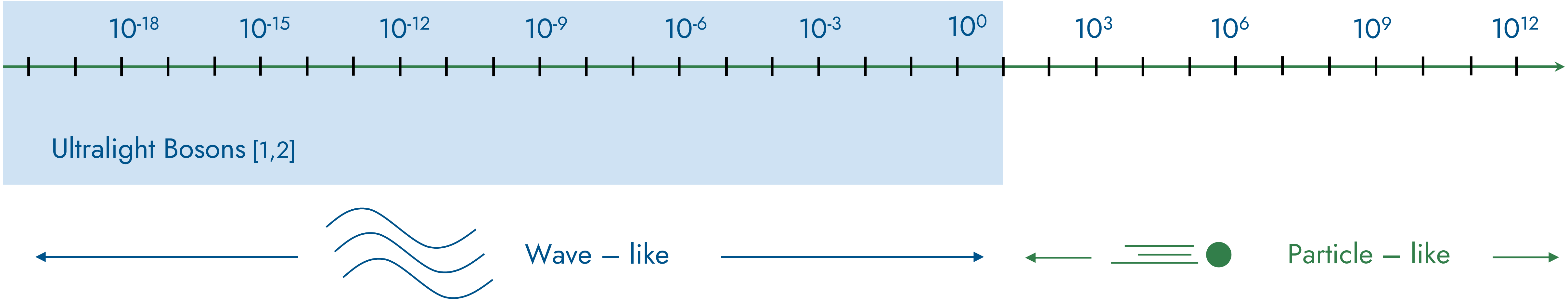

$$\varrho = 0.4 \ \mathrm{GeV/cm^3}$$

$$n\lambda^3 > 1$$

$$n\lambda^3 < 1$$

Classical field [1,2]

$$\Phi(\mathbf{r}, t) \approx \frac{\hbar\sqrt{2\varrho}}{mc} \cos(\omega t - \mathbf{k} \cdot \mathbf{r})$$

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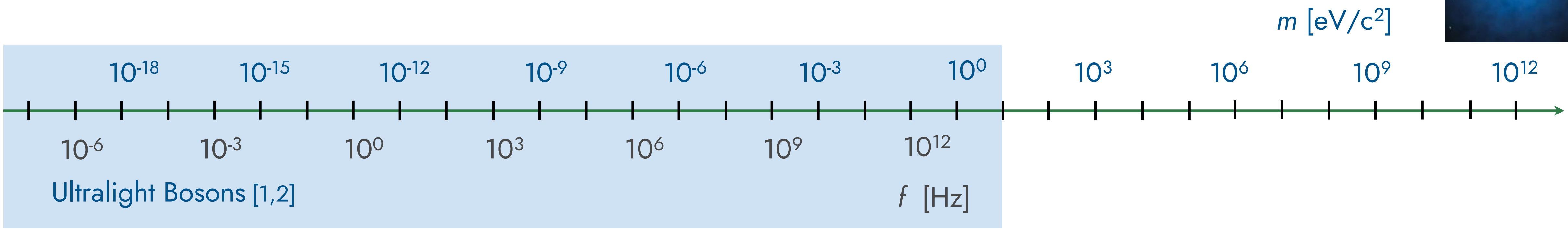

Wave – like

Particle – like

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Classical field [1,2]

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Frequency [1,2]

$$\omega = \frac{mc^2}{\hbar}$$

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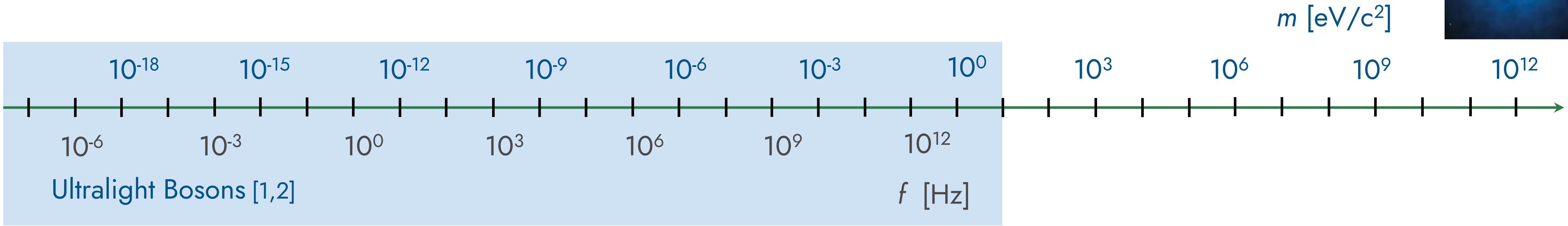
Ultralight Dark Matter (UDM)



Wave – like

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$\varrho = 0.4\ \mathrm{GeV/cm^3}$

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Classical field [1,2]

$$\Phi(\mathbf{r}, t) \approx \frac{\hbar\sqrt{2\varrho}}{mc} \cos(\omega t - \underbrace{\cancel{\mathbf{k}\cdot\mathbf{r}}}_{\text{const.}})$$

Coherence time [2]

$$\tau \approx \frac{10^6}{\omega} \longrightarrow \frac{\Delta\omega}{\omega} \approx 10^{-6}$$

Frequency [1,2]

$$\omega = \frac{mc^2}{\hbar}$$

Coherence length [2]

$$\lambda = 3 \times 10^5\ \mathrm{km} \left(\frac{1\ \mathrm{kHz}}{f}\right)$$

[1] Snowmass 2021 "New Horizons", D. Antypas et al., *arXiv*, 2203.14915 (2022).

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Mechanical Signature of UDM

Scalar Boson $S = 0$

Vector Boson $S = 1$

Mechanical Signature of UDM

Scalar Boson $S = 0$

Scalar field
Coupling to e^- / γ

$$\Phi(t) \approx \Phi_0 \cos(\omega t)$$

Vector Boson $S = 1$

Mechanical Signature of UDM

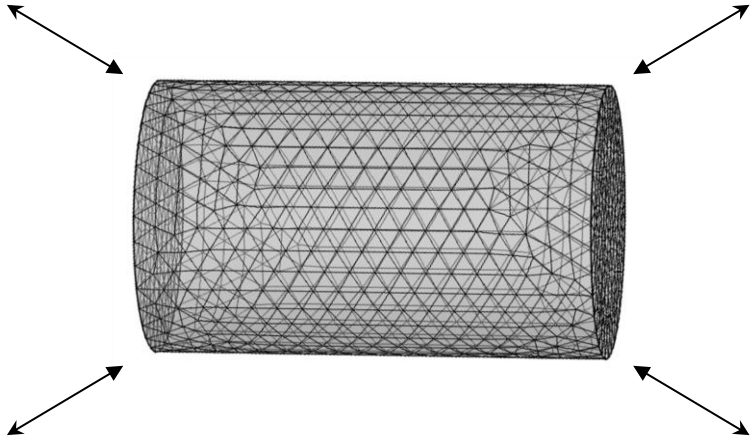
Scalar Boson S = 0

Scalar field
Coupling to e⁻ / γ

$$\Phi(t) \approx \Phi_0 \cos(\omega t)$$

Isotropic strain [1,2]

$$h(t) = -d\, h_0 \cos(\omega t)$$



Vector Boson S = 1

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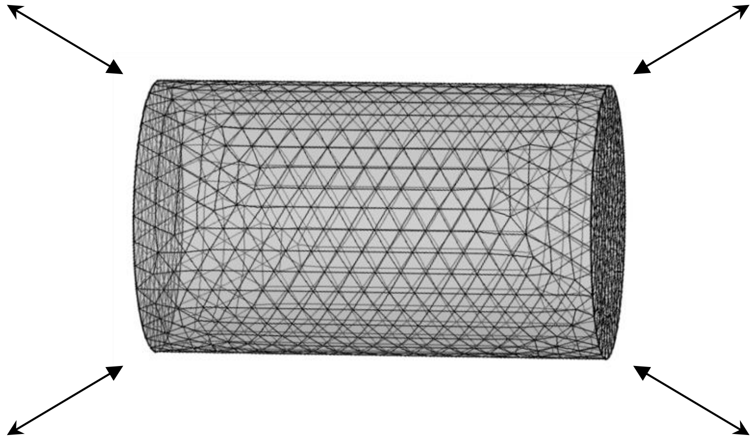

Vector Boson S = 1

Vector field
Coupling to B - L / B

$$\vec{A}(t) \approx \vec{A}_0 \cos(\omega t)$$

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Mechanical Signature of UDM

Scalar Boson S = 0

Scalar field
Coupling to e⁻ / γ

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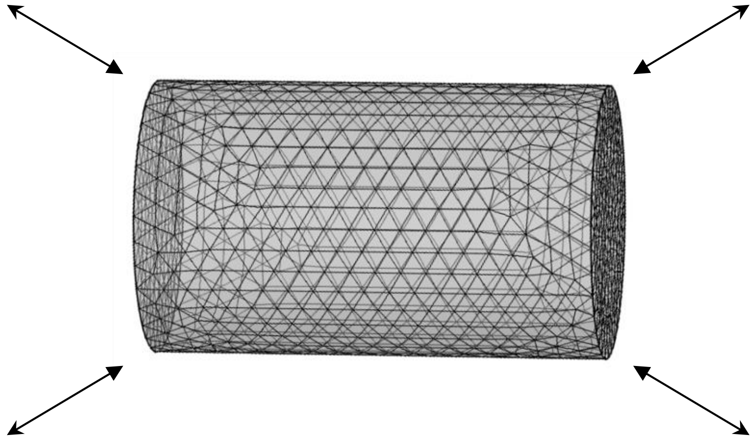
Isotropic strain [1,2]

$$h(t) = -d\, h_0 \cos(\omega t)$$



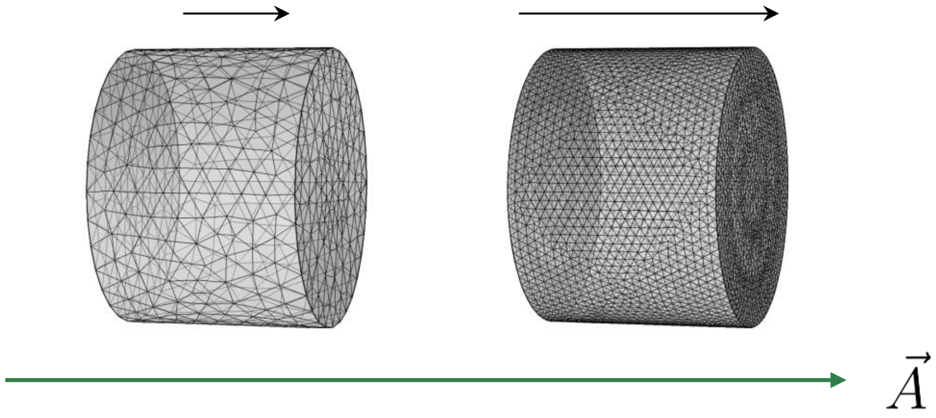
Vector Boson S = 1

Vector field
Coupling to B - L / B

$$\vec{A}(t) \approx \vec{A}_0 \cos(\omega t)$$

Differential acceleration [3]

$$\vec{a}(t) = g\, f\, \vec{a}_0 \cos(\omega t)$$



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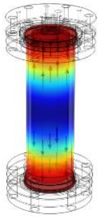
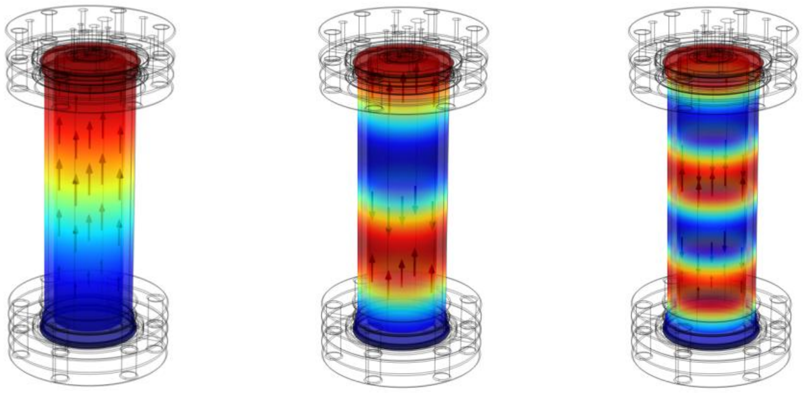
Superfluid UDM Detector



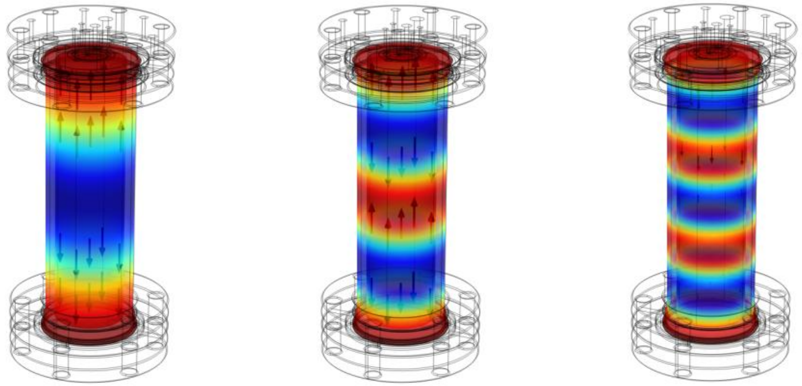
[1]

Odd
COM modes



930 Hz 2790 Hz 4650 Hz

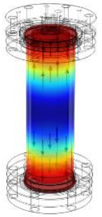
Even
breathing modes



1850 Hz 3710 Hz 5590 Hz

[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

Superfluid UDM Detector



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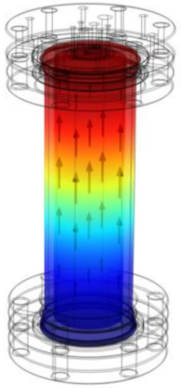
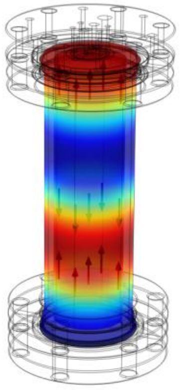
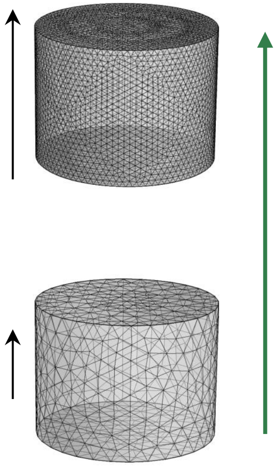
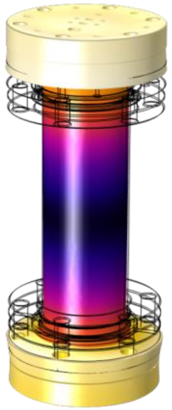




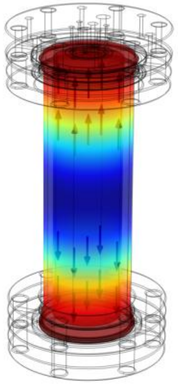
Vector UDM



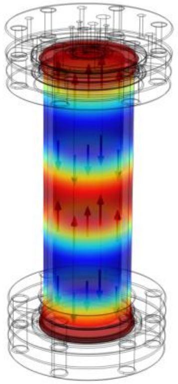


5250 Hz

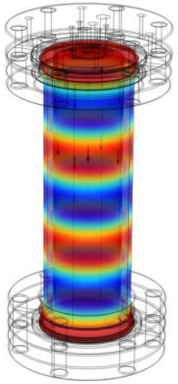
Even
breathing modes



1850 Hz



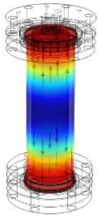
3710 Hz

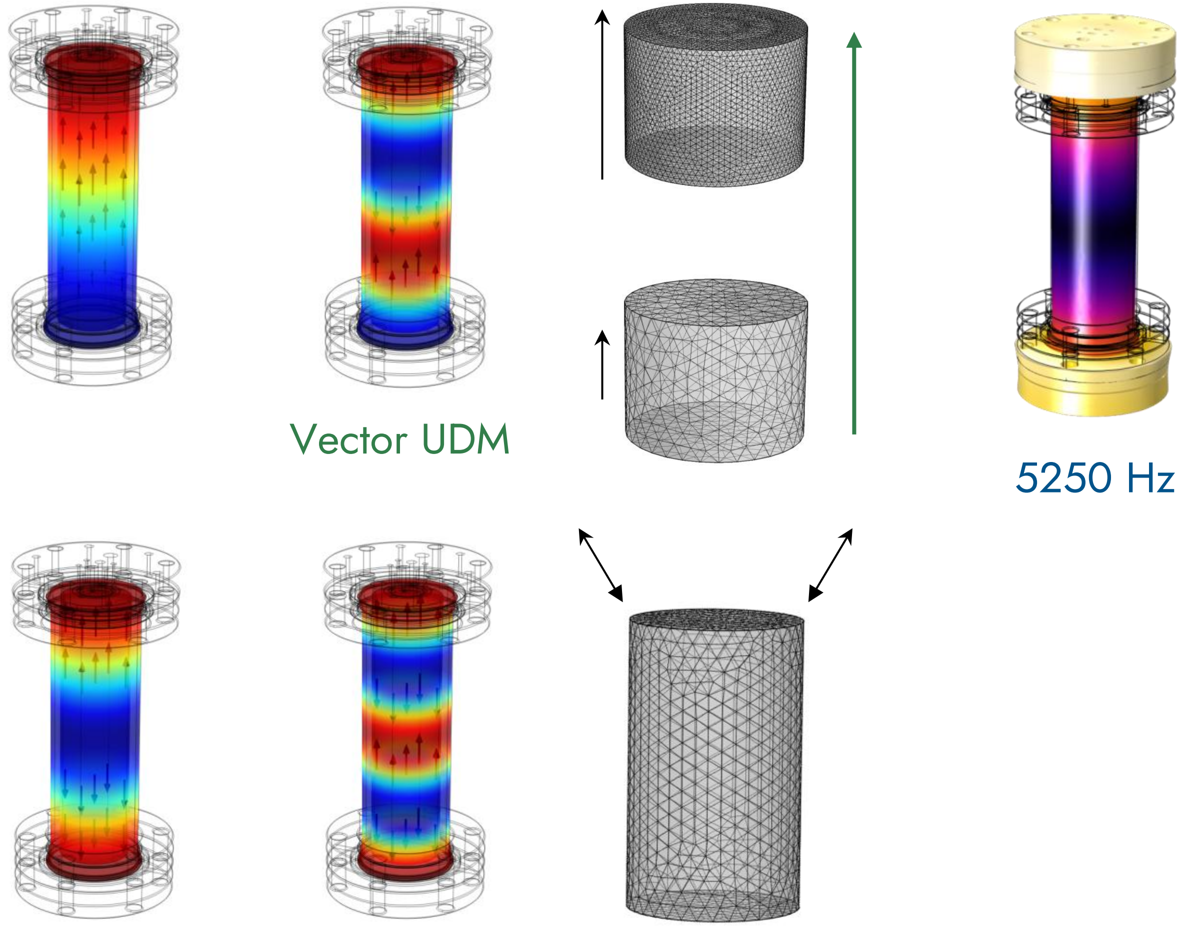


5590 Hz

[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

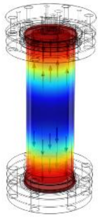
Superfluid UDM Detector





[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

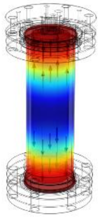
Superfluid UDM Detector



< 20 mK

[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

Superfluid UDM Detector



< 20 mK

[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

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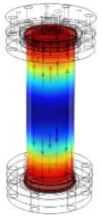
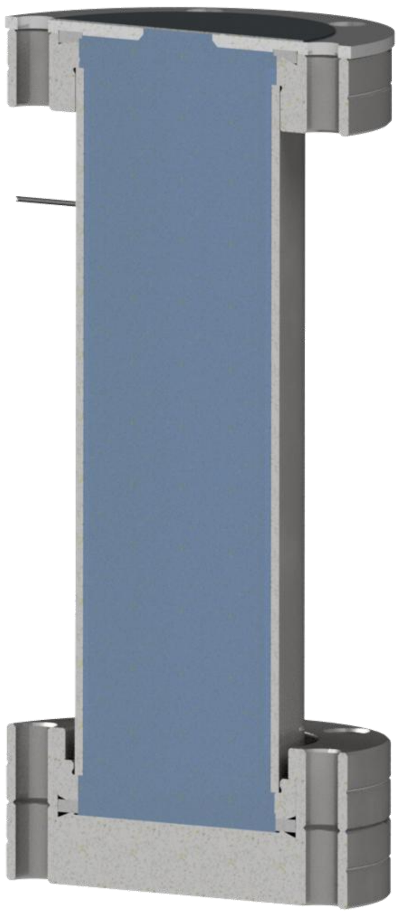
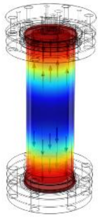


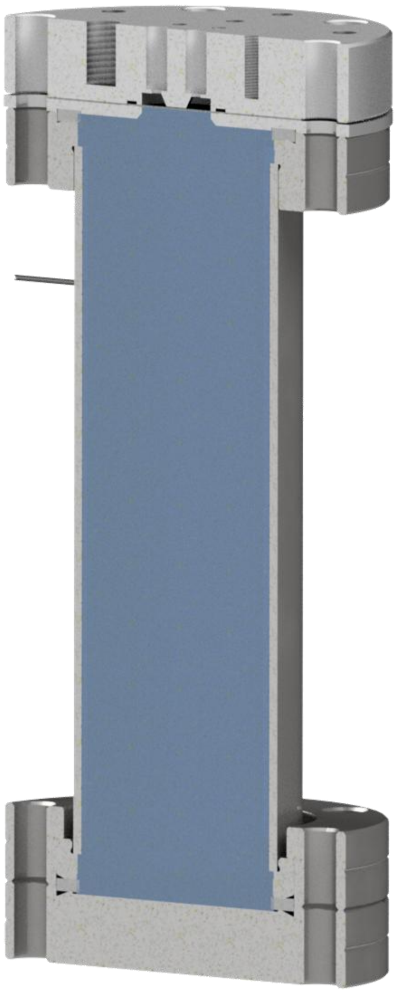


[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

Superfluid UDM Detector



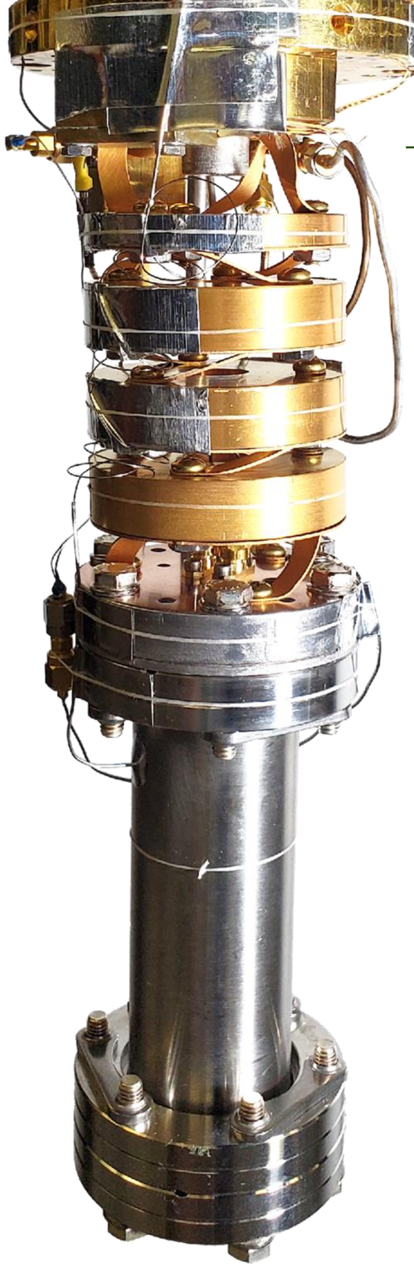
Microwave OM Transducer

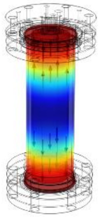


< 20 mK

[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

HeLIOS – First Prototype

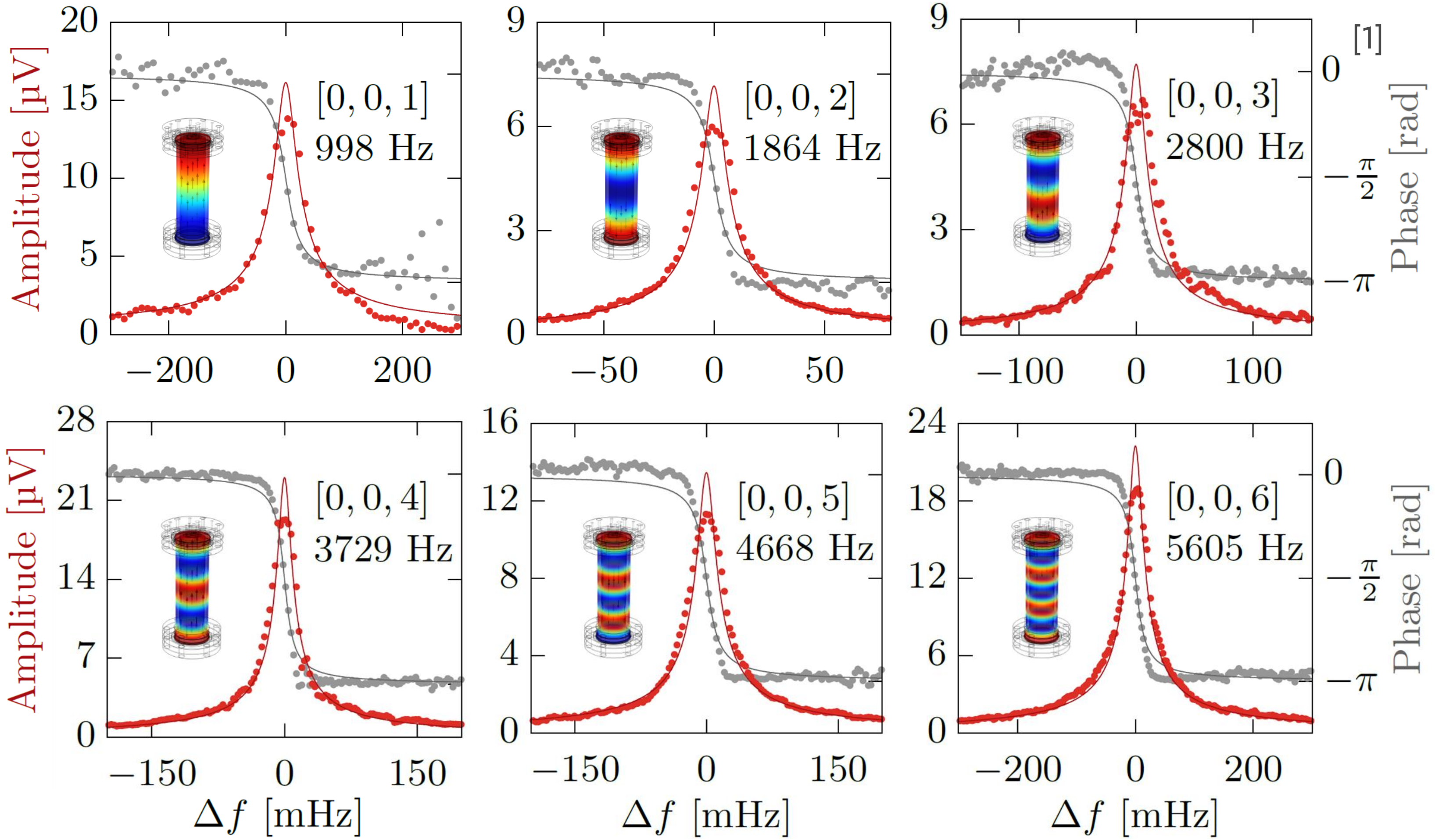


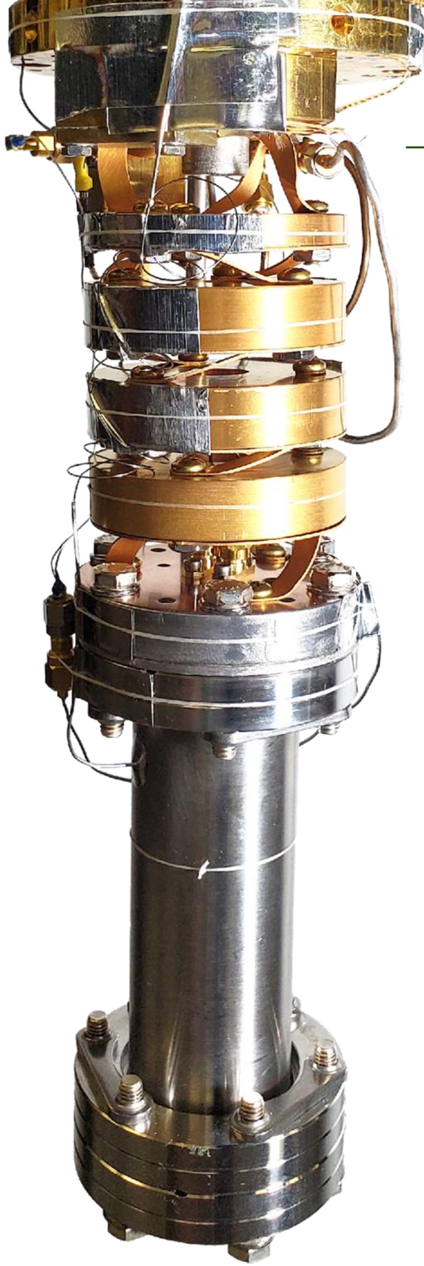


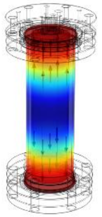
20 mK
70–170 mbar

[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

HeLIOS – First Prototype



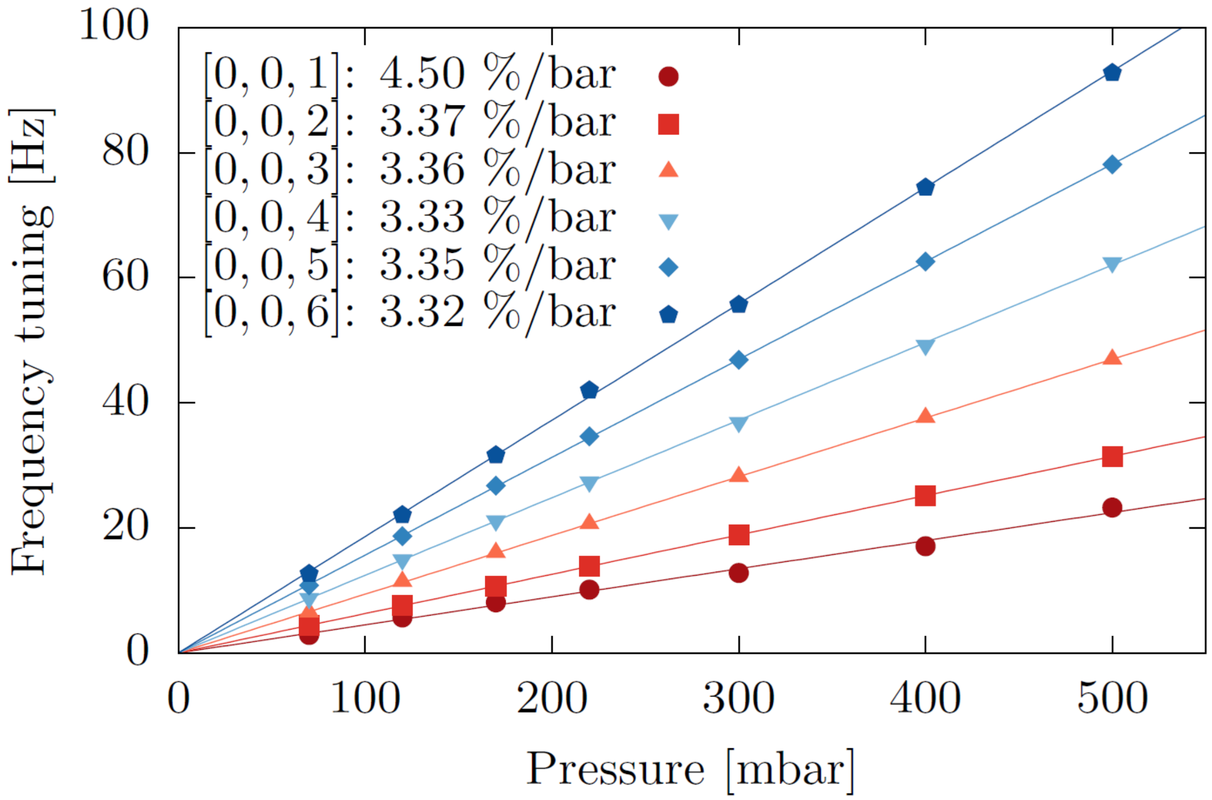




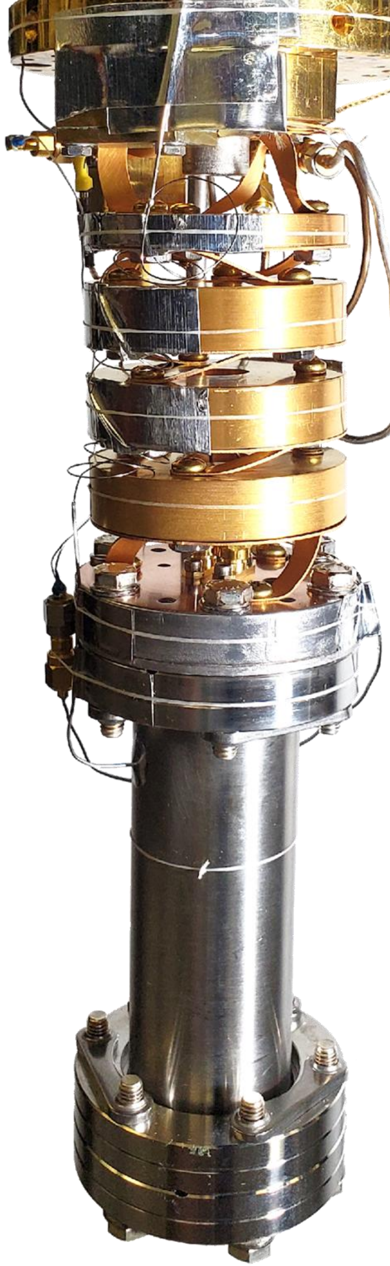
20 mK
70–170 mbar

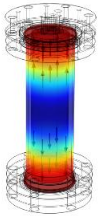
[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

HeLIOS – First Prototype



[1]

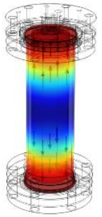




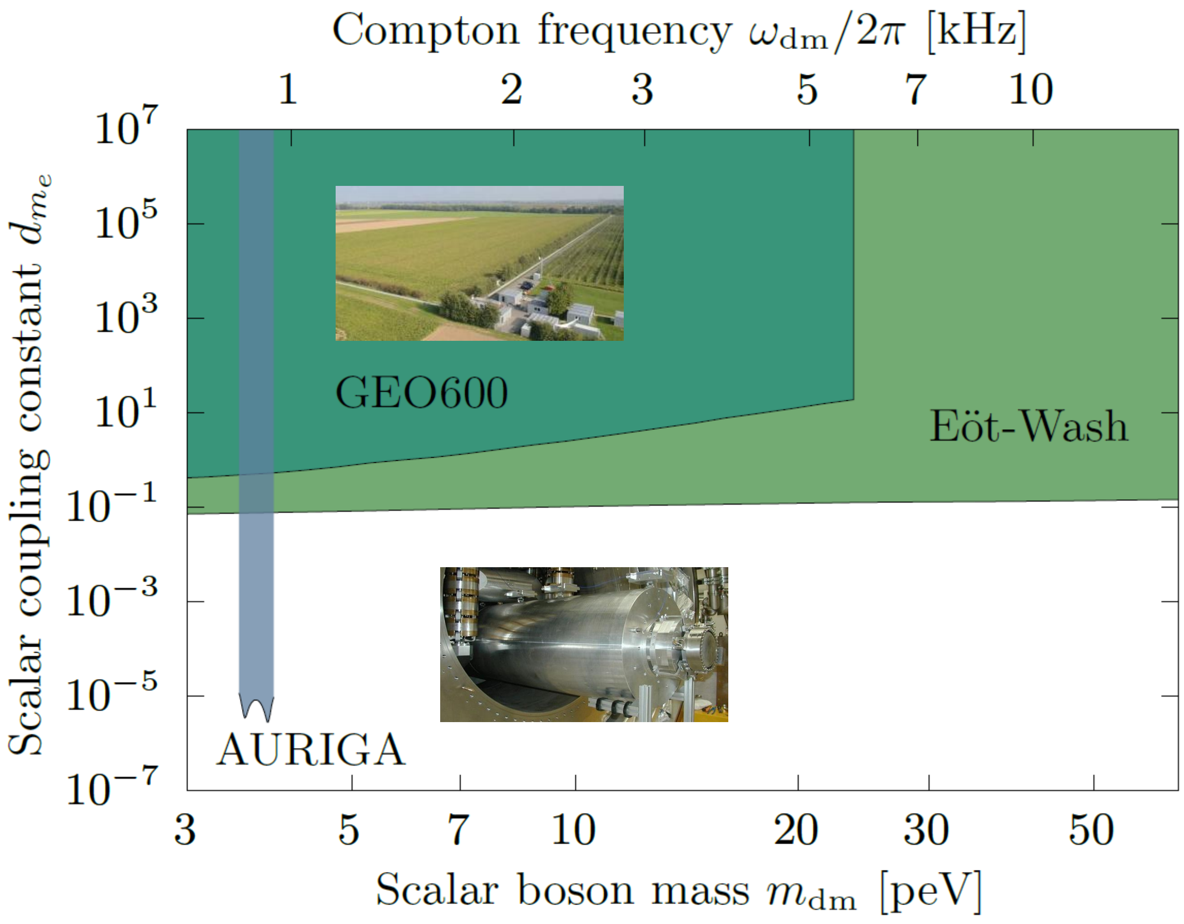
20 mK
70–500 mbar

[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

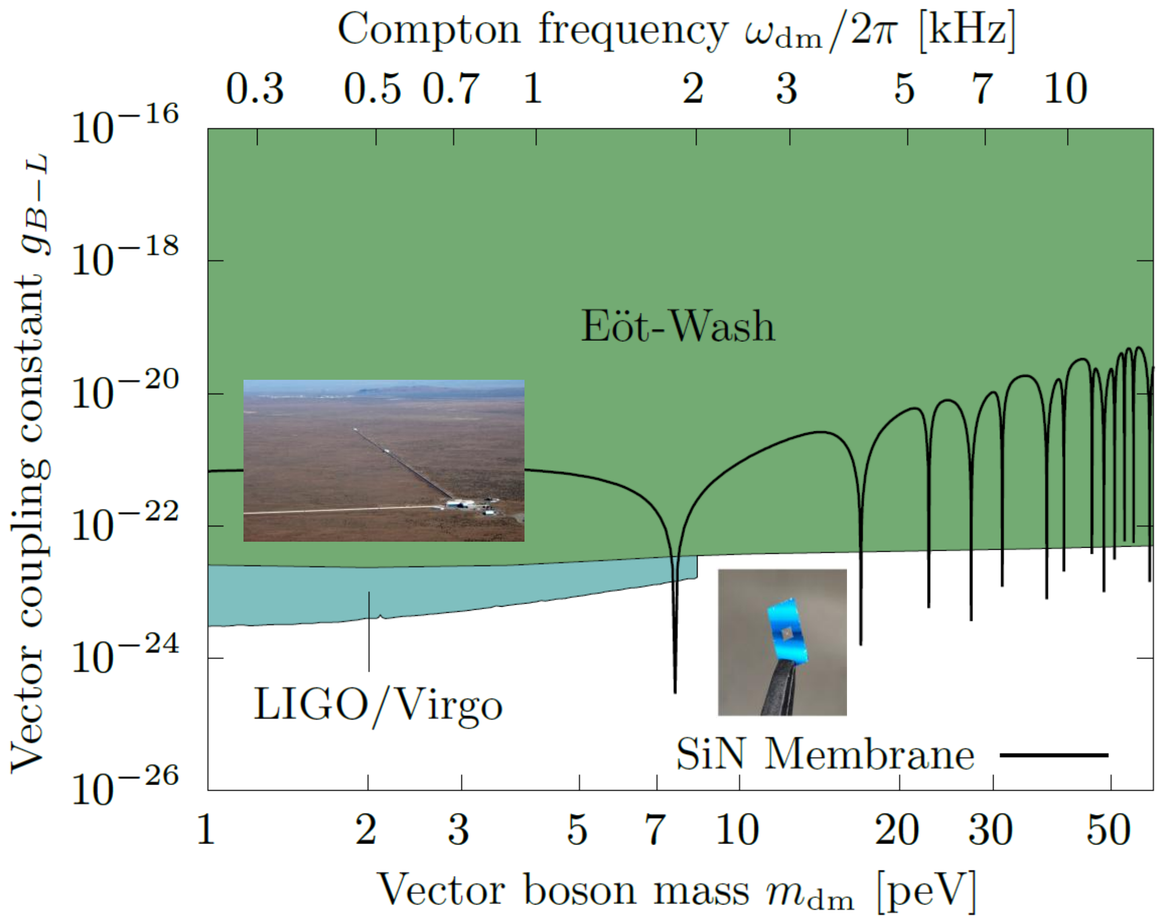
HeLIOS – First Prototype



Scalar Boson $S = 0$



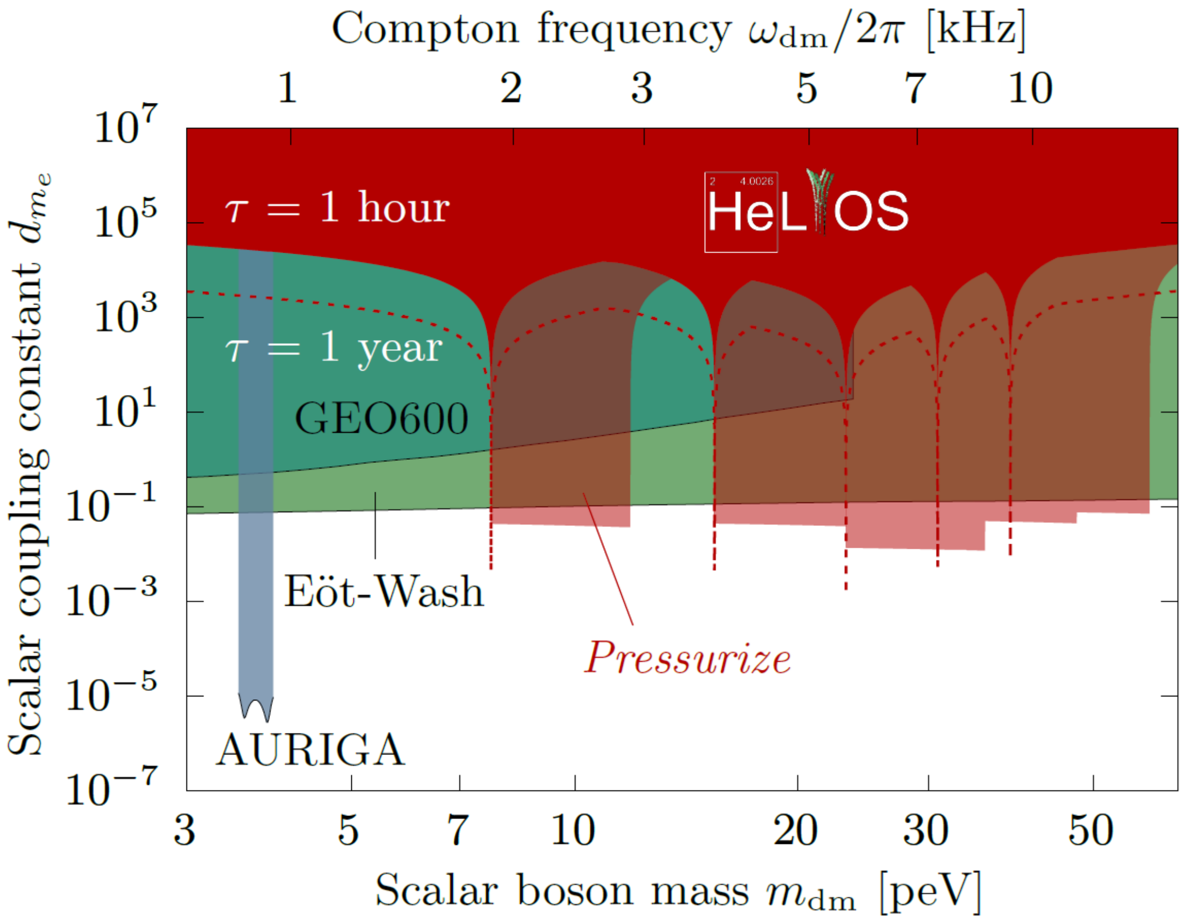
Vector Boson $S = 1$



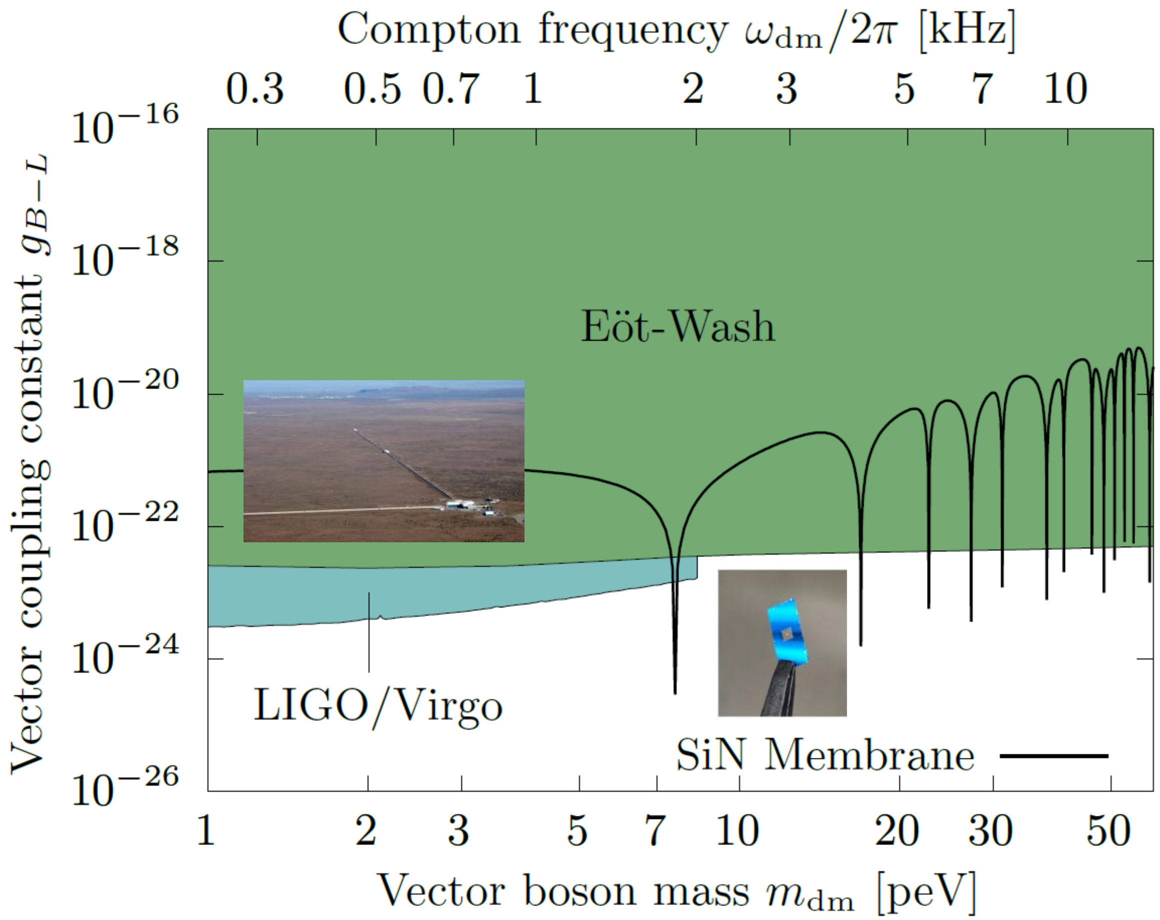
[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

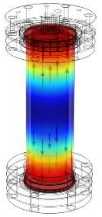
HeLIOS – First Prototype

Scalar Boson $S = 0$



Vector Boson $S = 1$





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HeLIOS – First Prototype

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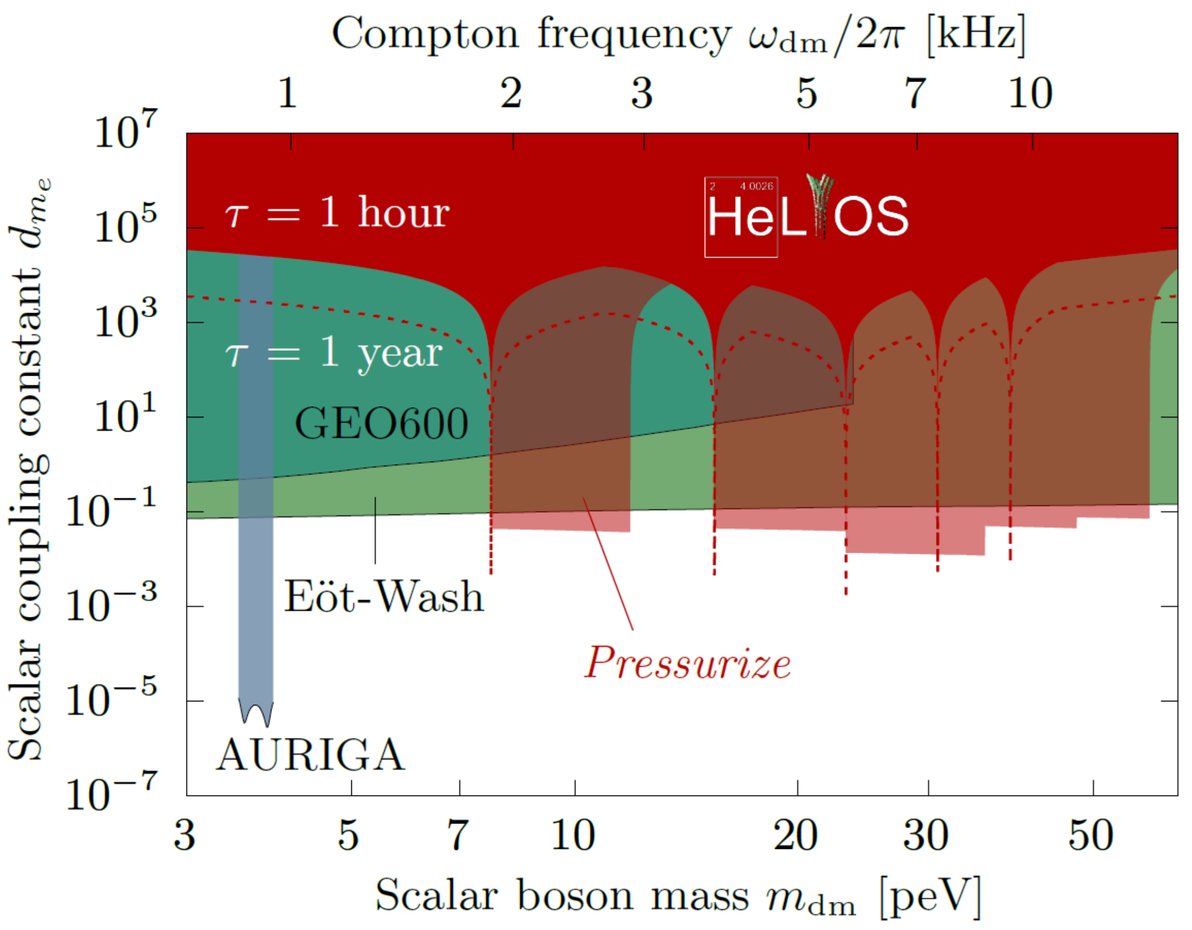
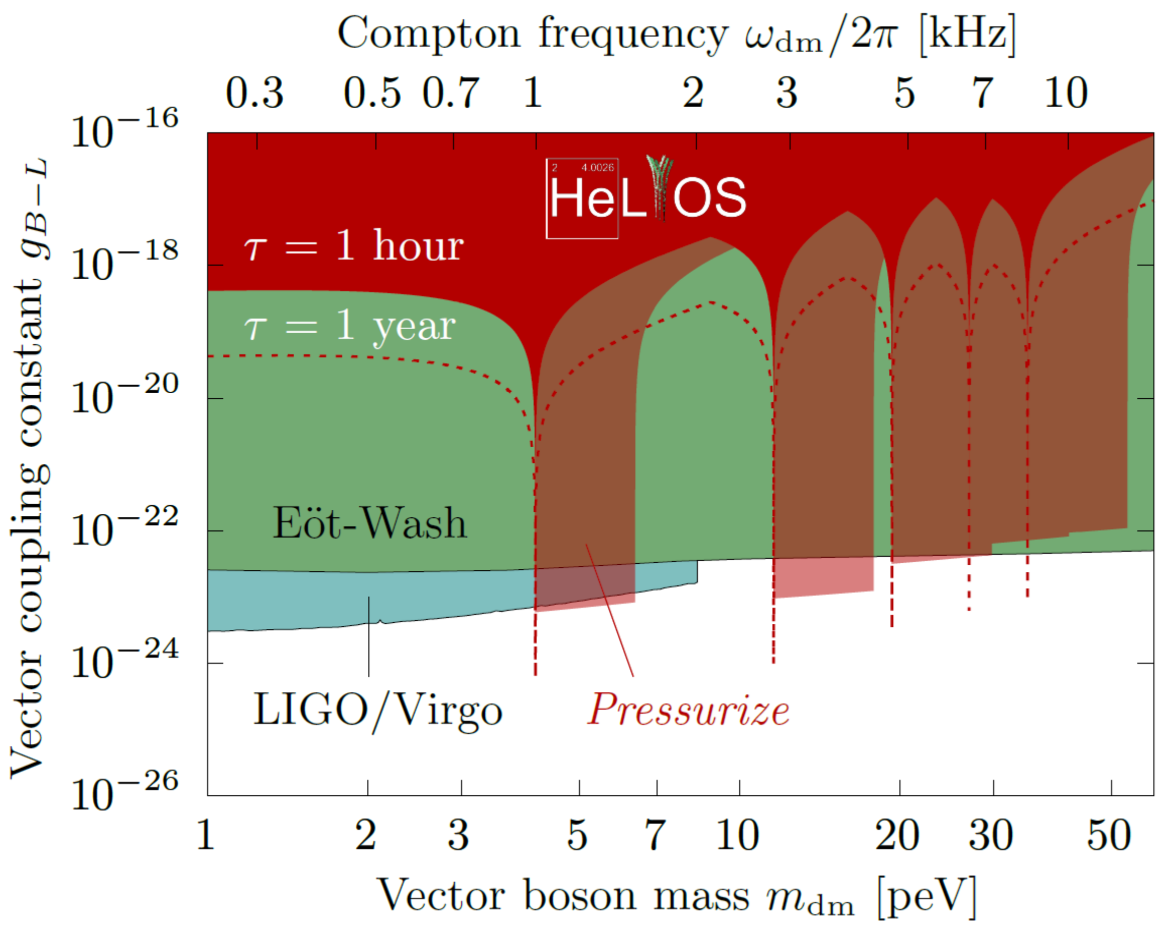


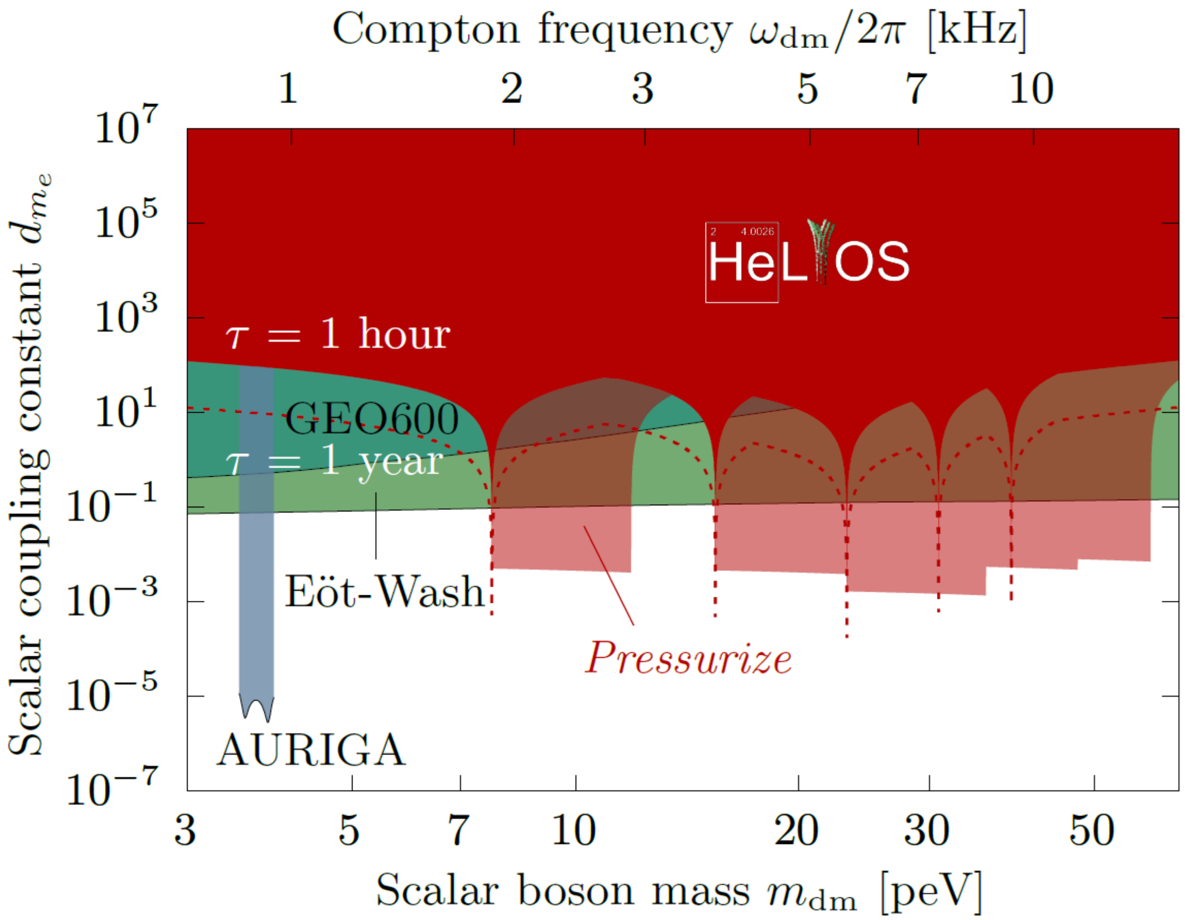
Vector Boson $S = 1$



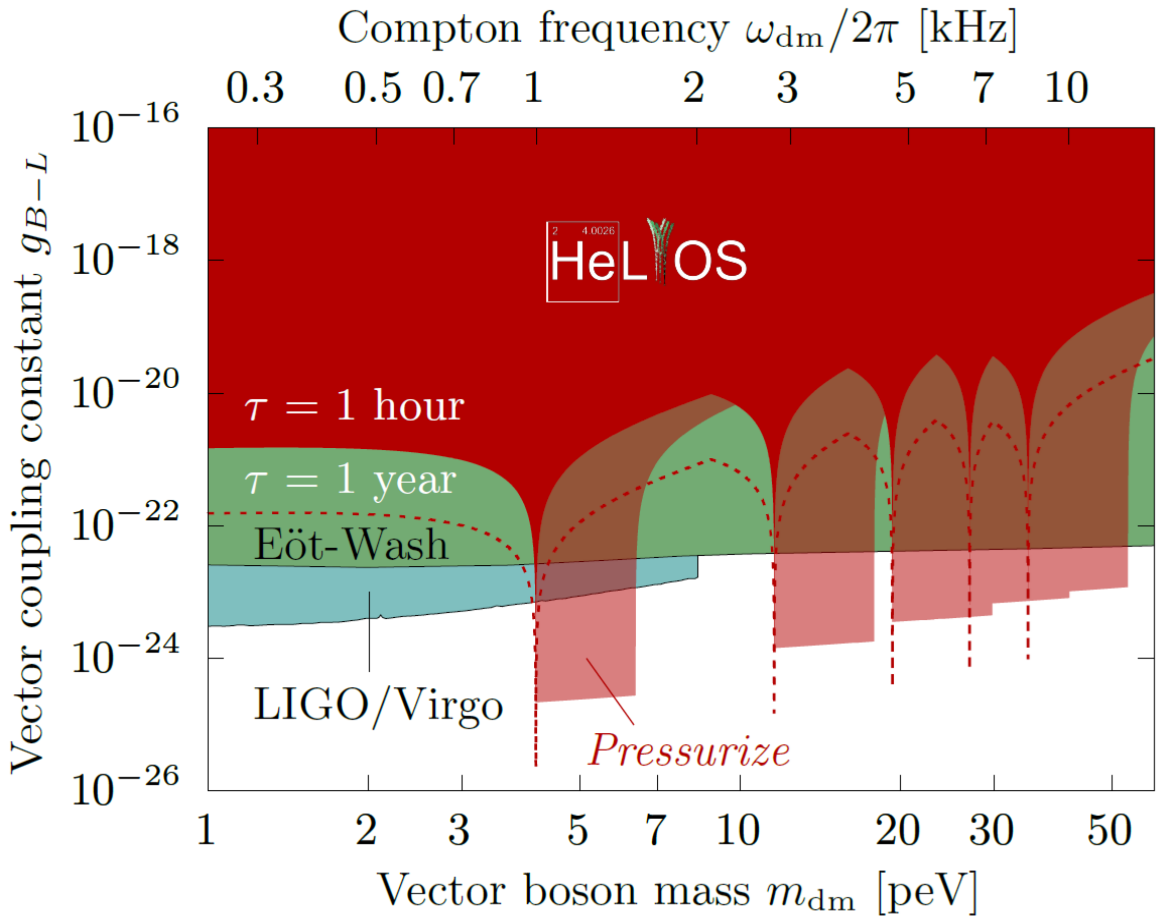
[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

HeLIOS – First Prototype

Scalar Boson S = 0



Vector Boson S = 1

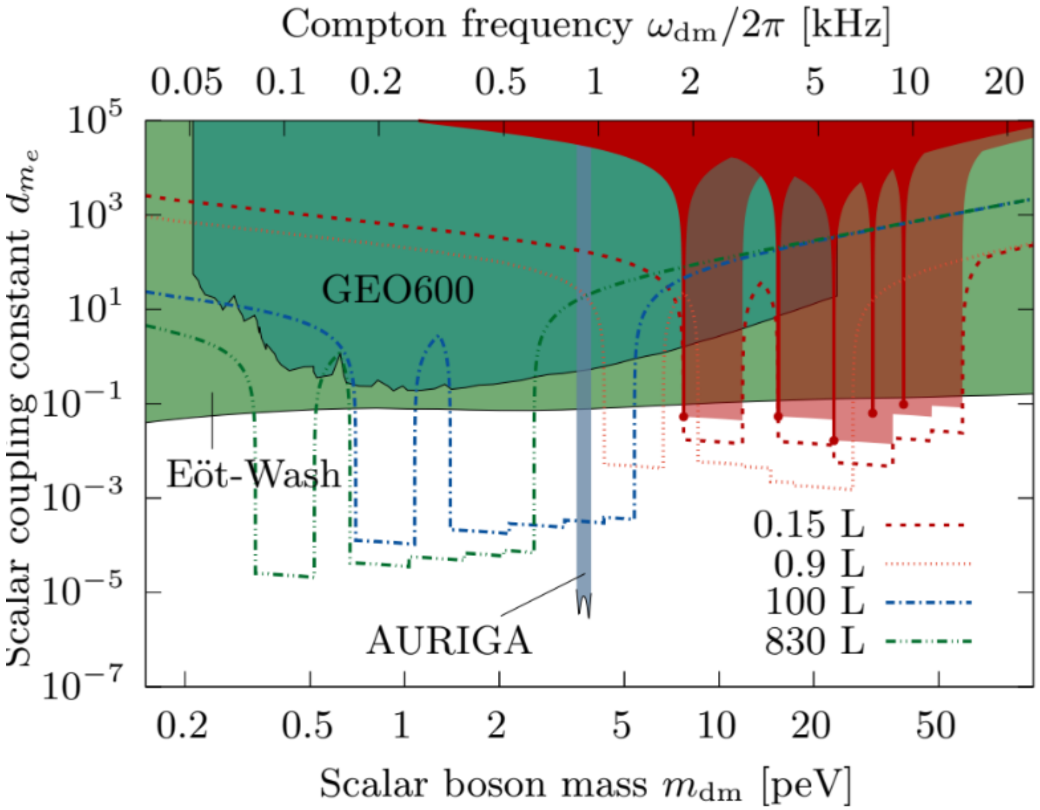


[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

HeLIOS – Next Generation

Scalar Boson S = 0

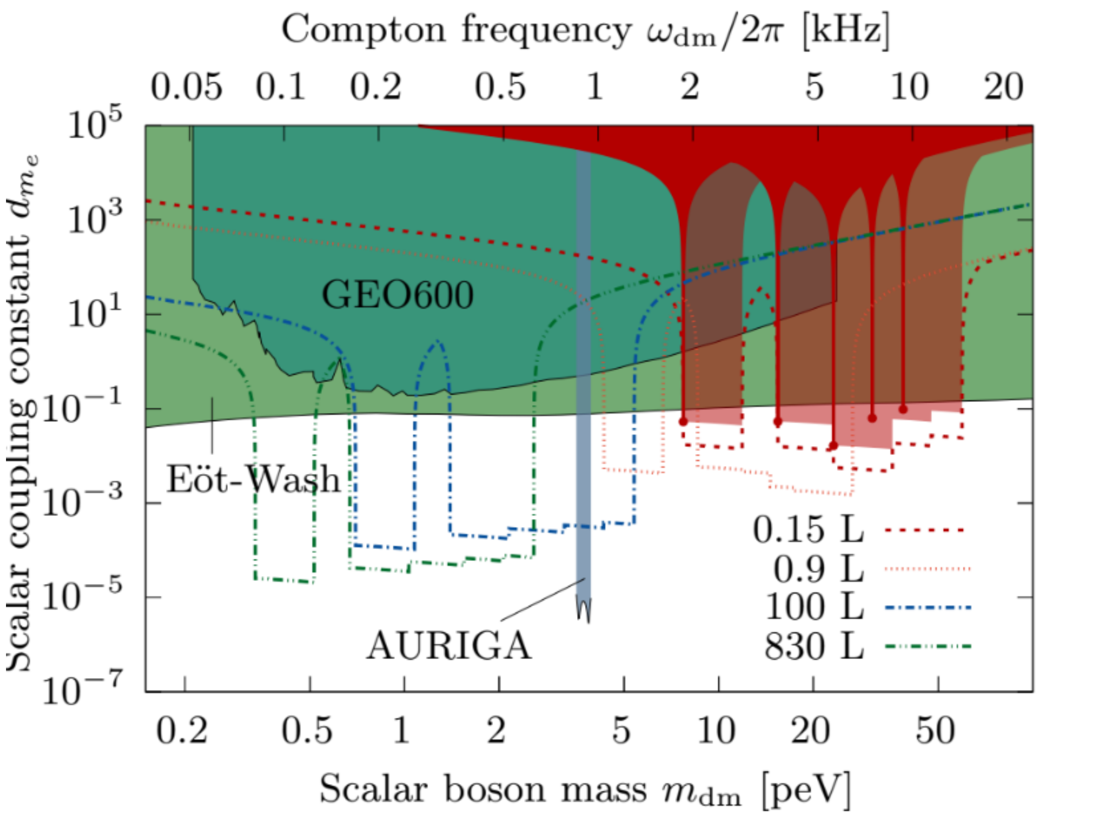
Size Matters



HeLIOS – Next Generation

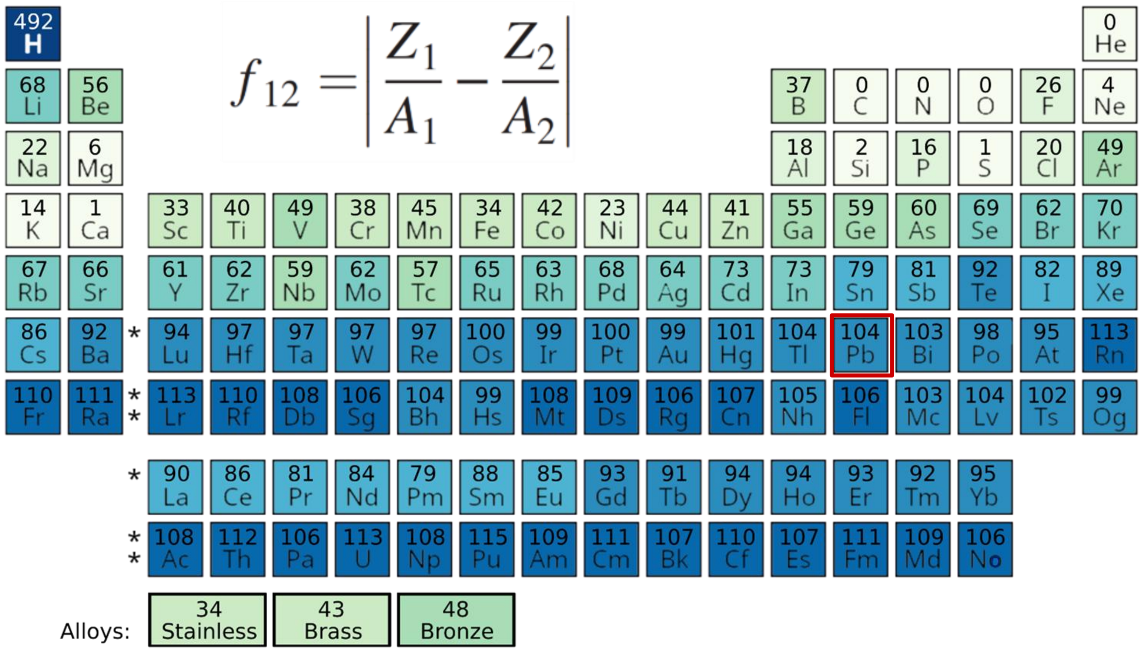
Scalar Boson $S = 0$

Size Matters



Vector Boson $S = 1$

Material Matters



HeLIOS – Next Generation

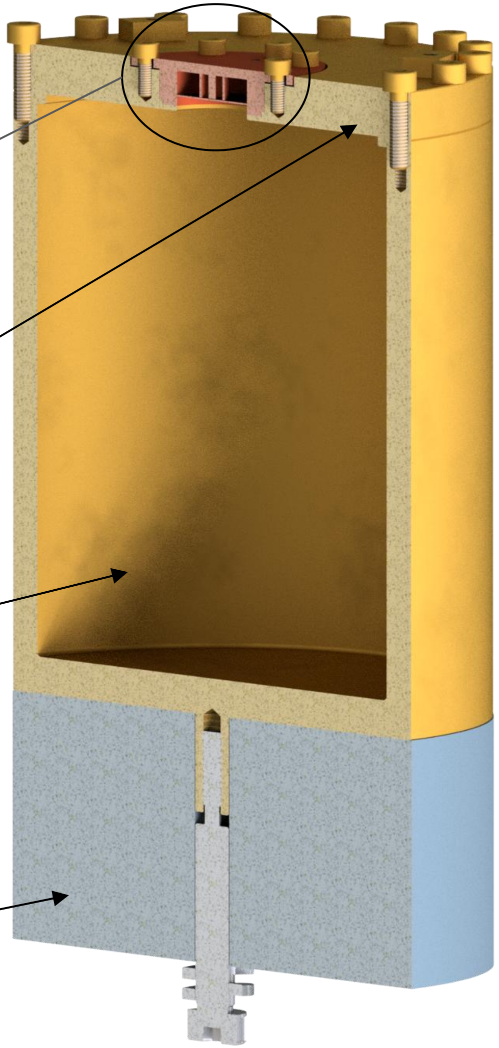
20.3 cm Total mass: 9.7 kg

Transducer Assembly
Aluminum

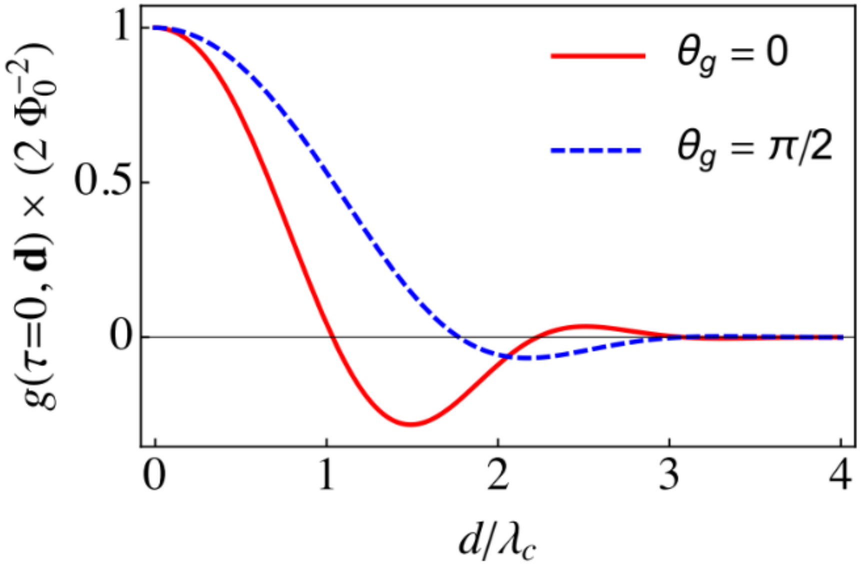
Lid
Brass
In-sealed to cell and transducer

Bucket
Brass
0.90 liter helium capacity
n x ~1kHz [0,0,*z*]-modes

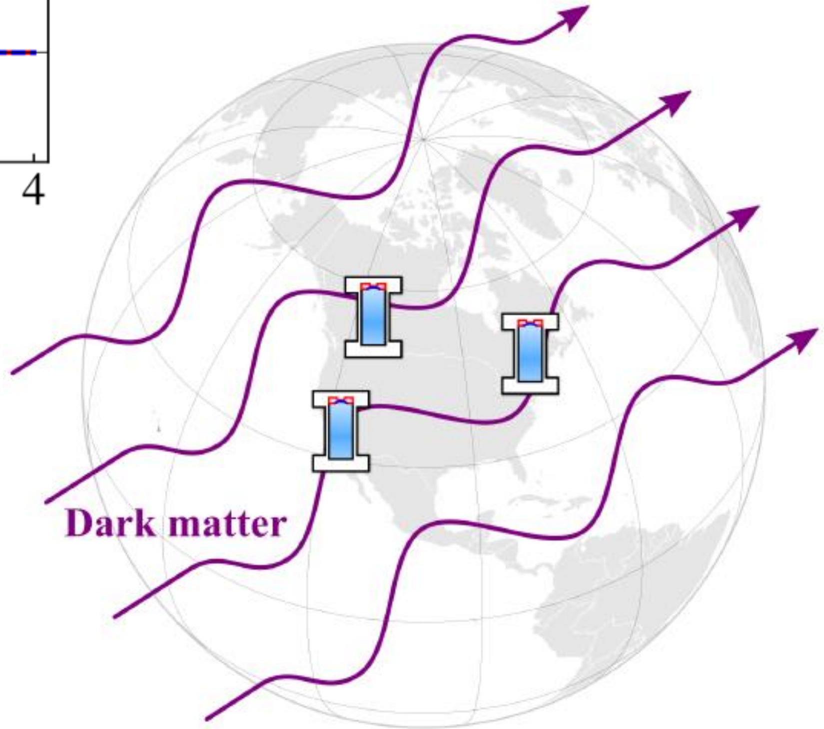
Coupling Mass
Lead, 13 lbs (5.9 kg)



HeLIOS – Network

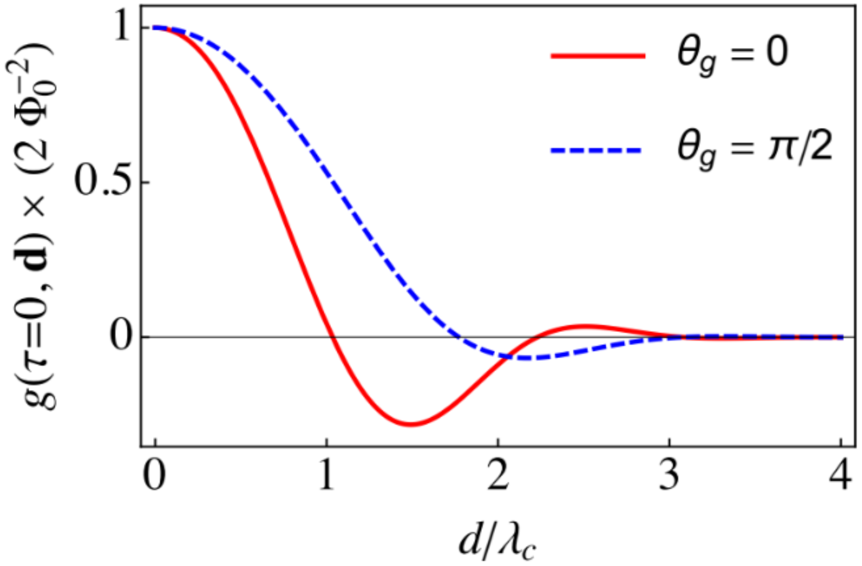


[1]

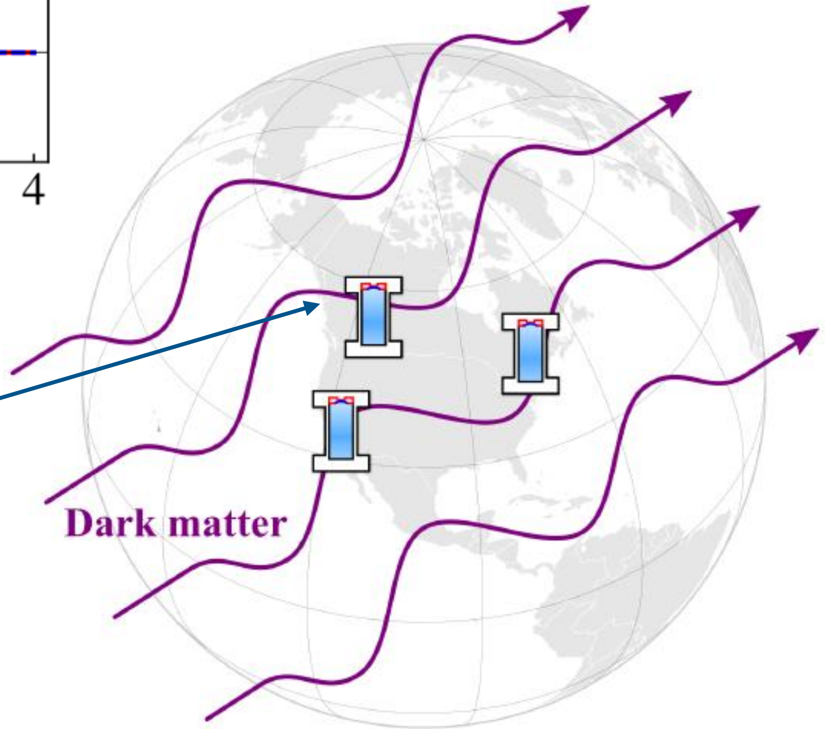


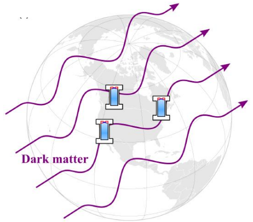
[1] A. Derevianko, *PRA* 97, 042506 (2018).

HeLIOS – Network



[1]





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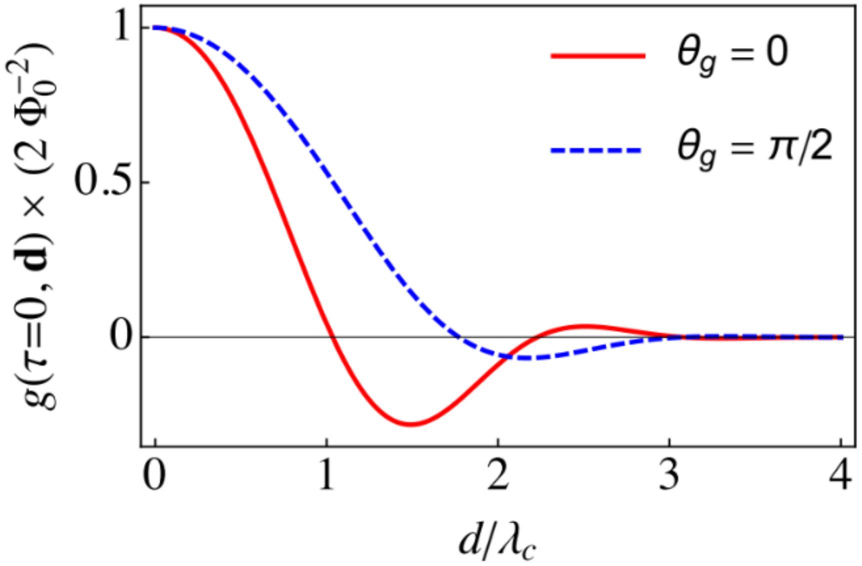

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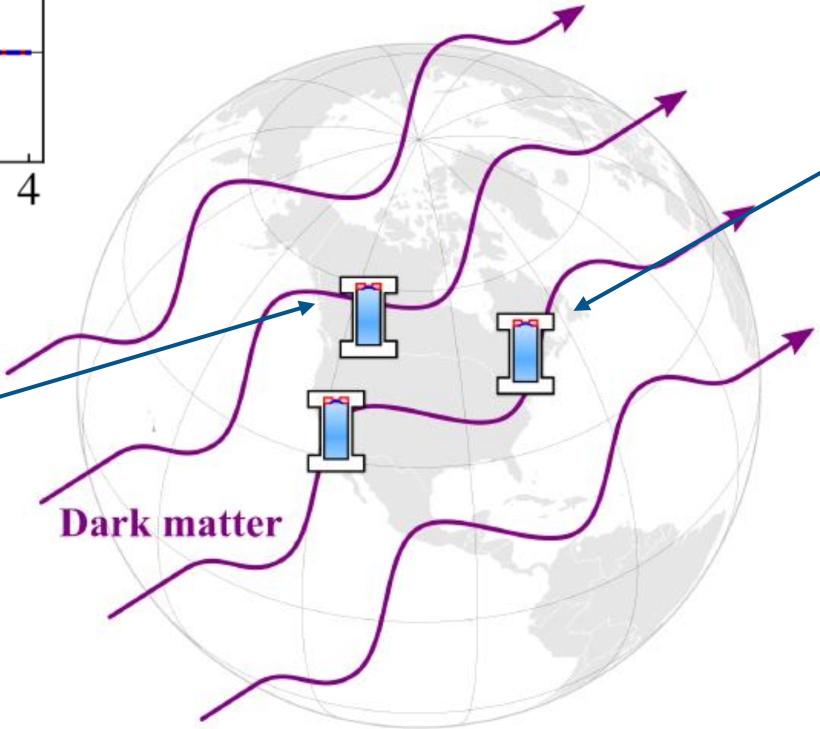
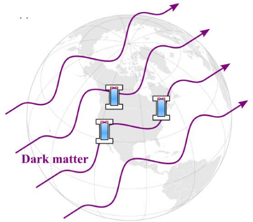


McGill UNIVERSITY

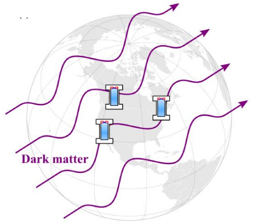
2 4.0026
HeLIOS
Helium UltraLIght Dark Matter Optomechanical Sensor

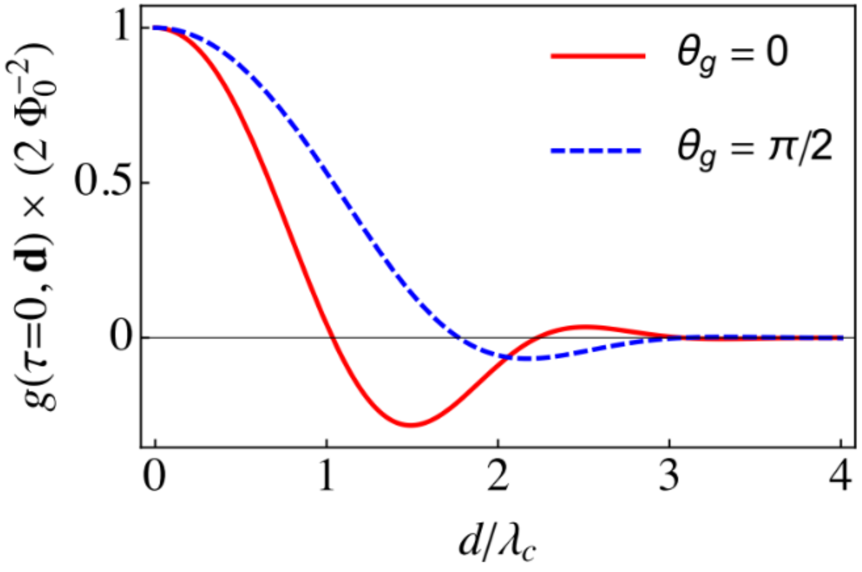
UNIVERSITY OF ALBERTA



[1] A. Derevianko, *PRA* 97, 042506 (2018).

HeLIOS – Network





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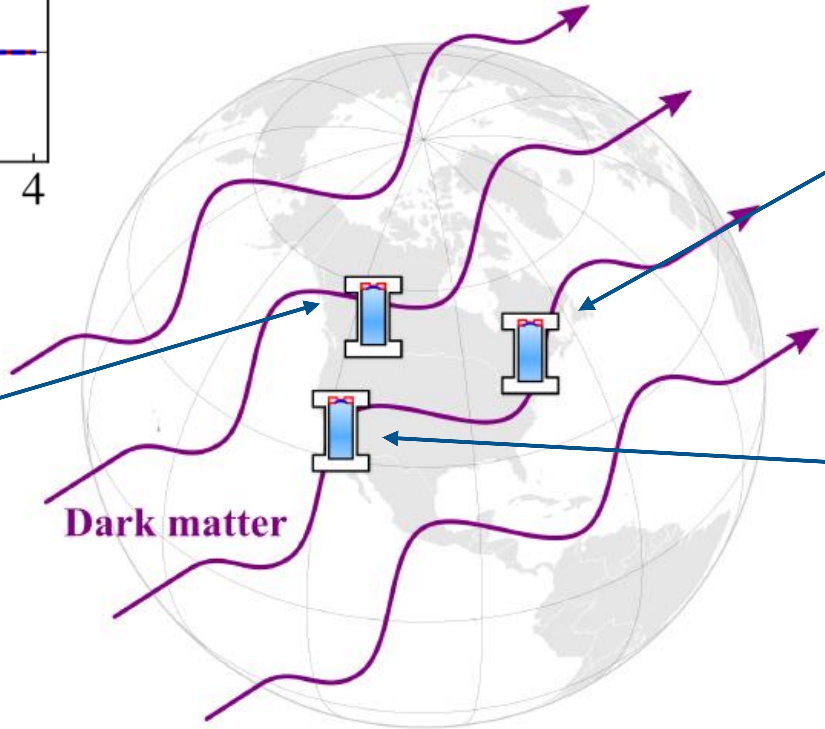


McGill UNIVERSITY

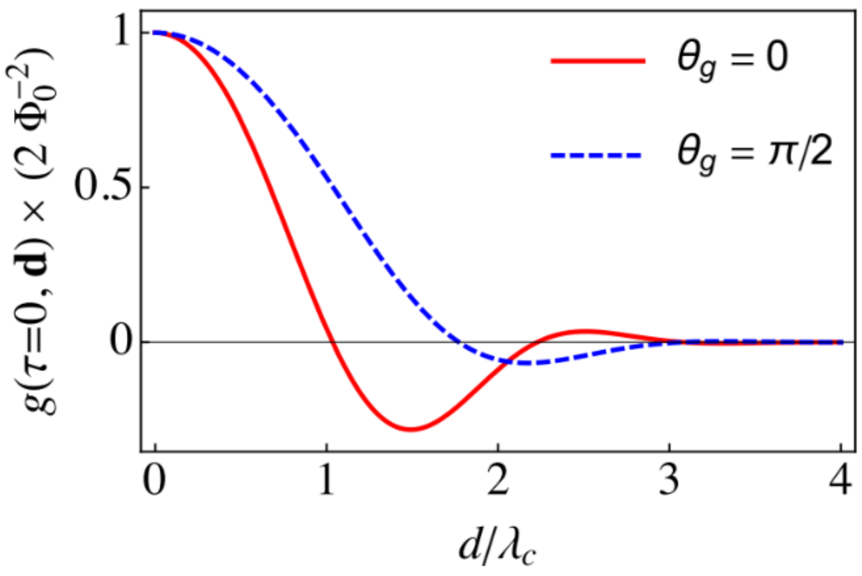
2 4.0026 HeLIOS
Helium UltraLIght Dark Matter Optomechanical Sensor

UNIVERSITY OF ALBERTA

Caltech

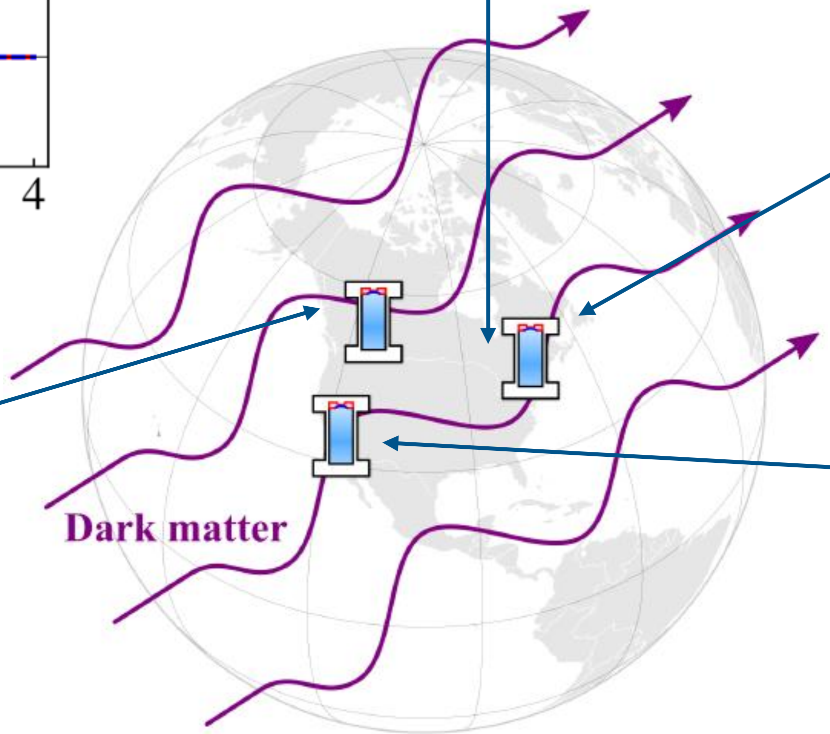
[1] A. Derevianko, *PRA* 97, 042506 (2018).

HeLIOS – Network



[1]

SNOLAB ?



McGill UNIVERSITY

HeLIOS
Helium UltraLIght Dark Matter Optomechanical Sensor

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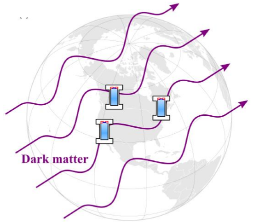
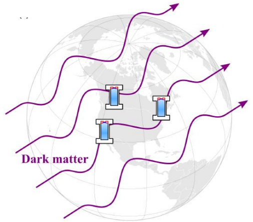
Caltech



[1] A. Derevianko, *PRA* 97, 042506 (2018).

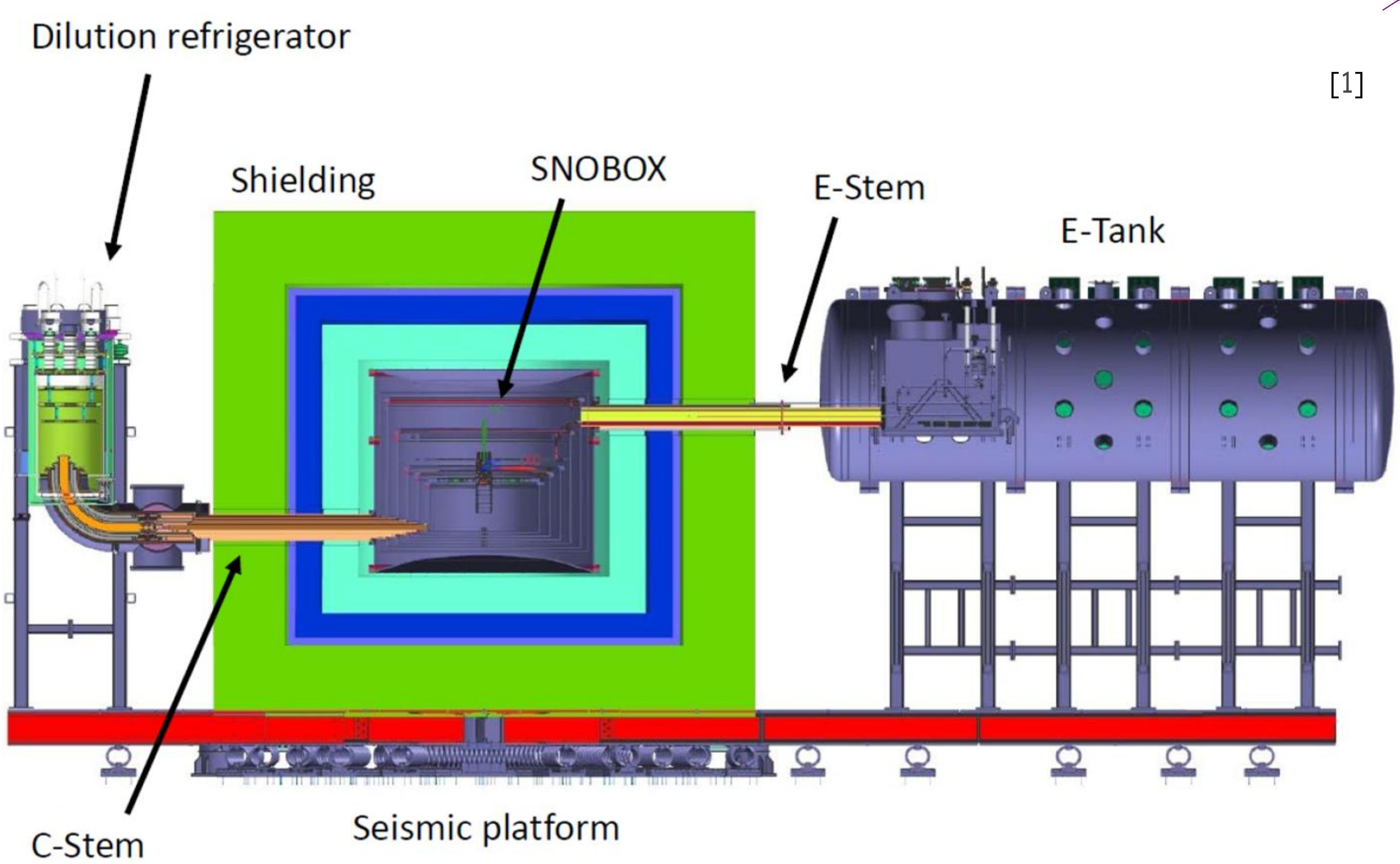
HeLIOS and SNOLAB



[1]

[1] M. I. Hollister et al., *IOP Conf. Ser.: Mater. Sci. Eng. 278*, 012118 (2017).

HeLIOS and SNOLAB



[1]

[1] M. I. Hollister et al., *IOP Conf. Ser.: Mater. Sci. Eng. 278*, 012118 (2017).

HeLIOS and SNOLAB

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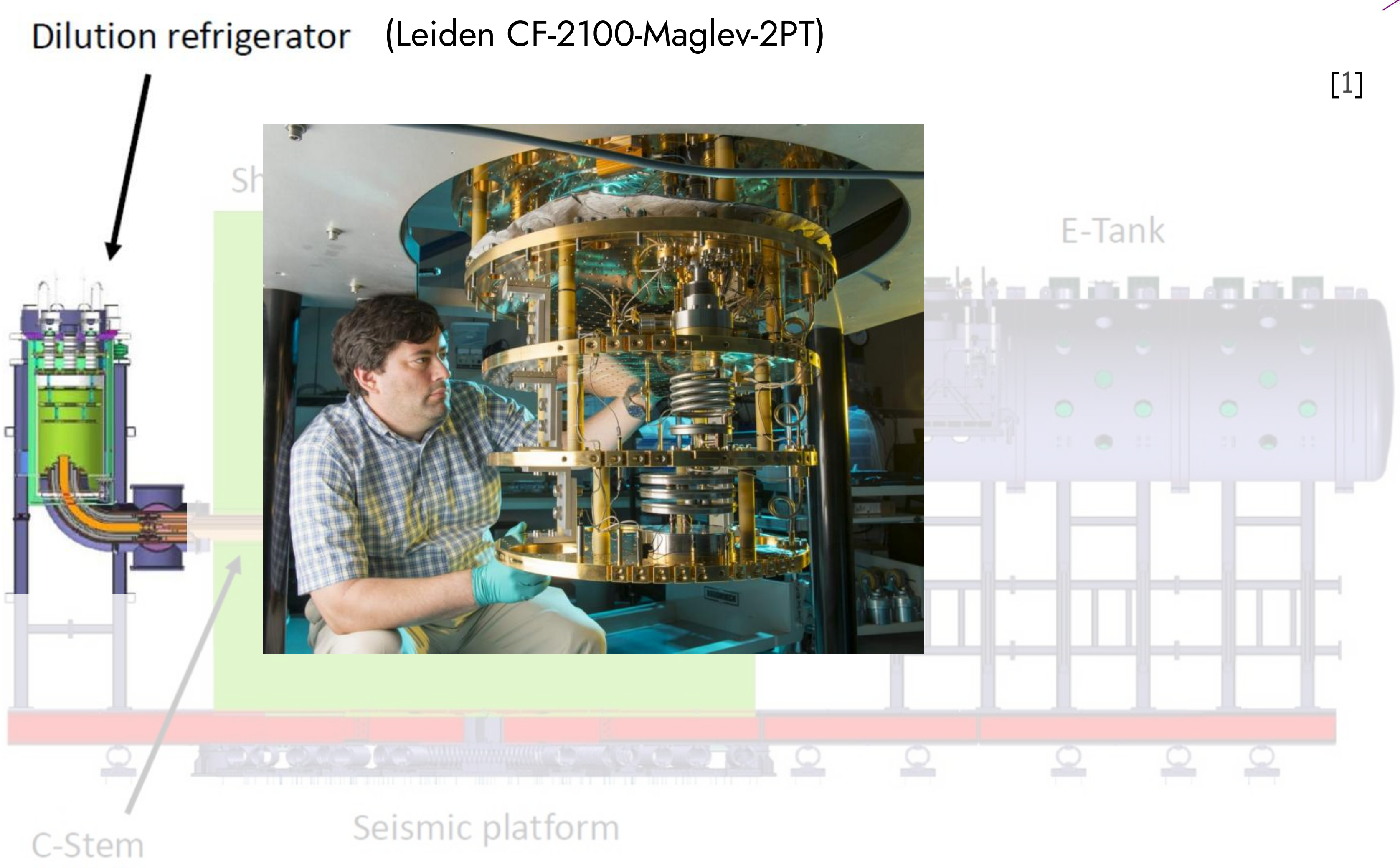
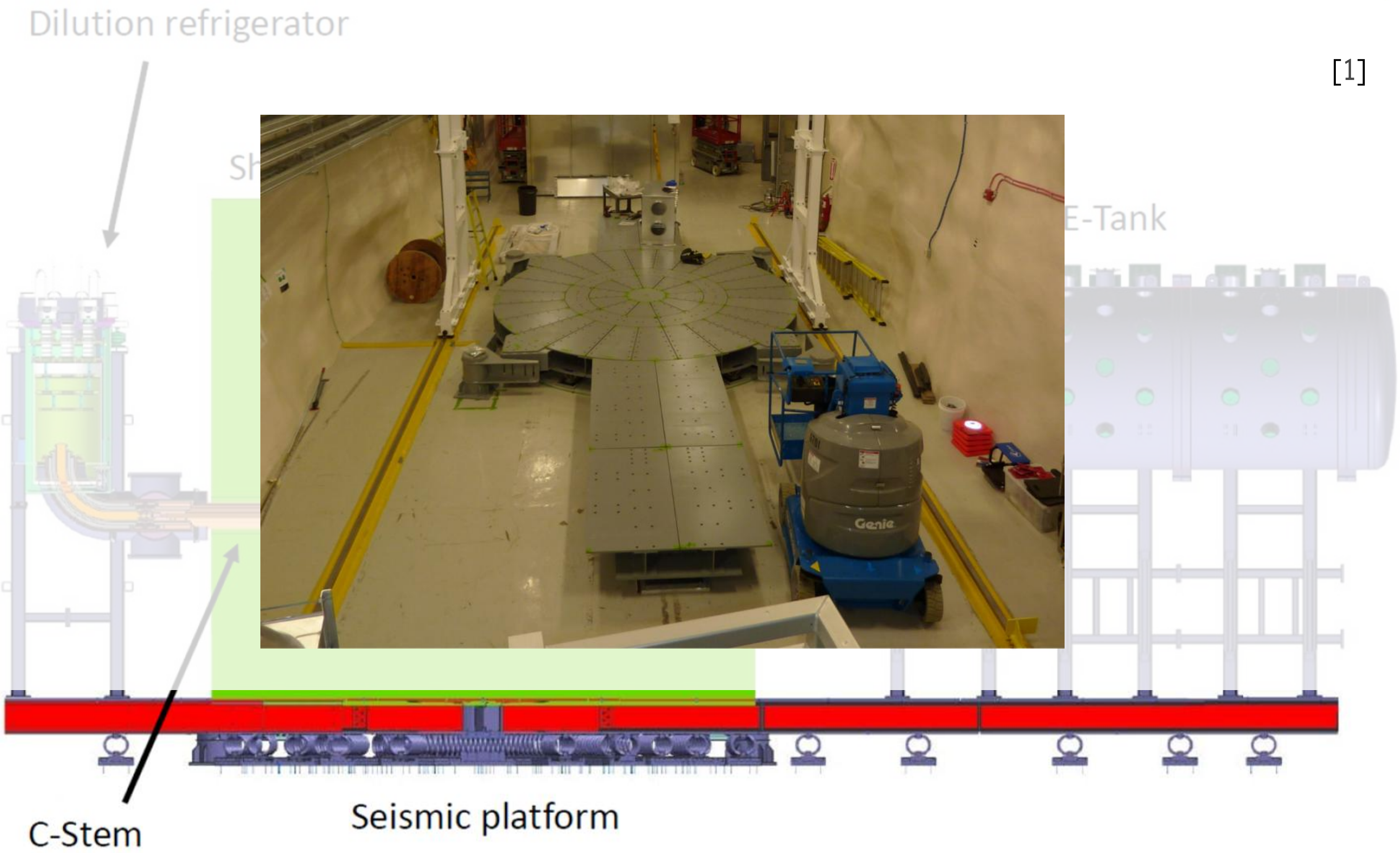


[1] M. I. Hollister et al., *IOP Conf. Ser.: Mater. Sci. Eng. 278*, 012118 (2017).

HeLIOS and SNOLAB



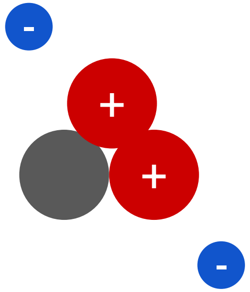
[1]

[1] M. I. Hollister et al., *IOP Conf. Ser.: Mater. Sci. Eng. 278*, 012118 (2017).

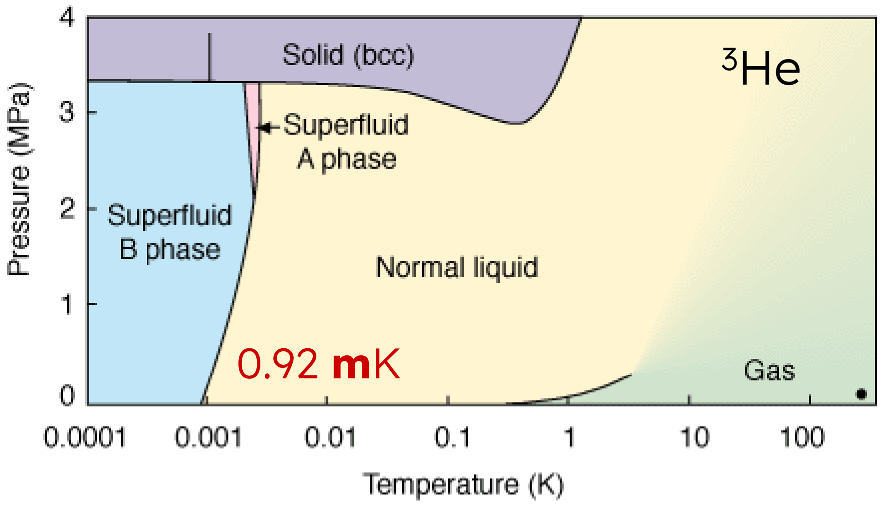
Helium-3 Dark Matter Detection

^{3}He

1.4 ppm



Fermion

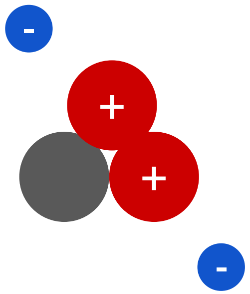


[1]

[1] Encyclopedia of Condensed Matter Physics 3, 51-67 (2024).

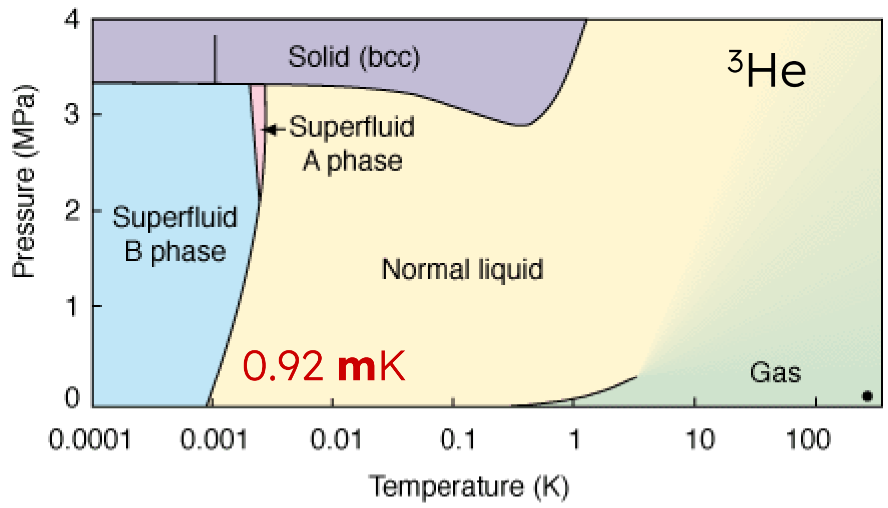
Helium-3 Dark Matter Detection

^{3}He

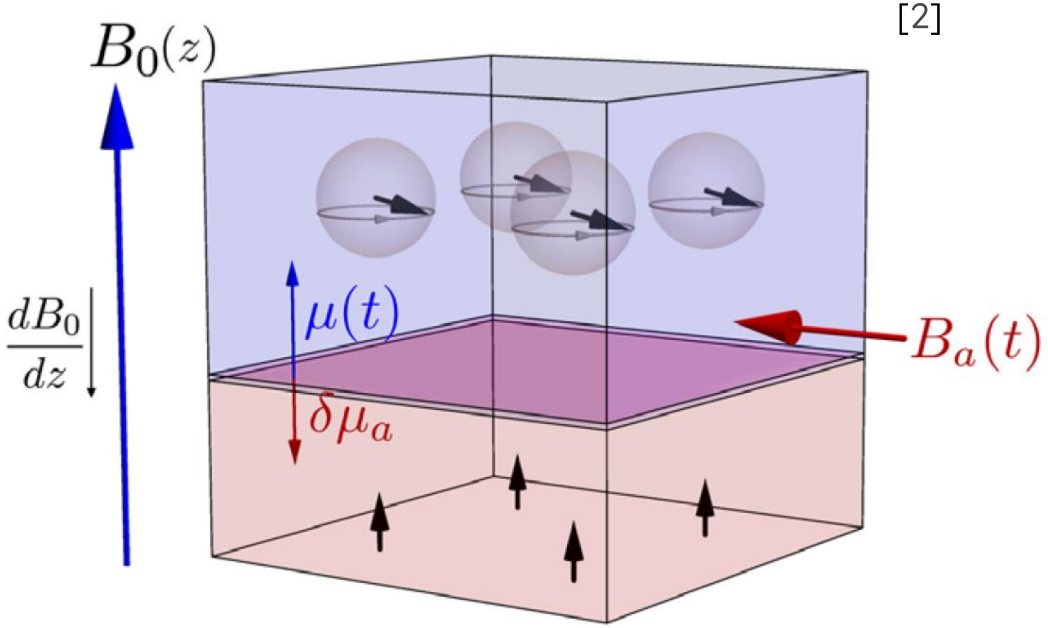


1.4 ppm

Fermion



[1]

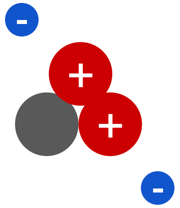


[2]

[1] Encyclopedia of Condensed Matter Physics 3, 51-67 (2024).

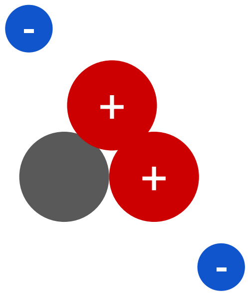
[2] C. Gao, W. Halperin, Y. Kahn, M. Nguyen, J. Schütte-Engel, and J.W. Scott, *PRL* 129, 211801 (2022).

Helium-3 Dark Matter Detection

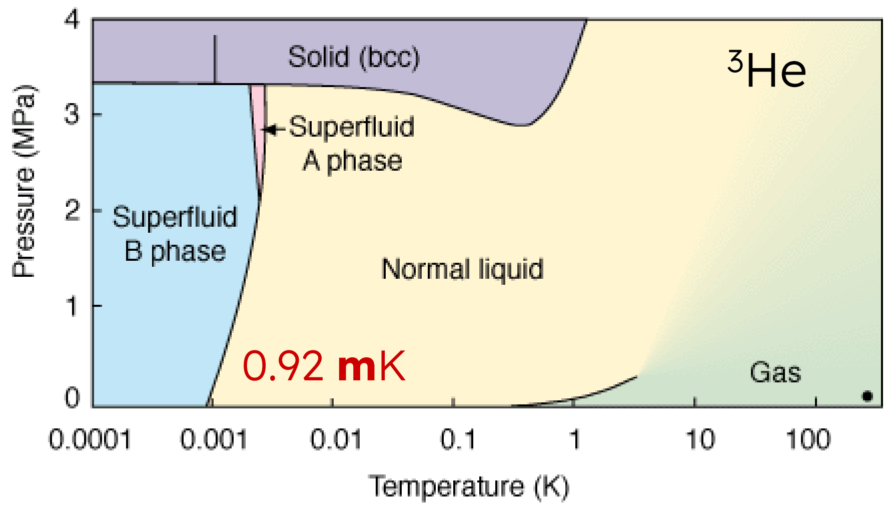


^{3}He

1.4 ppm



Fermion

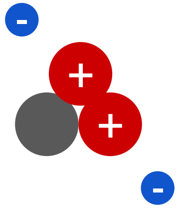


[1]

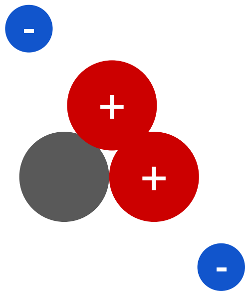
~ 0.5 mK

[1] Encyclopedia of Condensed Matter Physics 3, 51-67 (2024).

Helium-3 Dark Matter Detection



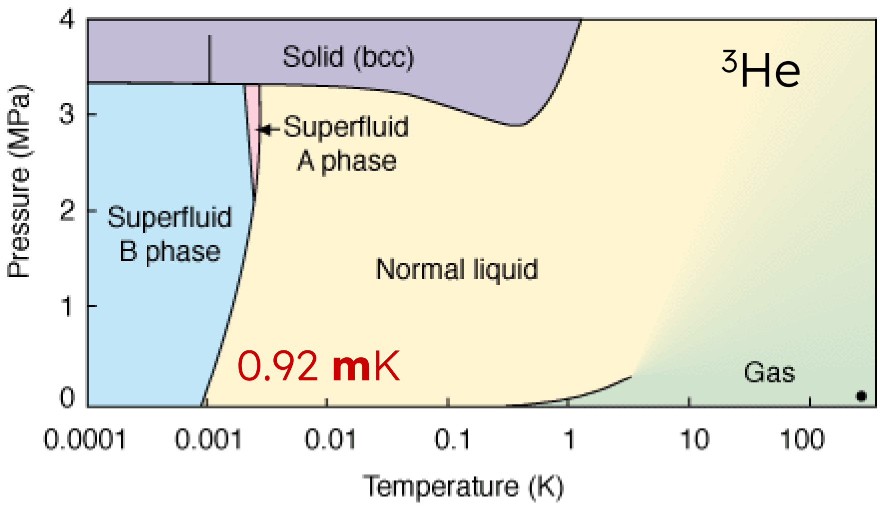
^{3}He



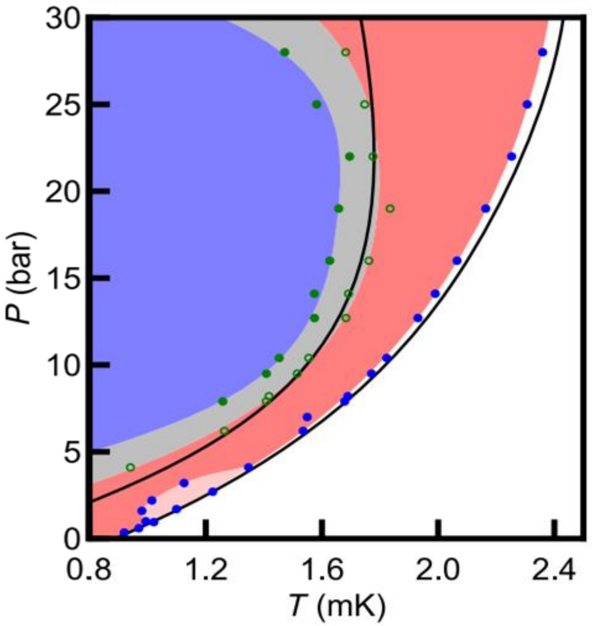
1.4 ppm

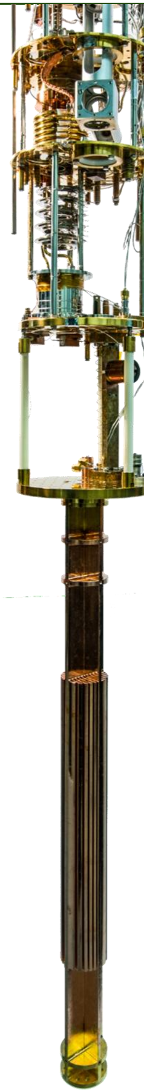
Fermion

[3]



[1]

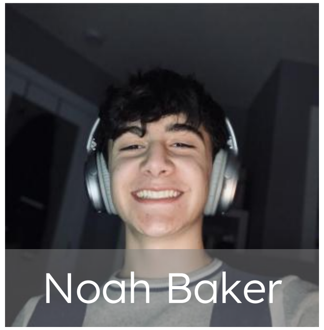




~ 0.5 mK

[1] Encyclopedia of Condensed Matter Physics 3, 51-67 (2024).

[3] A.J. Shook, V. Vadakkumbatt, P. Senarath Yapa, C. Doolin, R. Boyack et al., *PRL* 124, 015301 (2020).



Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

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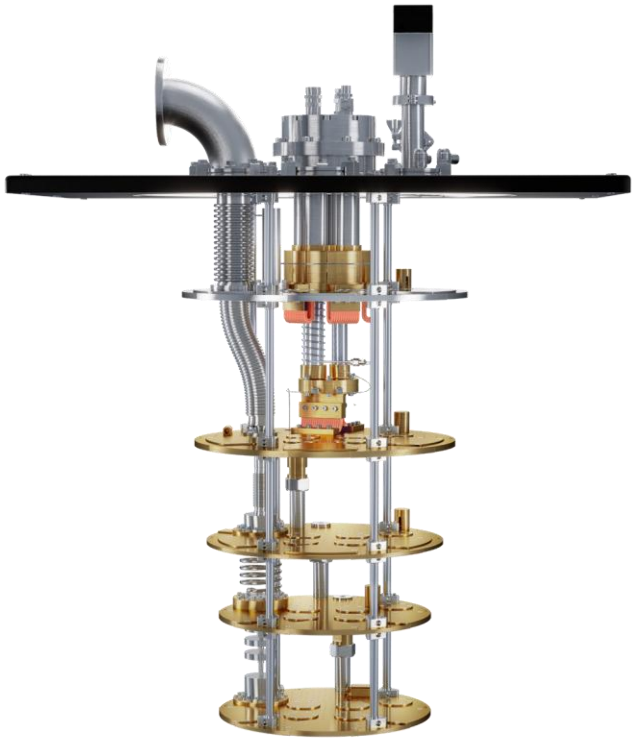
Made in Canada



ZERO POINT CRYOGENICS

9773 45 Avenue | Edmonton, AB | Canada

COLDER FOR LONGER

- Dilution refrigerators (10mK), continuous 0.5K / 1K systems, handcrafted in Canada
- Founded in 2017, 25 employes
- Vertically-integrated facility – highest quality standard, minimal costs and production times
- Highly customizable solutions

Resonant Mass Detector

Resonant mass for detection of small periodic forces

$$S_{xx} = \boxed{|\chi_m|^2}\left(\underbrace{S^{\mathrm{s}}_{ff}} + \underbrace{S^{\mathrm{th}}_{ff}}\right) + \cancel{S^{\mathrm{imp}}_{xx}}$$

$$f_{\mathrm{s}} = q\,\frac{\partial^2 h}{\partial t^2}$$

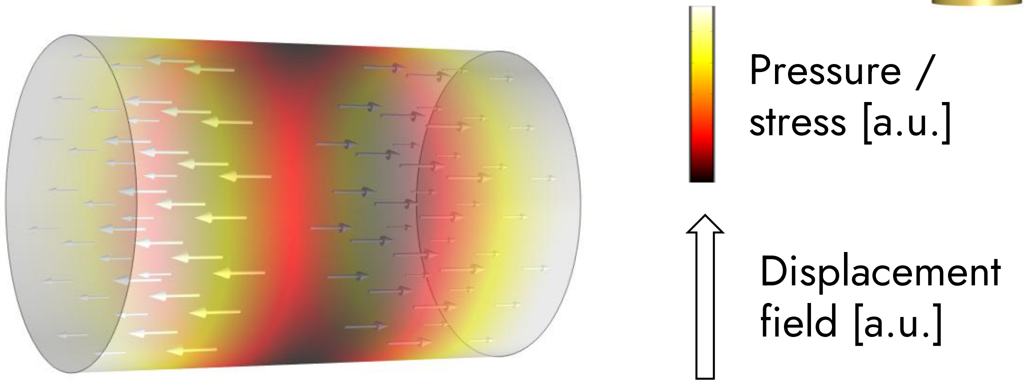
Signal

$$S^{\mathrm{th}}_{ff} = \frac{4k_{\mathrm{B}}T\mu\omega}{Q}$$

Thermal noise

$$\boxed{S^{\mathrm{s}}_{hh} \geq \frac{4k_{\mathrm{B}}T\mu}{Qq^2\omega^3}}$$

Strain sensitivity thermal limit



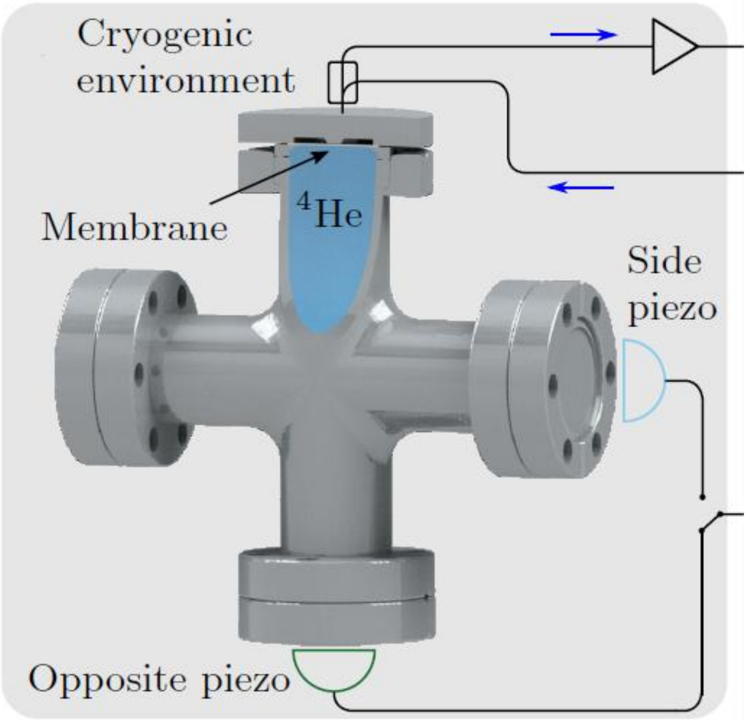
[1]

1960s: Weber Bar (Joseph Weber)

[1] S. Gottardo, *Substantia* 1, 61-67 (2017).

Superfluid Gravitational Wave Detector

[1]



[1] V. Vadakkumbatt, M. Hirschel, J. Manley, T. J. Clark, S. Singh & J. P. Davis, PRD 104, 082001 (2021).

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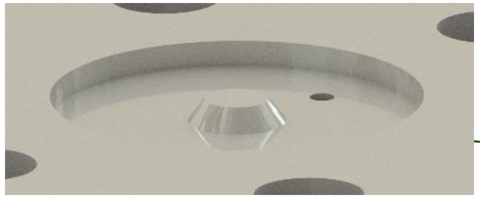

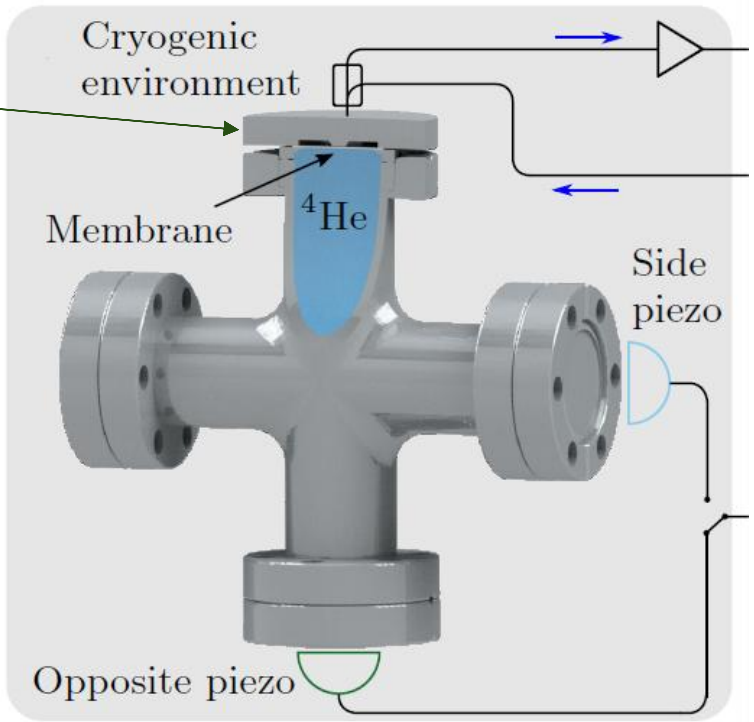

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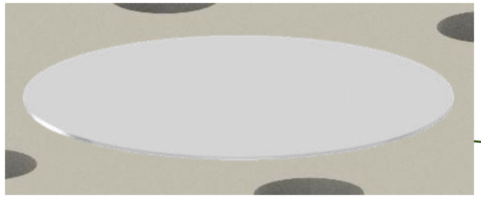

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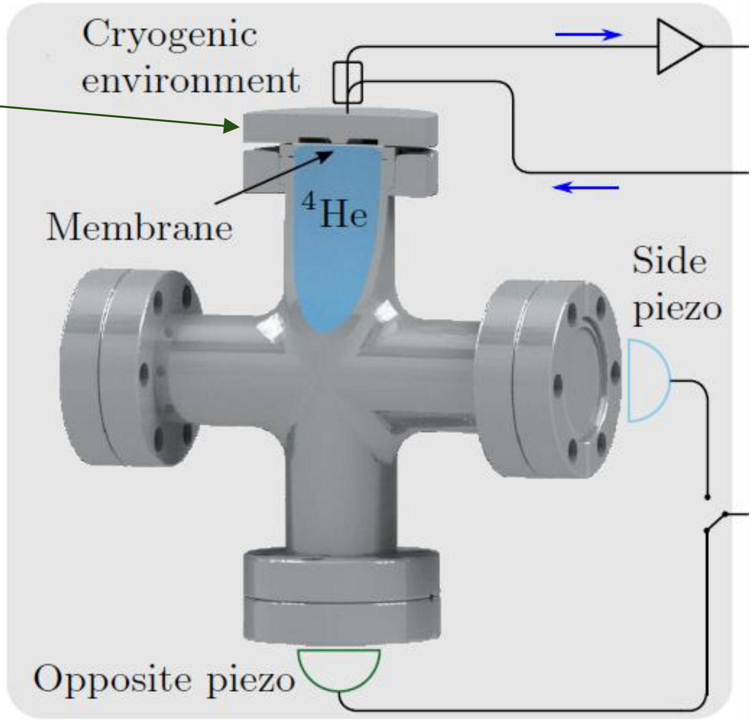

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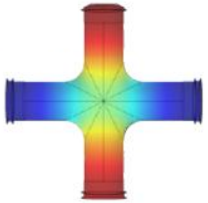
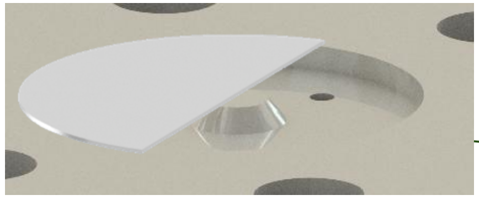


Electric Field [a.u.]



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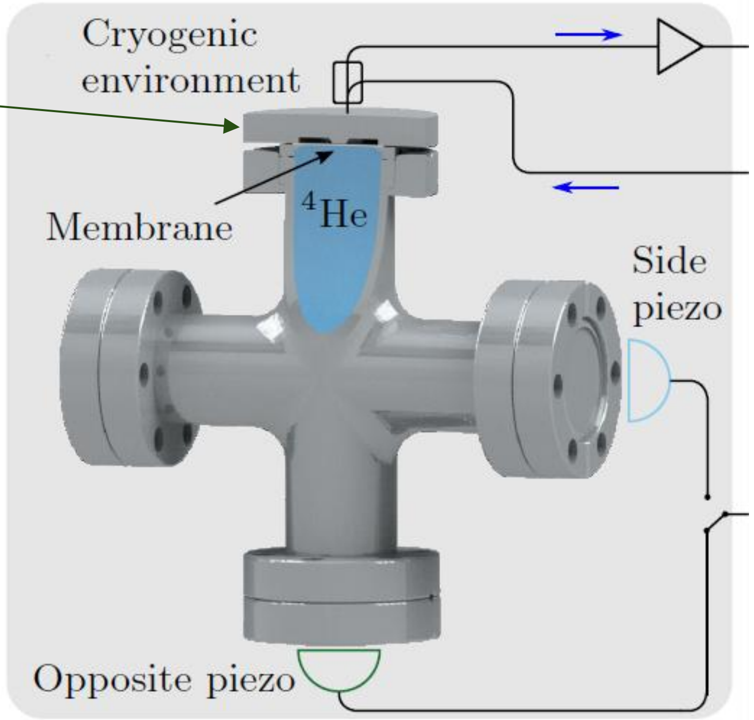

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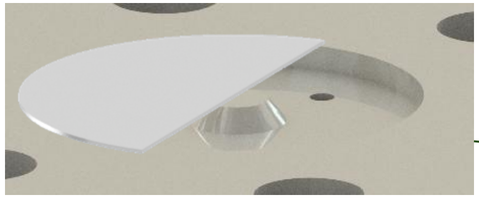

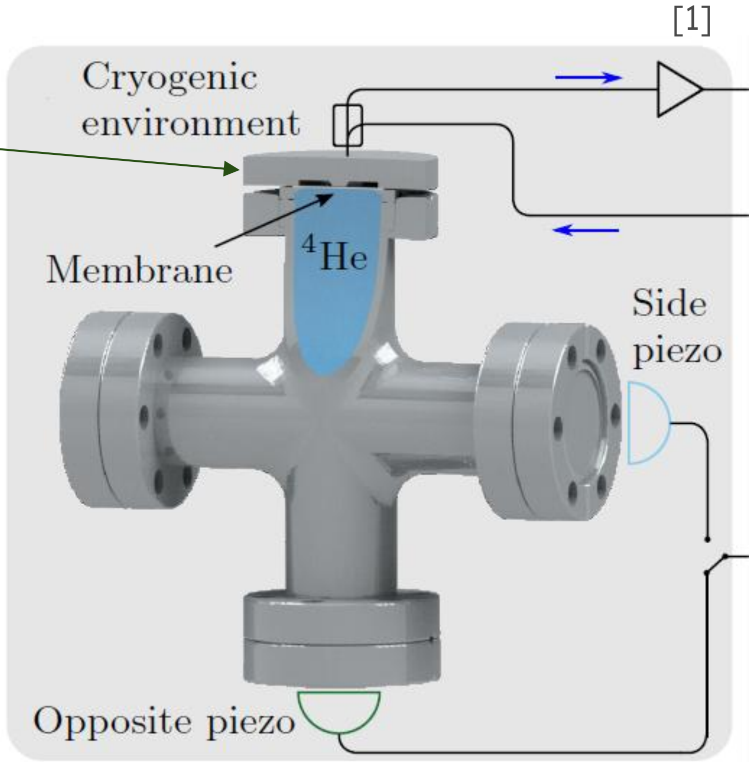

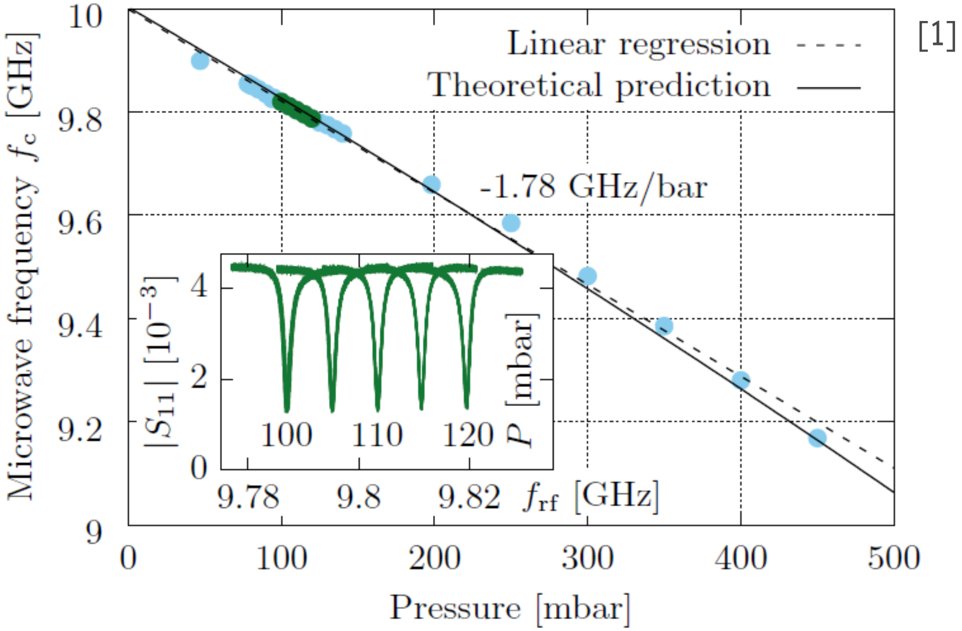

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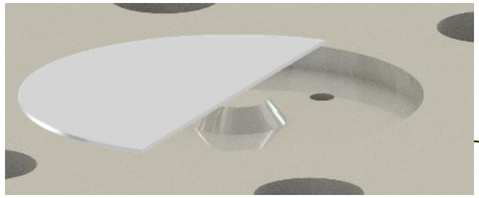

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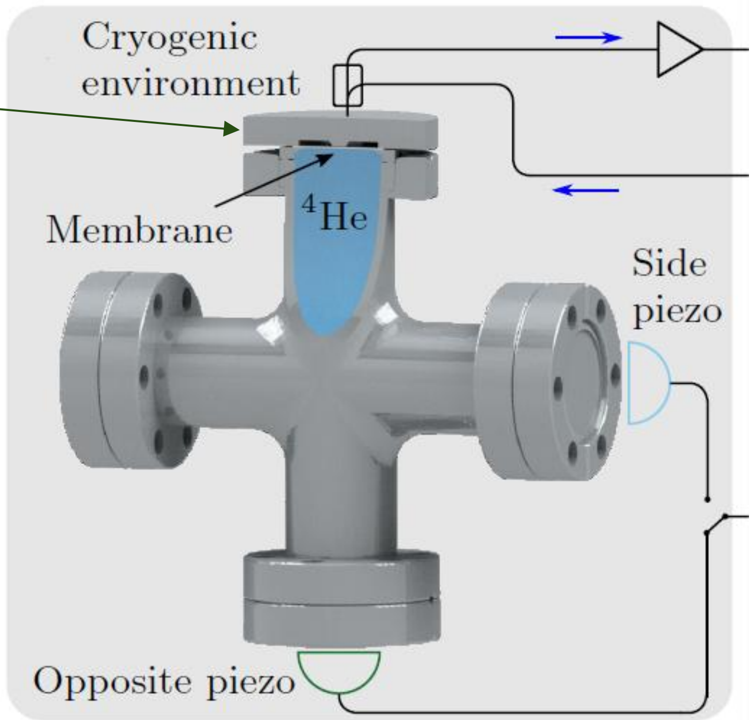
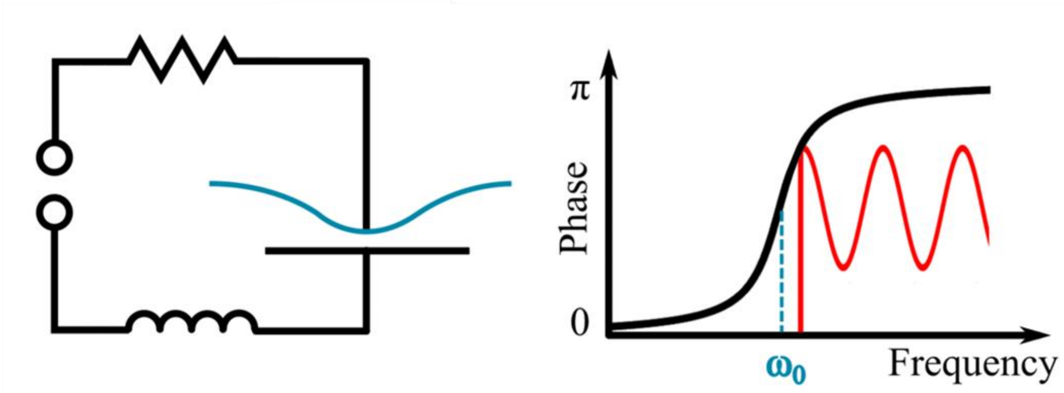


$$\omega_0(t) \approx \frac{1}{\sqrt{LC(t)}} \propto \sqrt{d_0 - x(t)}$$



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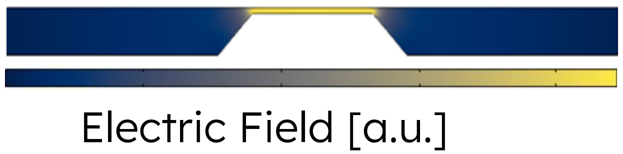

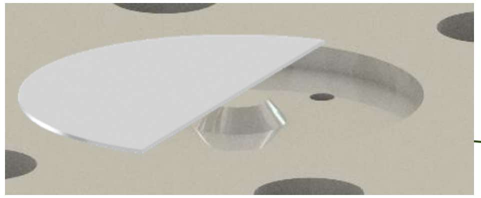

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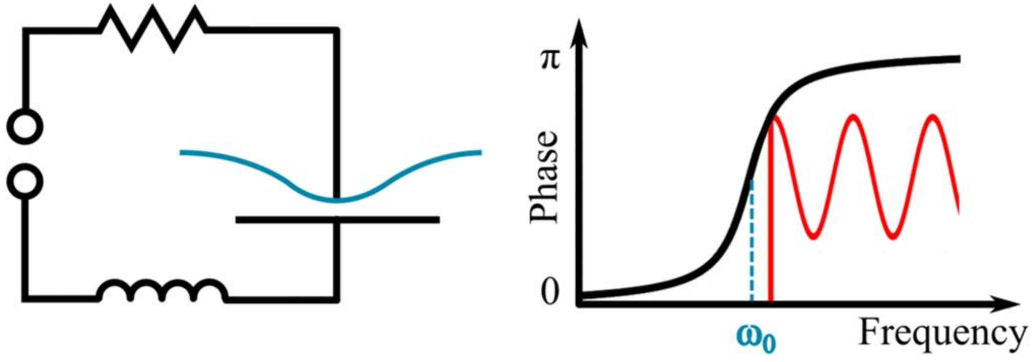

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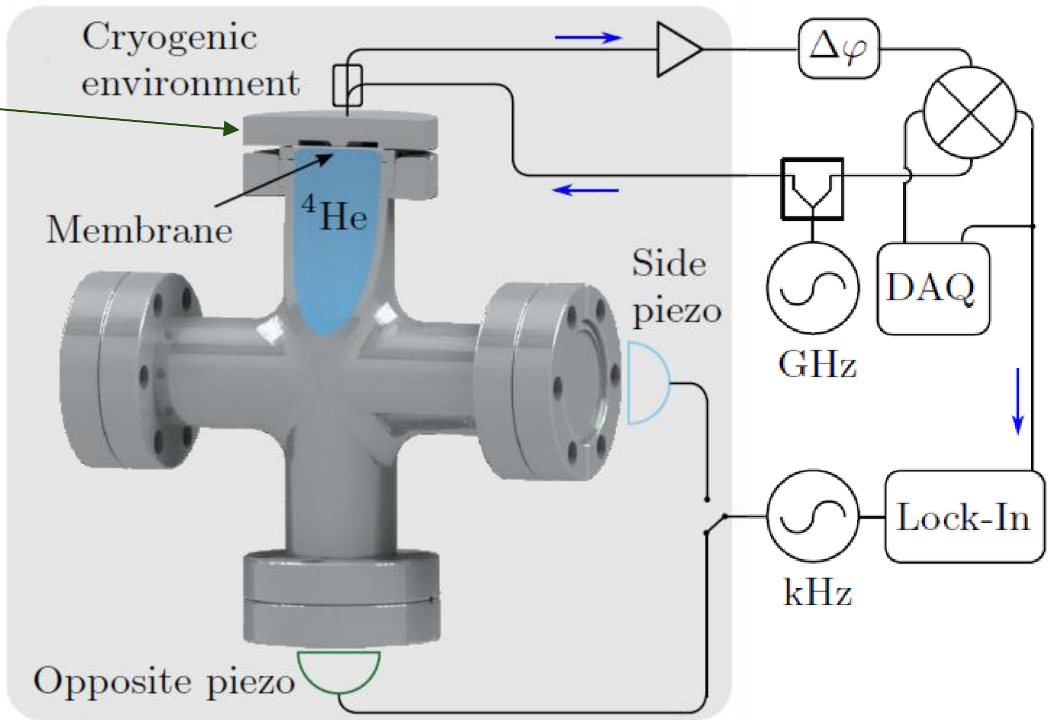

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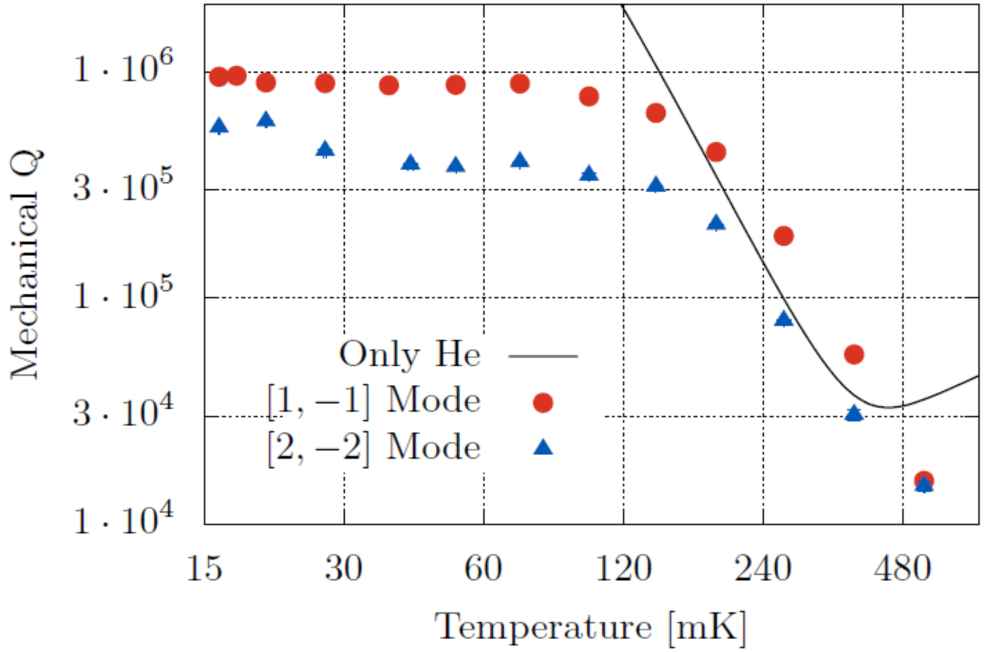

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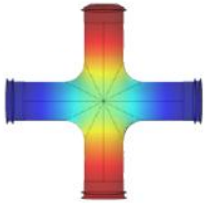

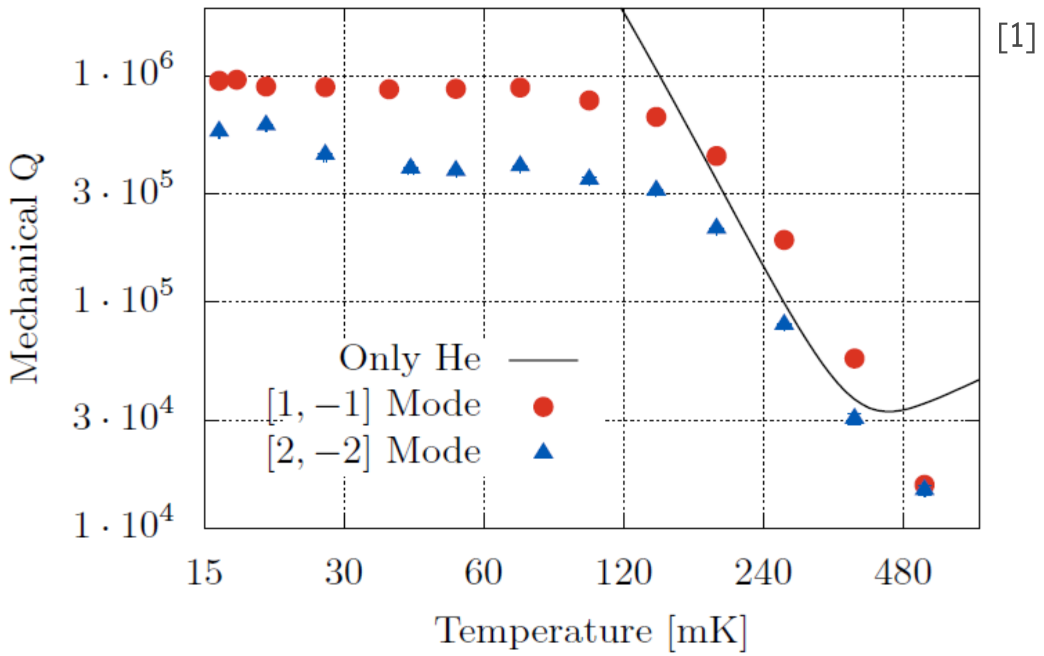

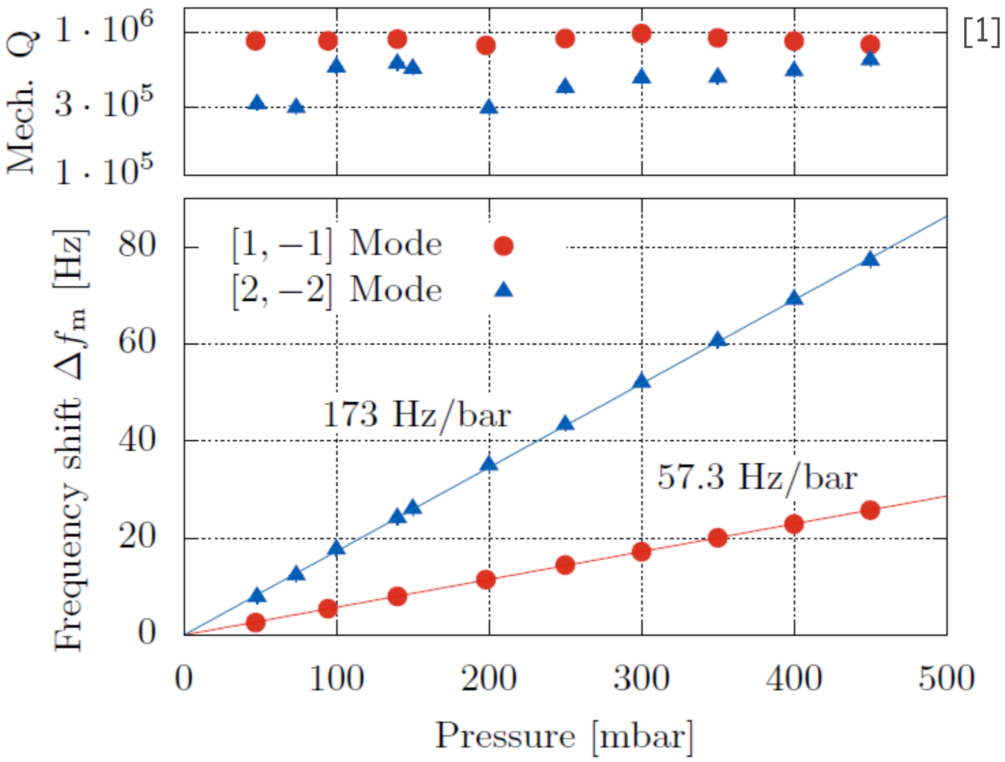

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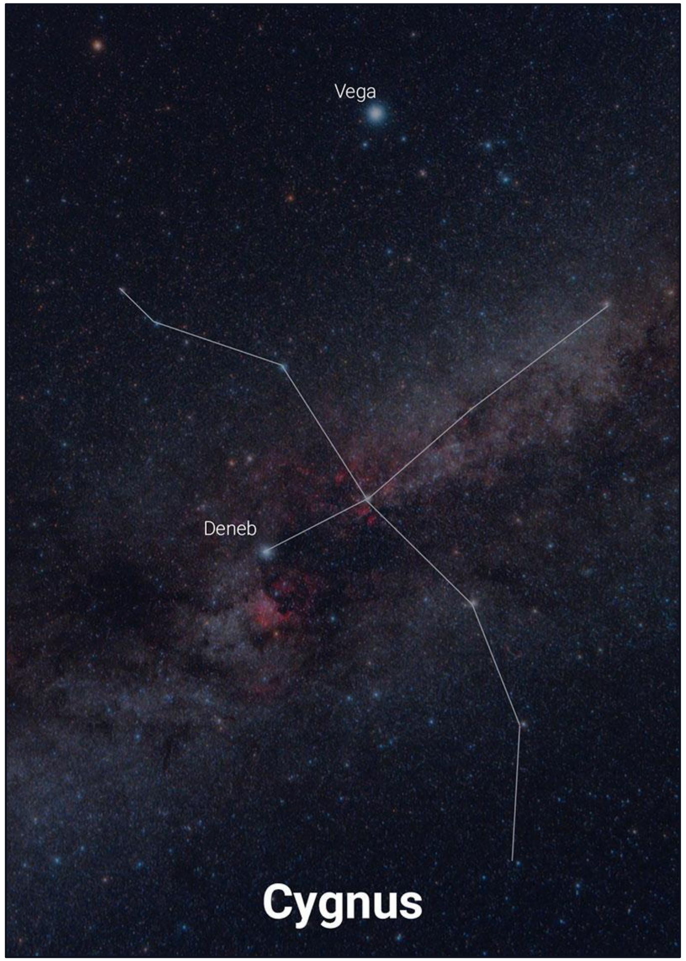
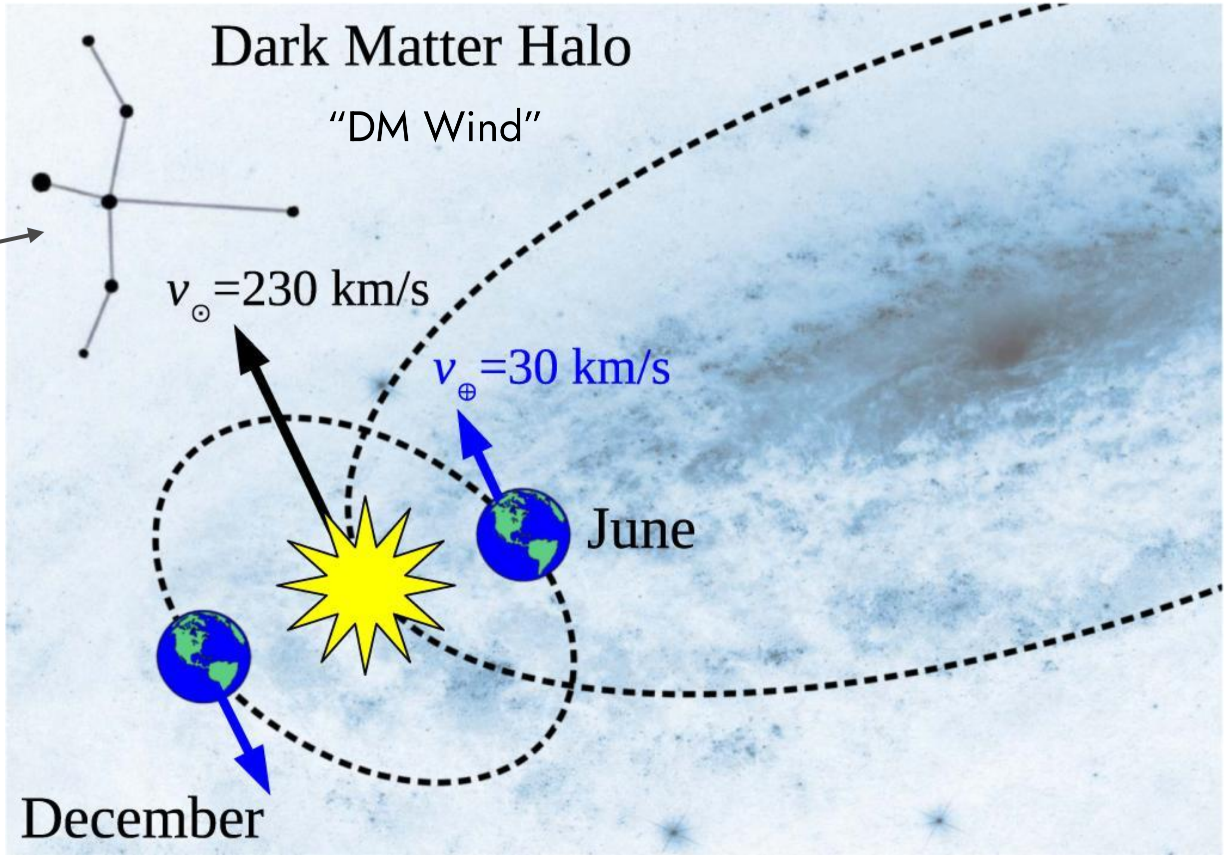
UDM Lineshape





[1]

[1] M. Schumann, *J. Phys. G: Nucl. Part. Phys.* 46, 103003 (2019)

UDM Lineshape

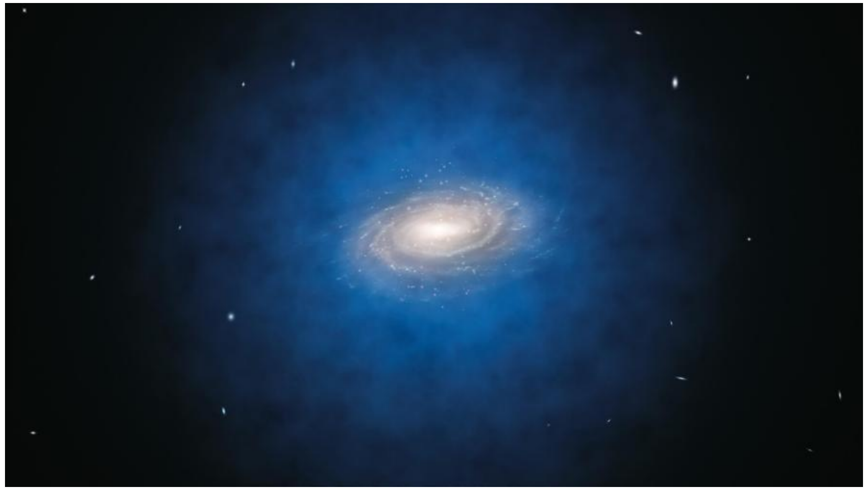
Particle velocity distribution:

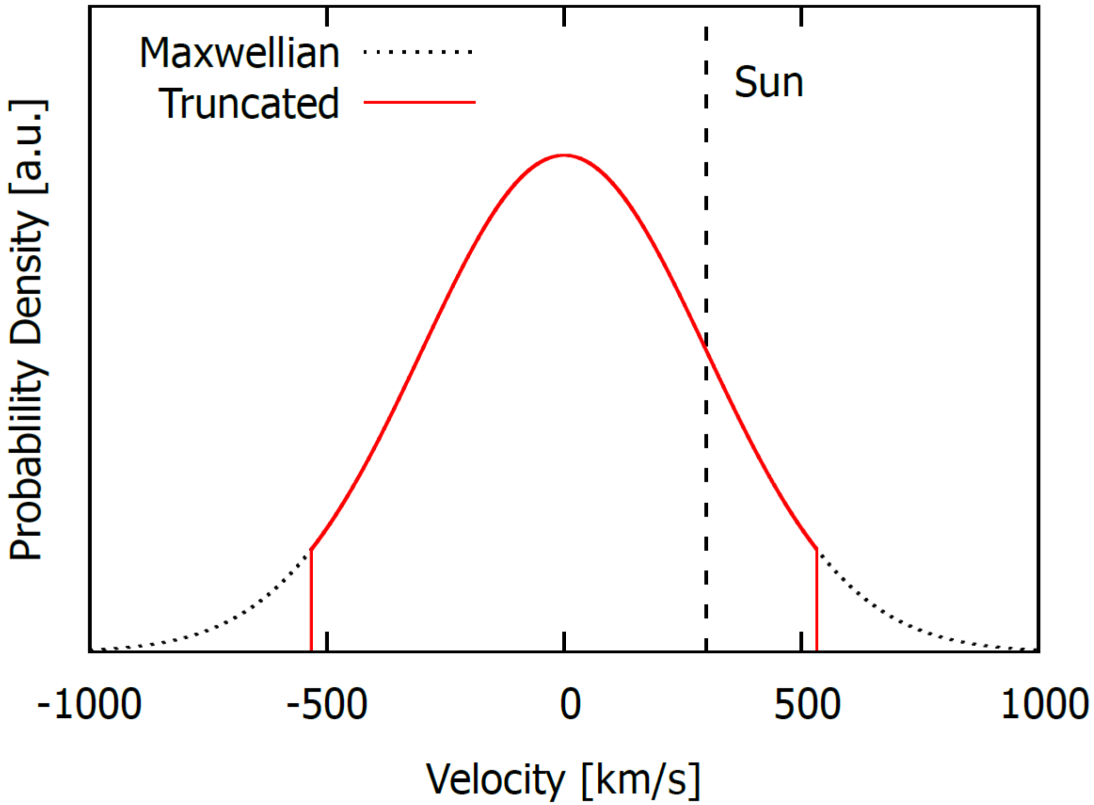
Truncated **Maxwell–Boltzmann**
(isotropic Gaussian)

$v_c \approx 230$ km/s

$v_{esc} \approx 530$ km/s

$$f_{\mathrm{gal}}(\vec{v}) = \begin{cases} N\exp\left(-|\vec{v}-\vec{v}_c|^2/v_c^2\right) & |\vec{v}-\vec{v}_c| < v_{\mathrm{esc}} \\ 0 & |\vec{v}-\vec{v}_c| \geq v_{\mathrm{esc}} \end{cases}$$





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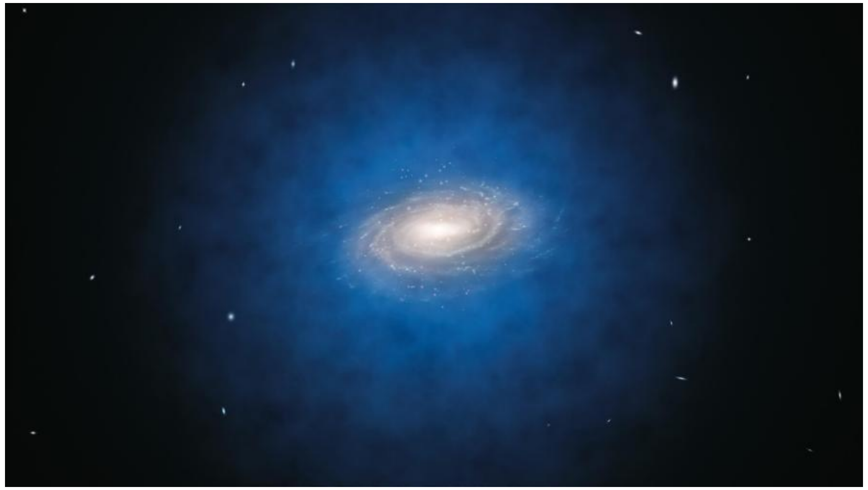

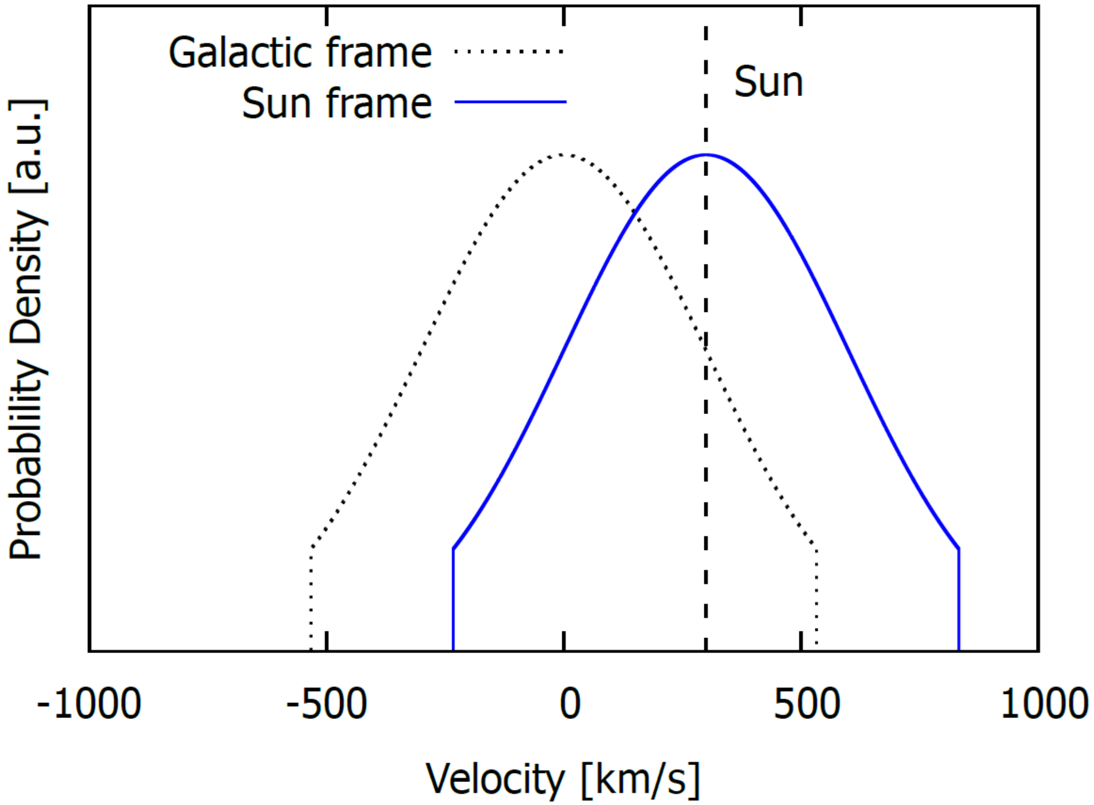

UDM Lineshape

Doppler shifted frequency: $$\omega'_\Phi = \omega_\Phi + \frac{m_\Phi v^2}{2\hbar}$$

UDM Lineshape

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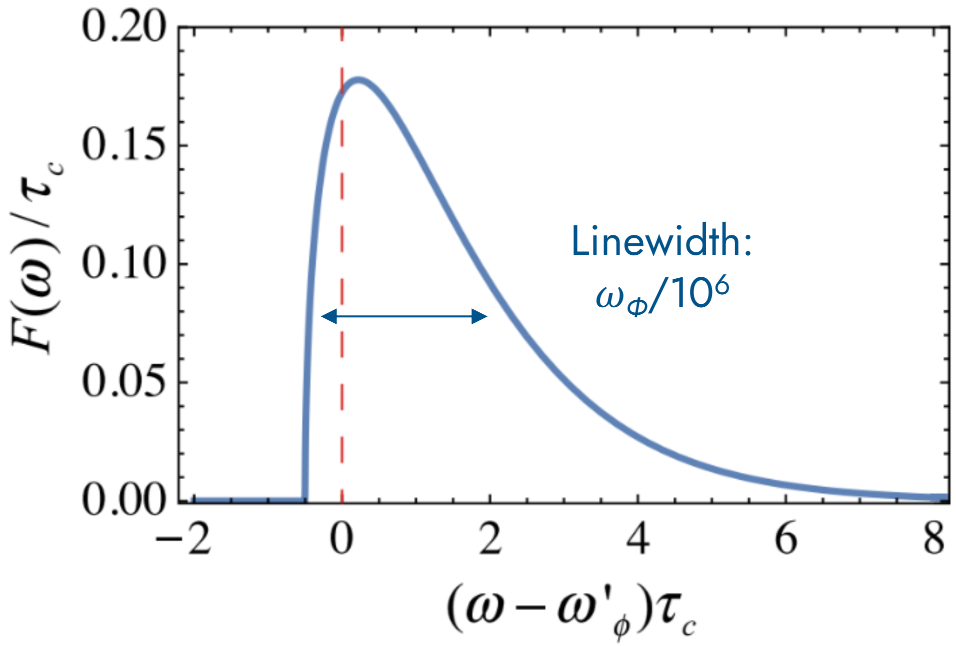
Single detector spectrum



[1]

[1] A. Derevianko, *PRA* 97, 042506 (2018).

UDM Lineshape

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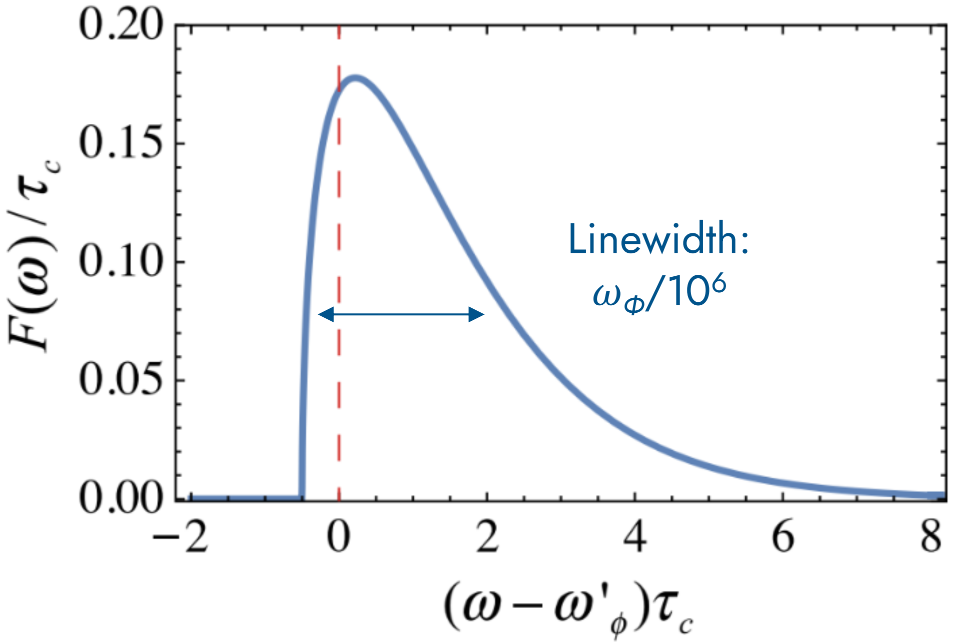
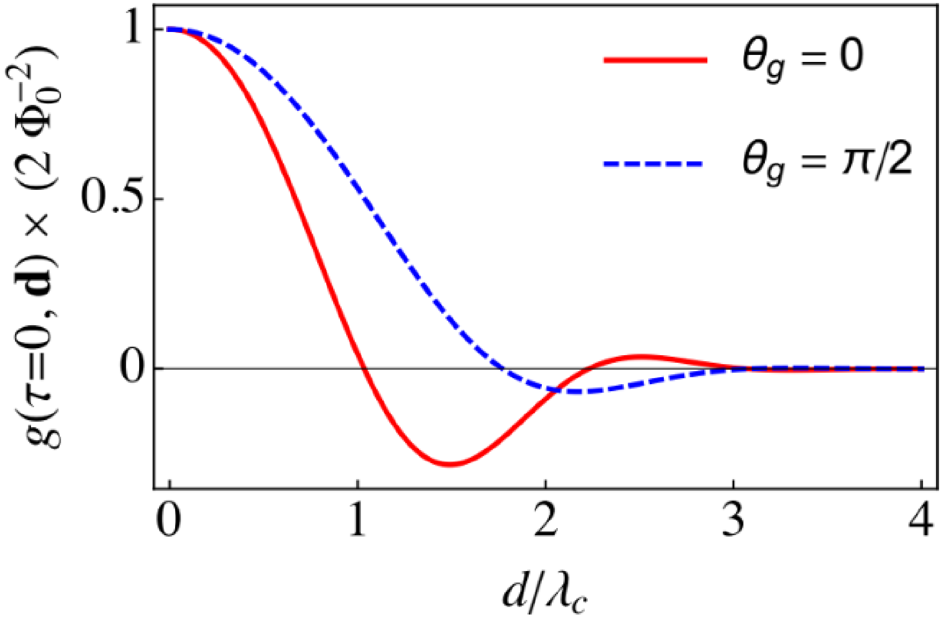


[1]

Two detectors, same time, different location



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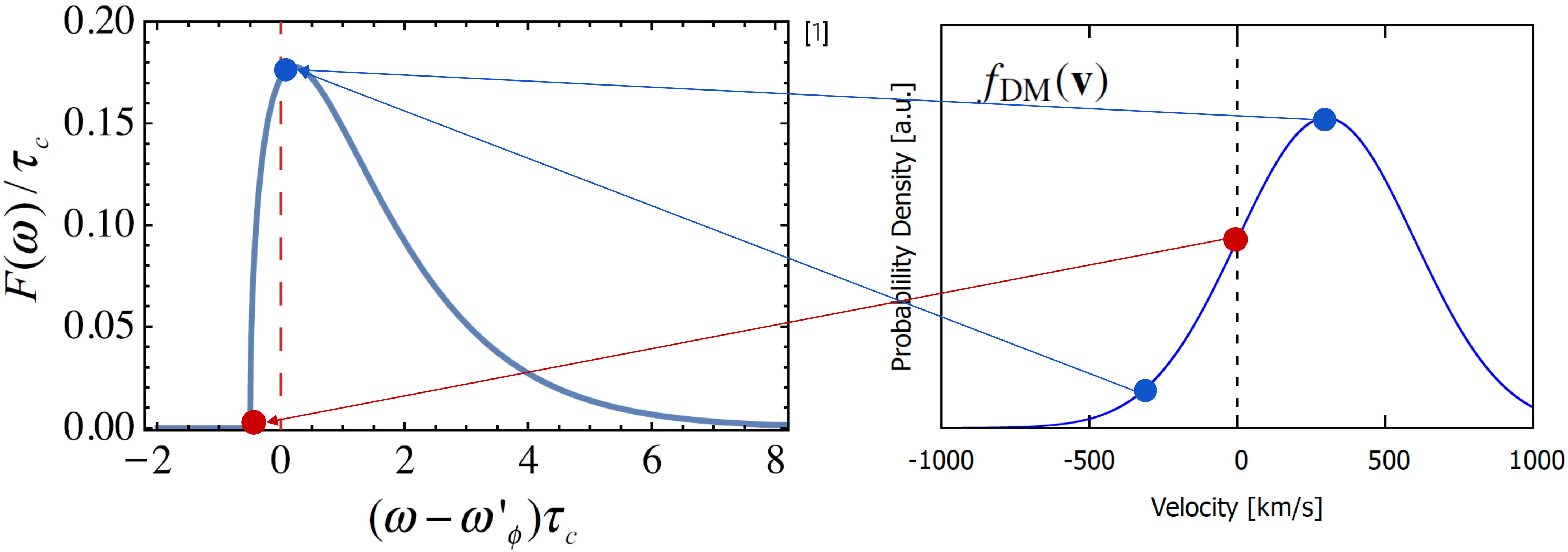
UDM Lineshape



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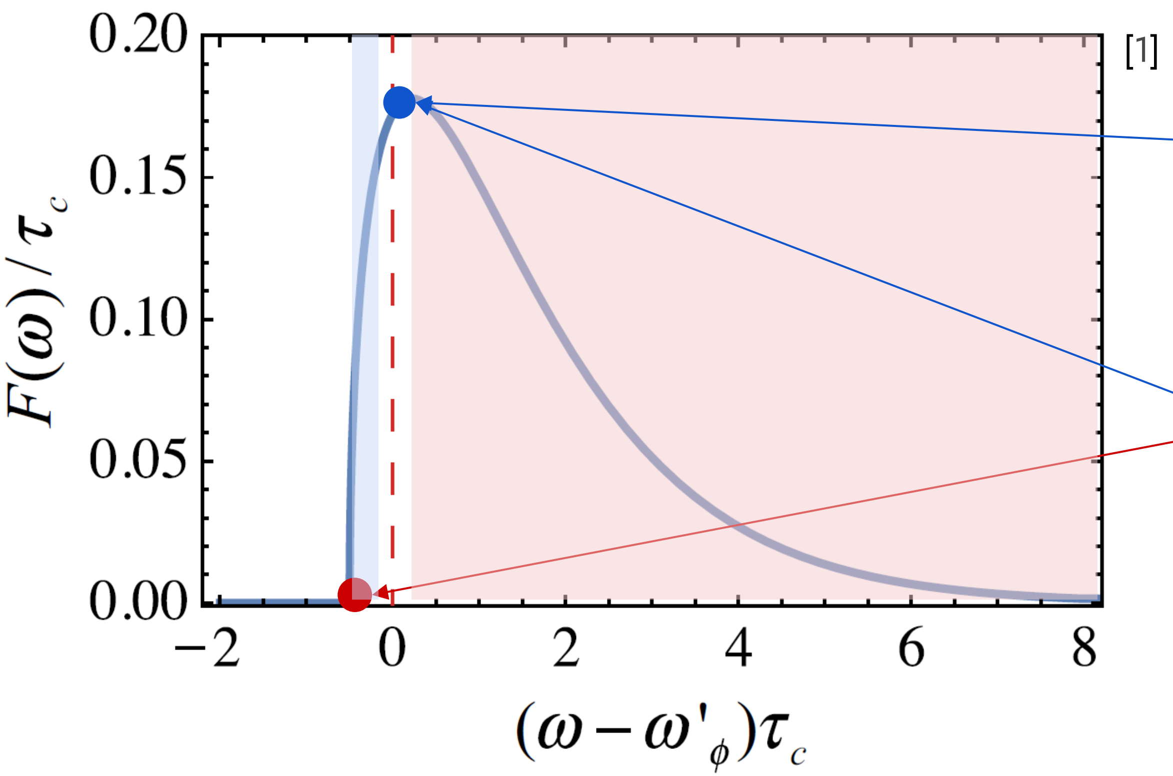

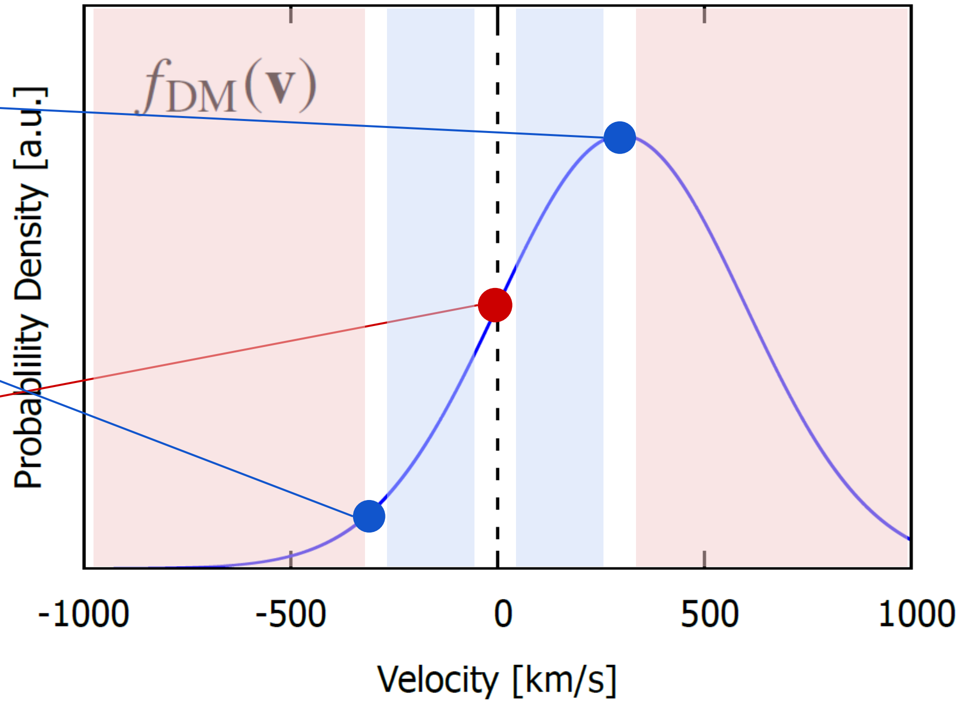

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Mechanical Sensors for UDM

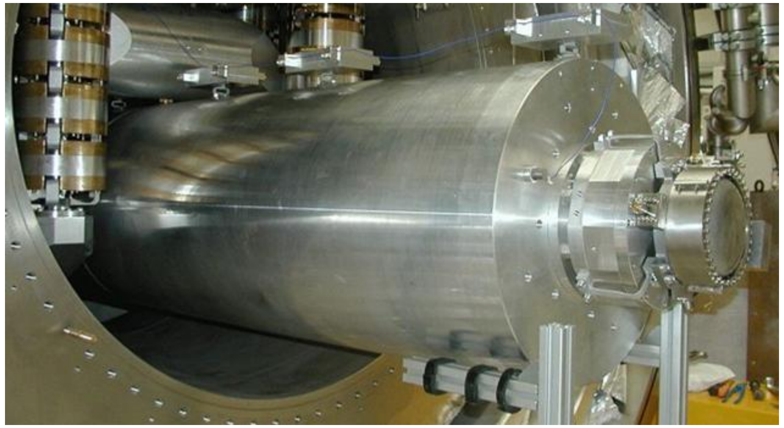
Scalar Boson $S = 0$

Vector Boson $S = 1$

Mechanical Sensors for UDM

Scalar Boson $S = 0$

AURIGA [1]



Vector Boson $S = 1$

[1] A. Branca, M. Bonaldi, M. Cerdonio et al., *PRL* 118, 021302 (2017).
[2] S.M. Vermeulen, P. Relton, H. Grote et al., *Nature* 600, 424–428 (2021).

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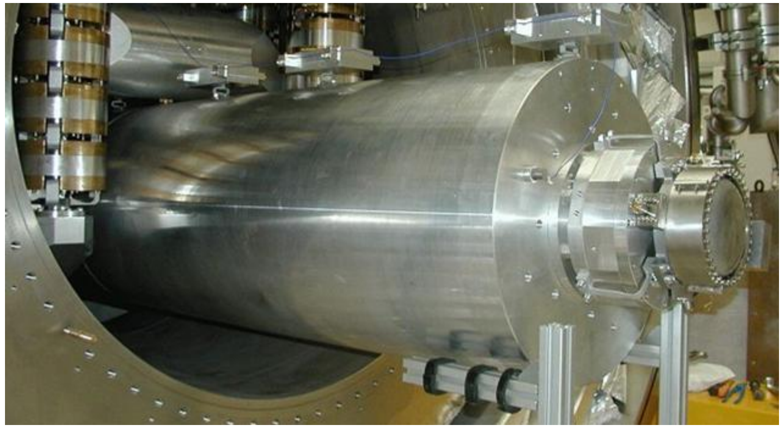

GEO600 [2]

Vector Boson $S = 1$

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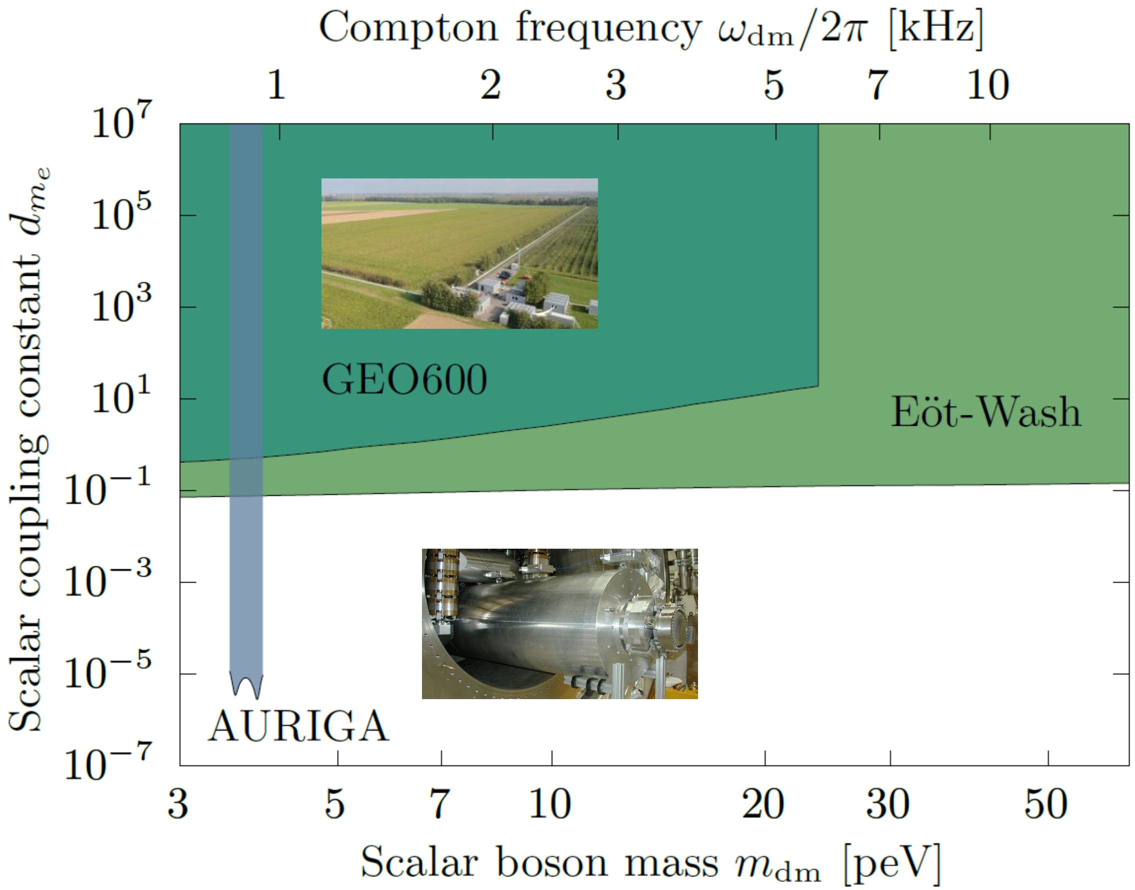

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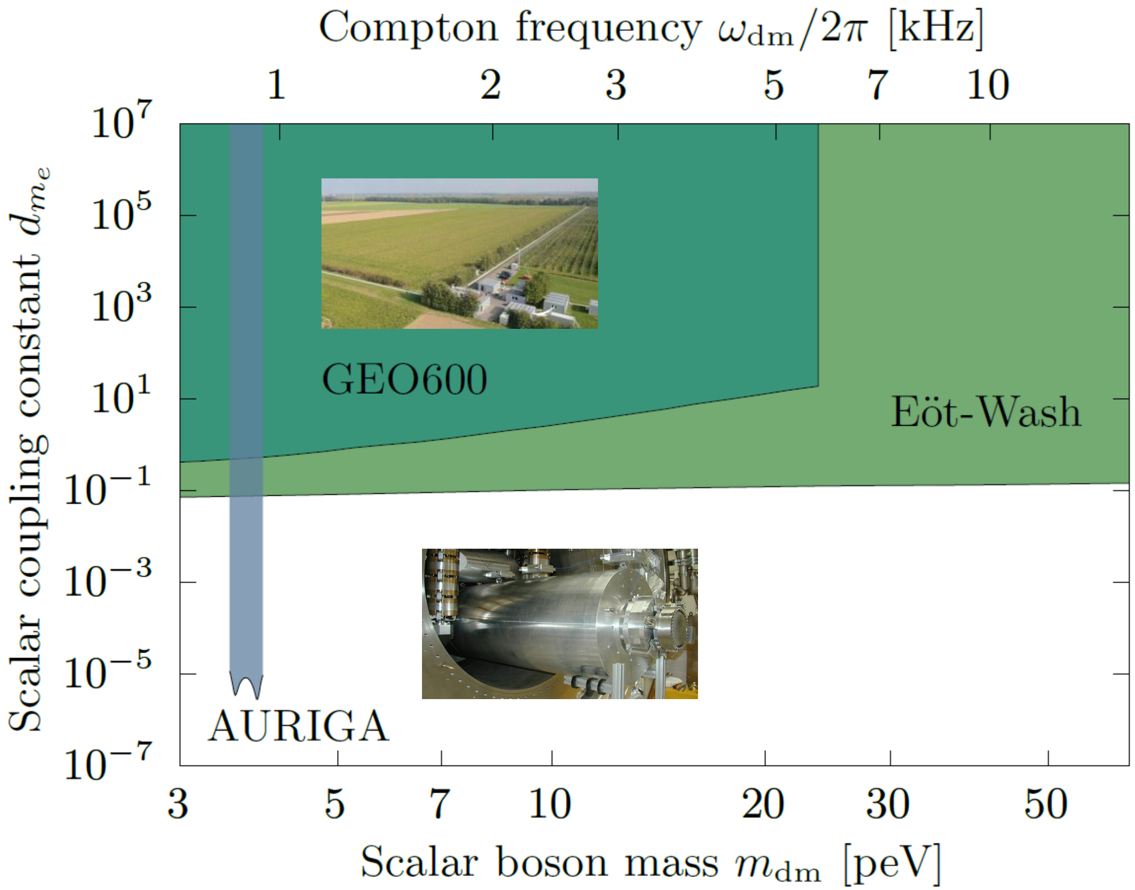

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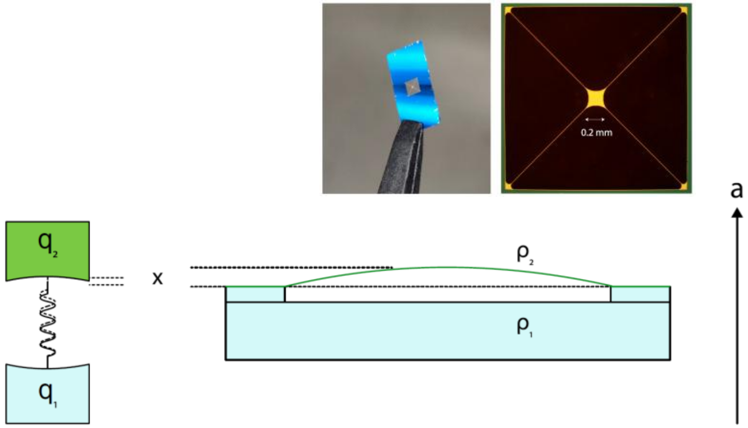

SiN Membrane
[3]

[3] J. Manley, M. Dey Chowdhury, D. Grin, S. Singh & D. J. Wilson, *PRL* 126, 061301 (2021).
[4] LIGO, Virgo & KAGRA collaborations, *PRD* 105, 063030 (2022).

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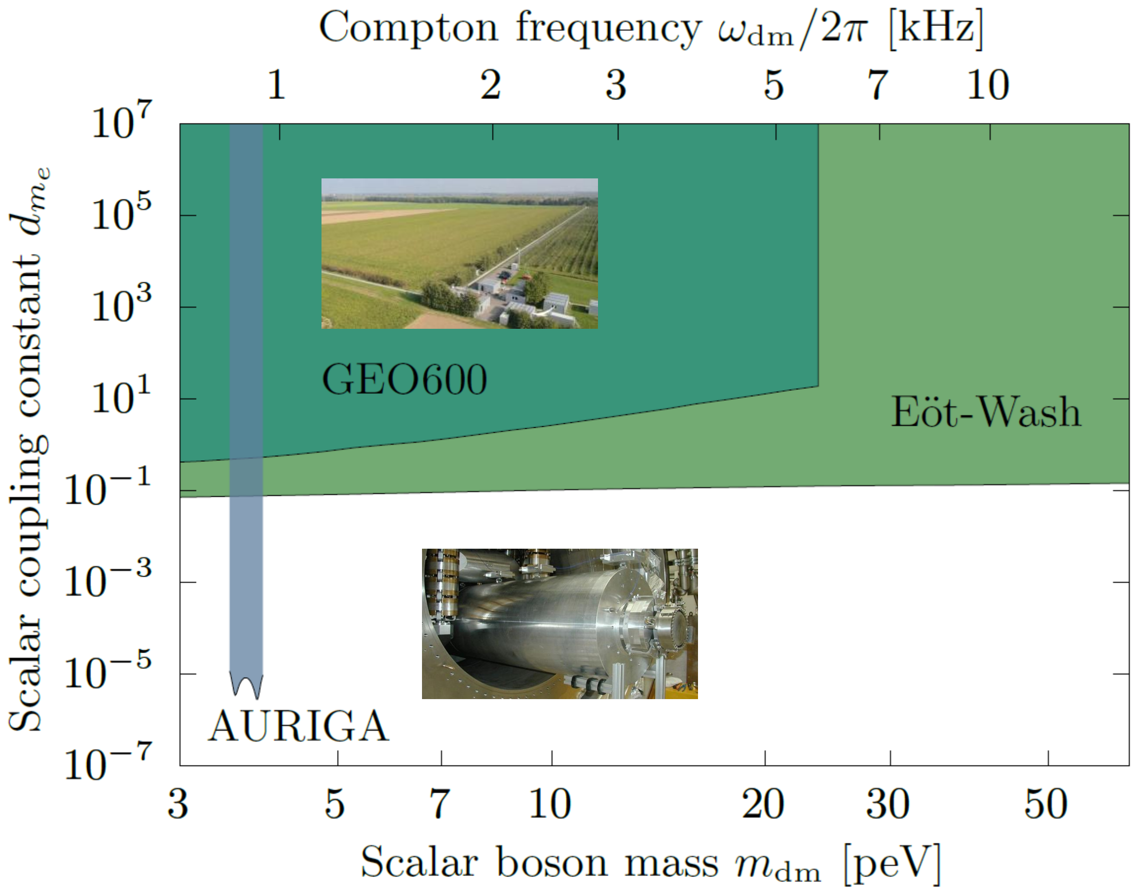

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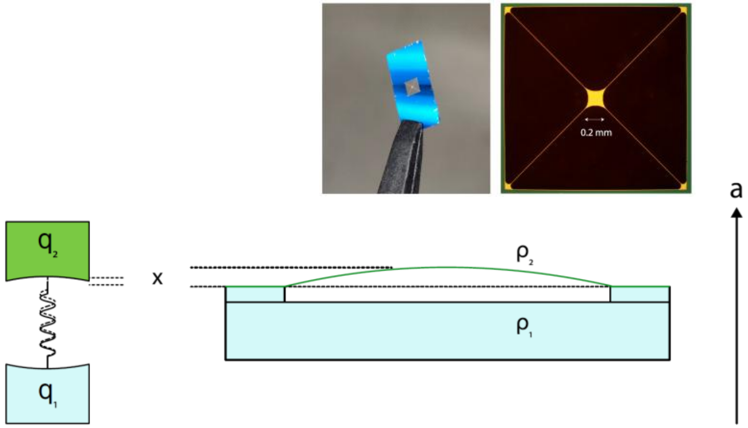

SiN Membrane [3]

LIGO & Virgo [4]

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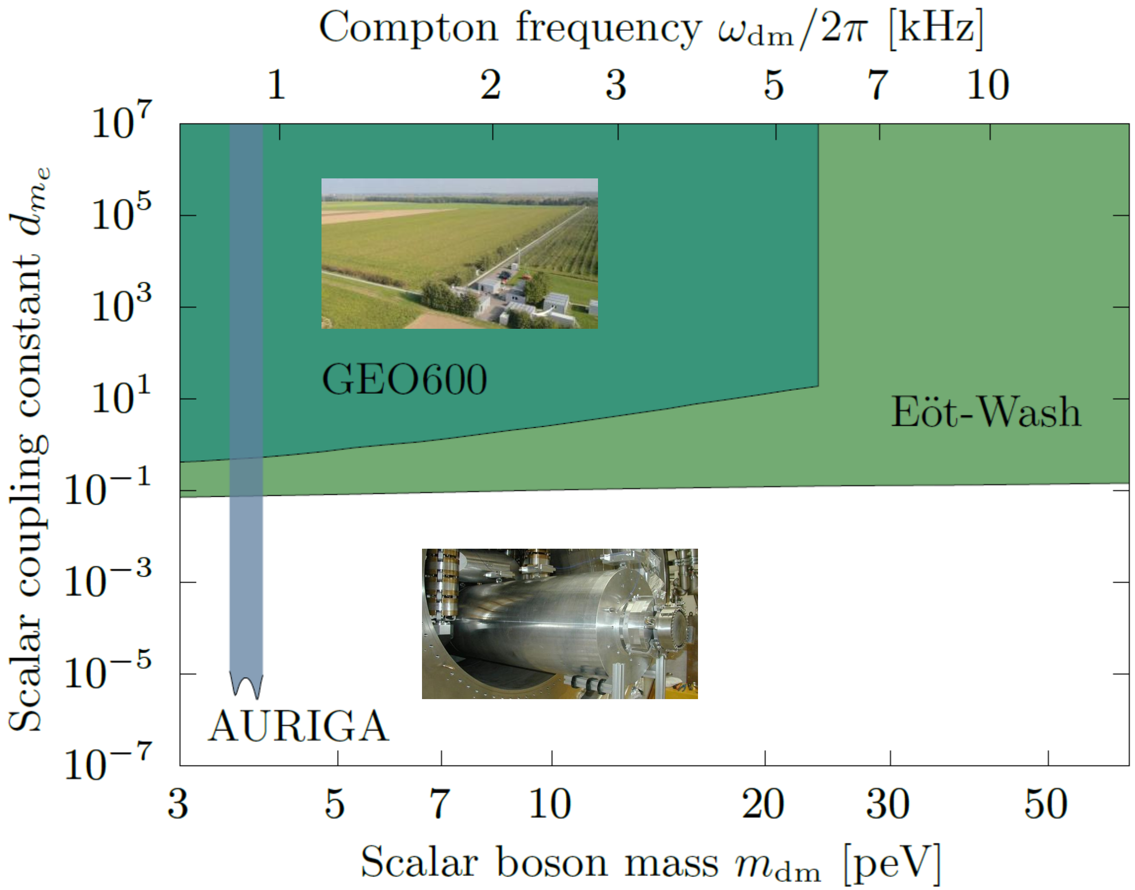

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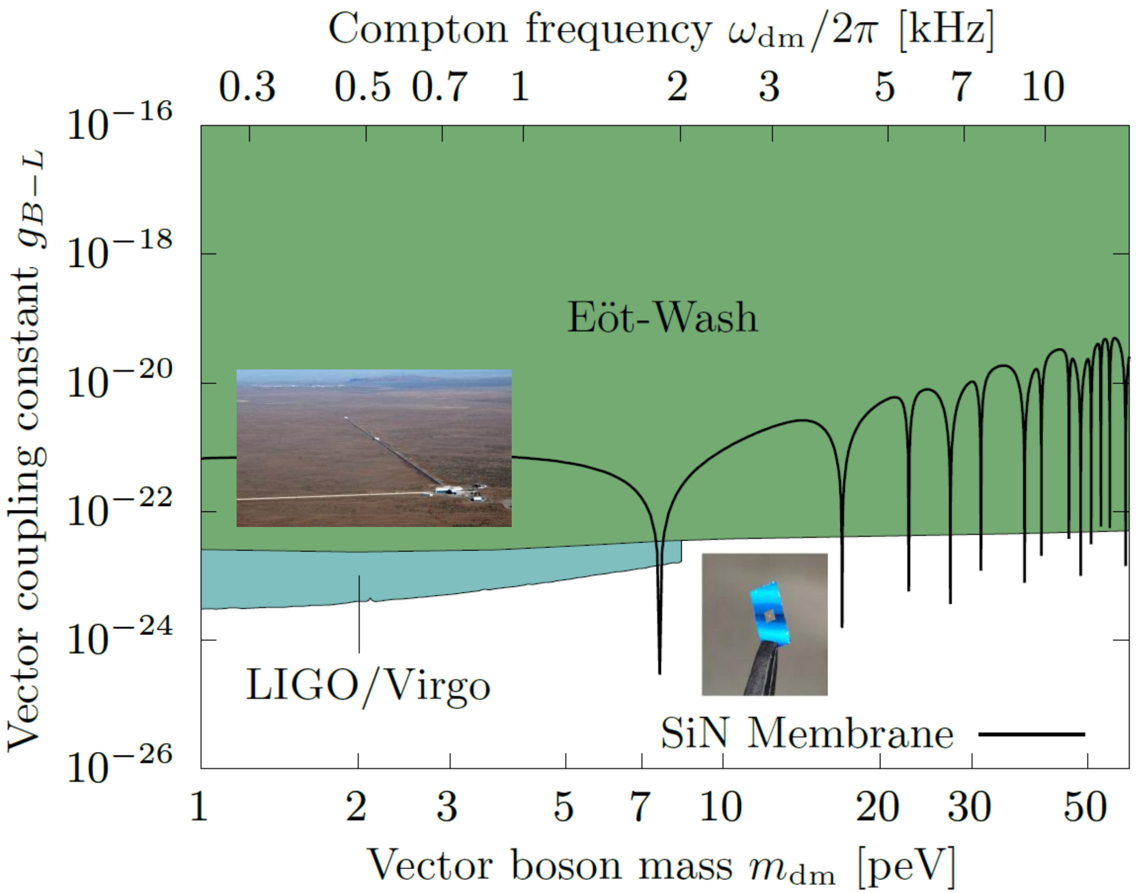

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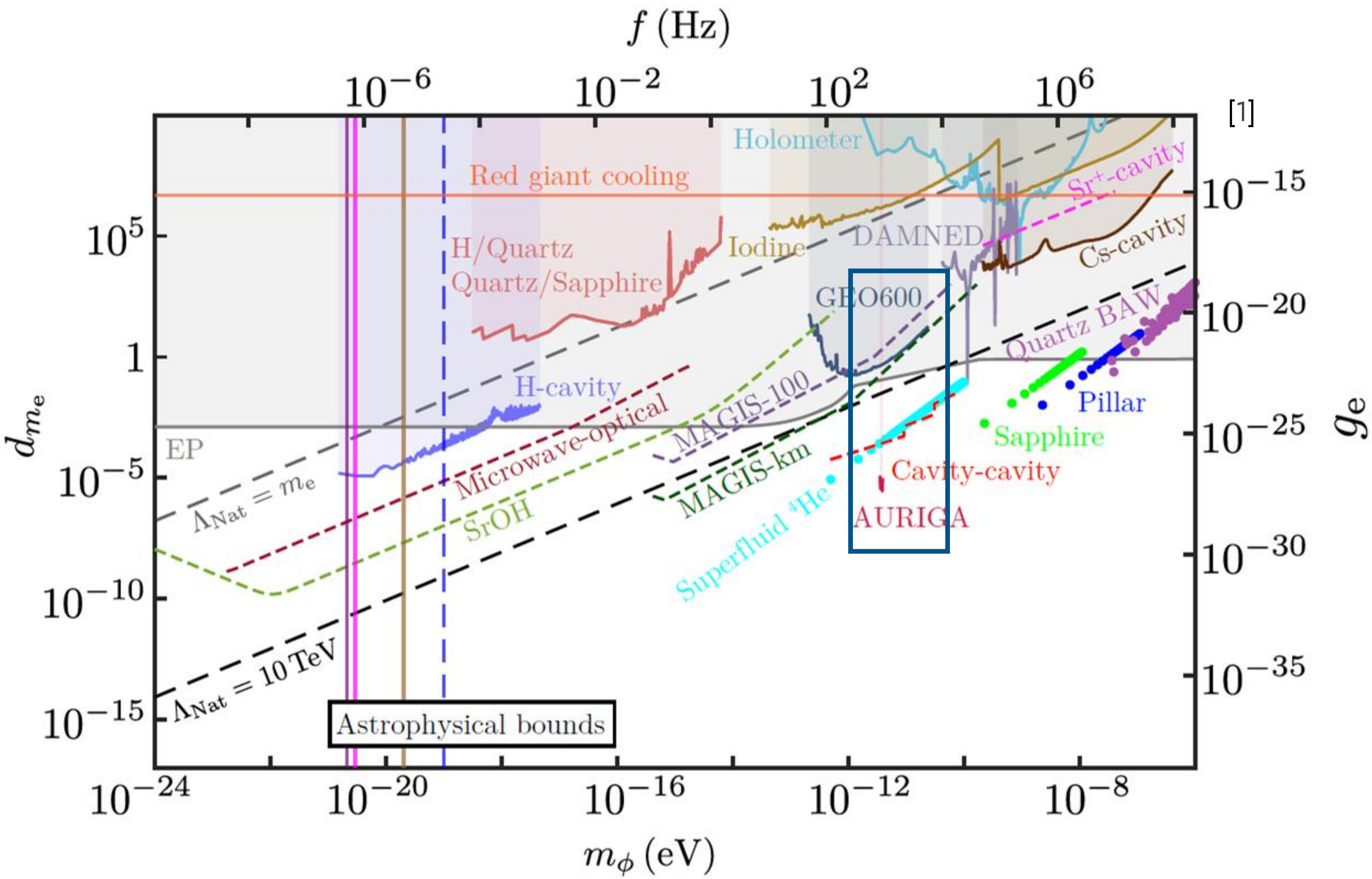
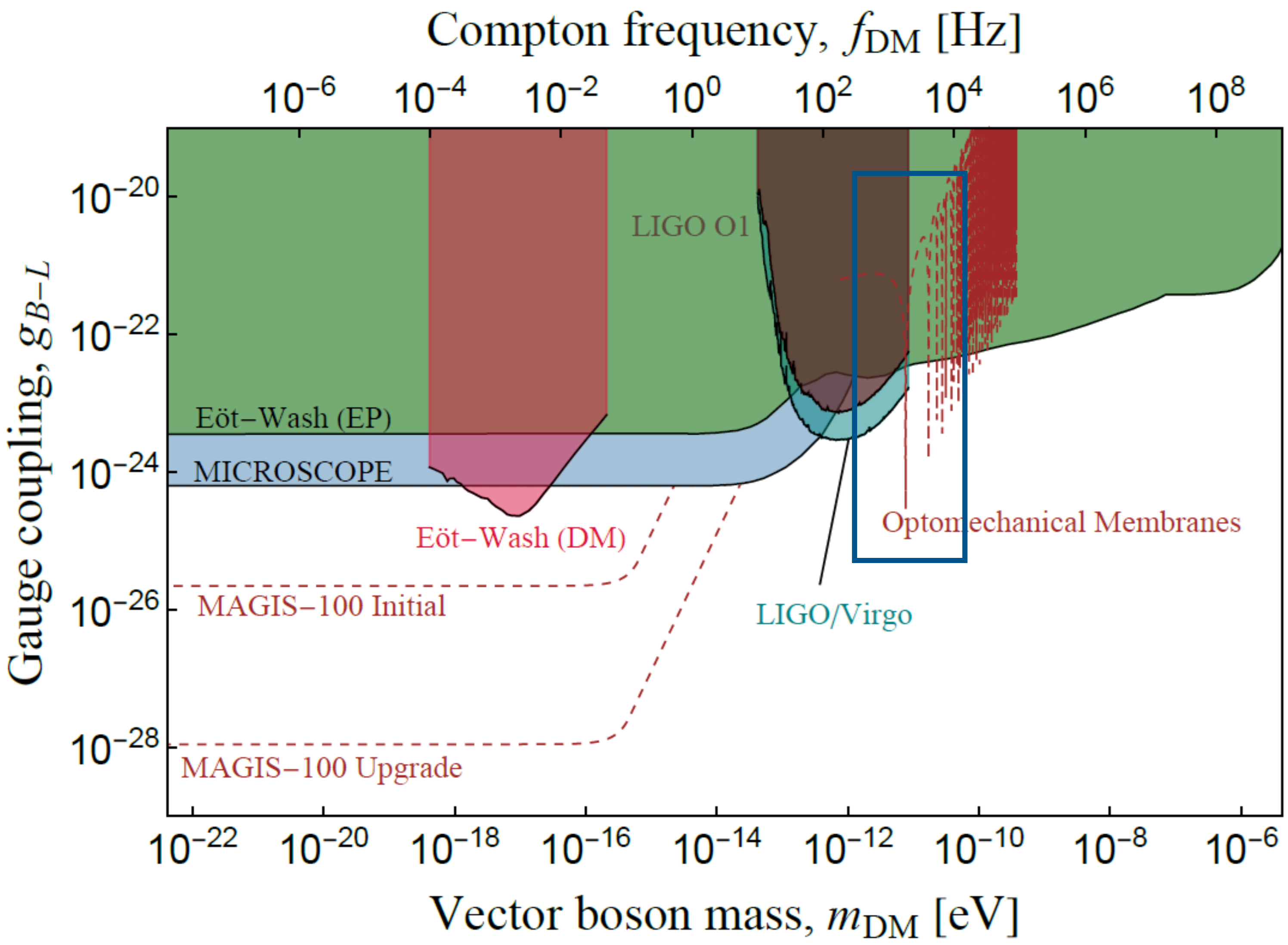
Scalar UDM Searches



[1] Snowmass 2021 "New Horizons", D. Antypas et al., arXiv: 2203.14915 (2022).

Vector UDM Searches



[1]

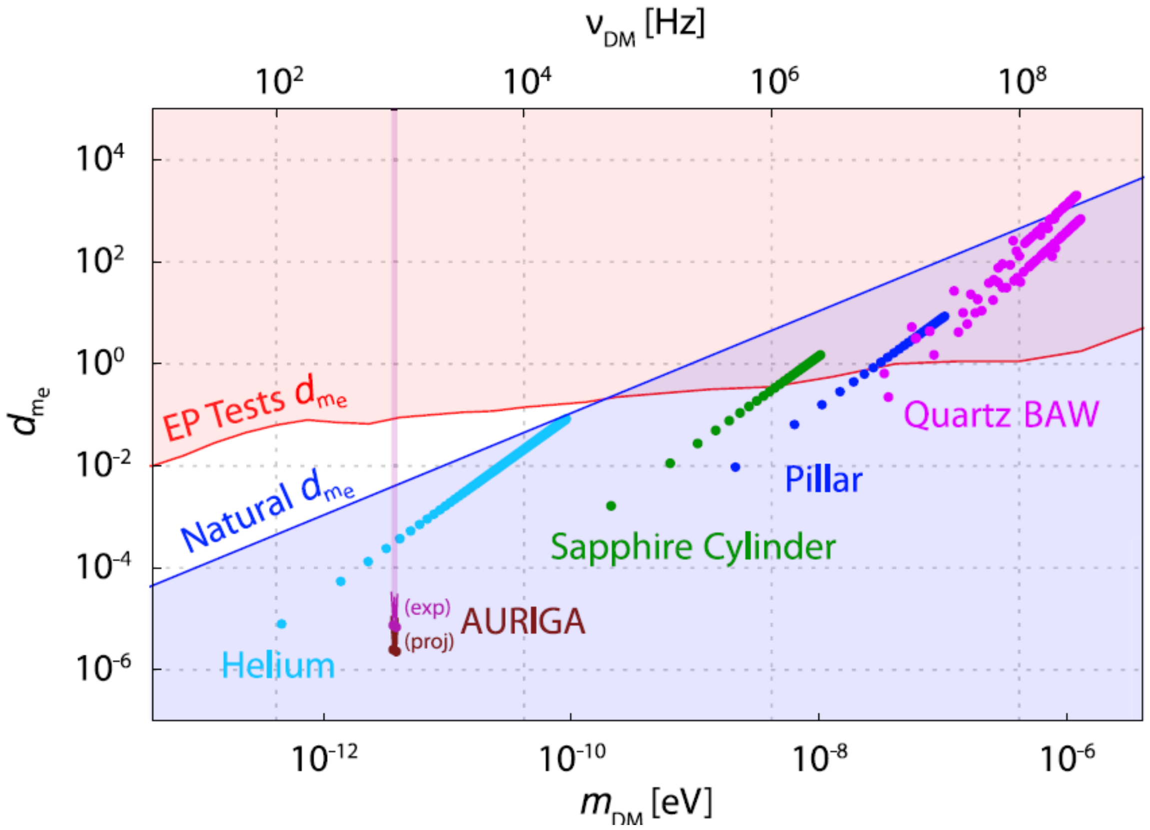
[1] Snowmass 2021 "New Horizons", D. Antypas et al., arXiv: 2203.14915 (2022).

Mechanical Detection of Scalar UDM

PHYSICAL REVIEW LETTERS **124,** 151301 (2020)

Searching for Scalar Dark Matter with Compact Mechanical Resonators

Jack Manley,[1] Dalziel J. Wilson,[2] Russell Stump,[1] Daniel Grin,[3] and Swati Singh[1,*]



[1] J. Manley, D. J. Wilson, R. Stump, D. Grin & S. Singh, *PRL* 124, 151301 (2020).

Scalar UDM Coupling

$$\Phi(\mathbf{r}, t) \approx \frac{\hbar\sqrt{2\varrho}}{mc}\cos(\omega t - \mathbf{k}\cdot\mathbf{r})$$

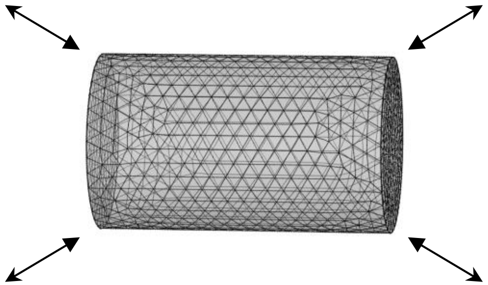
$$\mathscr{L}_{\text{int}}^{\text{lin}} = \frac{\sqrt{4\pi G}}{c^2}\,\phi(\boldsymbol{x},t)\left[d_e \frac{c^2\varepsilon_0}{4} F_{\mu\nu}F^{\mu\nu} - \sum_{\text{f}} d_{m_\text{f}} m_\text{f} c^2\, \bar{\psi}_\text{f}\psi_\text{f}\right]$$

$$\alpha(t) = \alpha_0\left[1 + d_e \frac{\sqrt{4\pi G}}{c^2}\Phi(\boldsymbol{r}_0, t)\right]$$

$$m_e(t) = m_{e,0}\left[1 + d_{m_e} \frac{\sqrt{4\pi G}}{c^2}\Phi(\boldsymbol{r}_0, t)\right]$$

$$a_0(t) = \frac{\hbar}{c\, m_e(t)\, \alpha(t)}$$

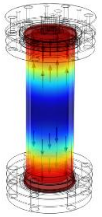
Modulation of Bohr radius



Isotropic strain

$$h(t) = \underbrace{d_{\text{DM}} \frac{\sqrt{8\pi G\varrho}}{\omega c}}_{h_0}\cos(\omega t)$$

HeLIOS – First Prototype



Mode	Simulated f [Hz]	μ/M	q [g cm]	$\beta_{12} f_{12}$	Measured f [Hz]	Q [10^6]
[0, 0, 1]	933	0.50	2.97	4.20×10^{-2}	998	0.26
[0, 0, 2]	1854	0.49	49.5	1.63×10^{-6}	1864	2.2
[0, 0, 3]	2785	0.47	1.26	1.44×10^{-2}	2800	3.7
[0, 0, 4]	3712	0.43	42.6	2.70×10^{-6}	3729	1.9
[0, 0, 5]	4648	0.42	2.55	0.90×10^{-2}	4668	2.2
[0, 0, 6]	5589	0.40	103	2.38×10^{-6}	5605	2.6

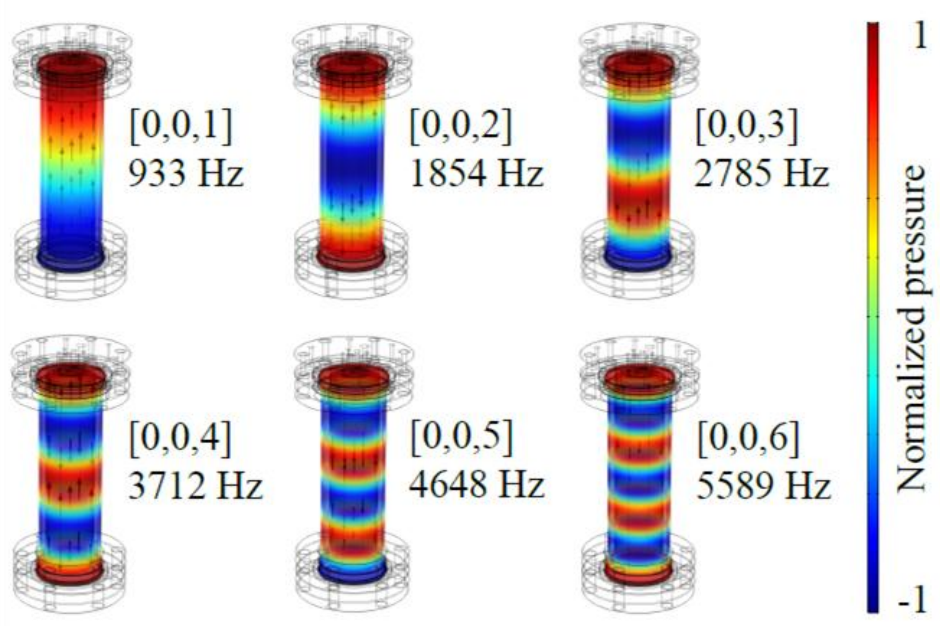
[1]

$$\mu_n = \int \rho\, |\tilde{\boldsymbol{u}}_n(\boldsymbol{x})|^2 \, \mathrm{d}^3 x$$

$$q_n = \int \rho\, \tilde{\boldsymbol{u}}_n(\boldsymbol{x}) \cdot \boldsymbol{x}\, d^3 x$$

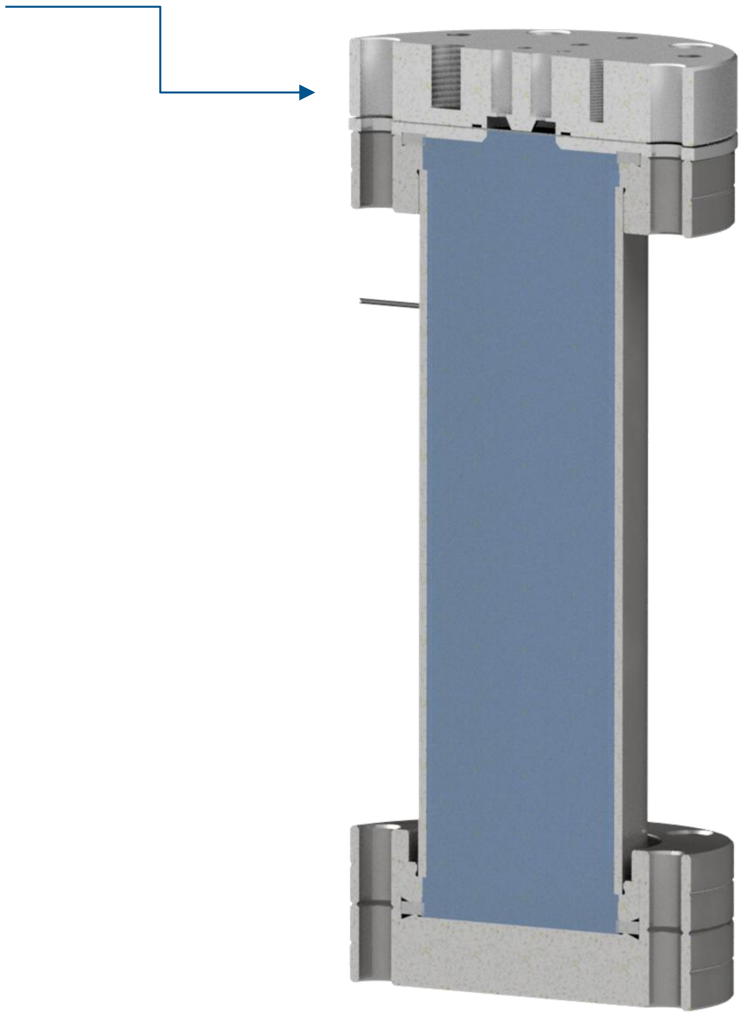
$$\beta_{n,j} = \int_j \hat{\boldsymbol{a}} \cdot \tilde{\boldsymbol{u}}_n(\boldsymbol{x})\, \mathrm{d}^3 x / \int_{1\cap 2} |\tilde{\boldsymbol{u}}_n(\boldsymbol{x})|^2 \, \mathrm{d}^3 x$$

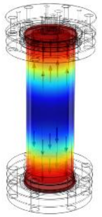
[1]



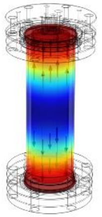
[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

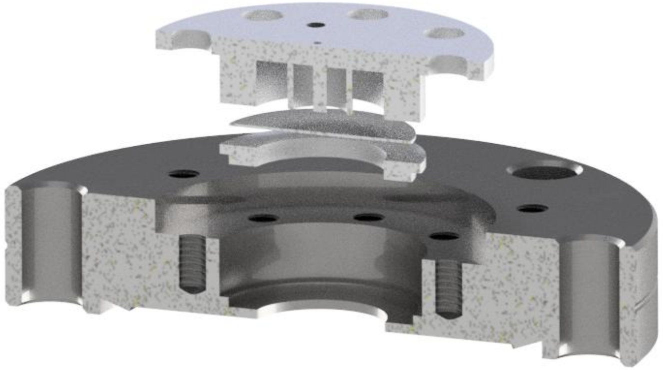
HeLIOS Microwave Optomechanical Transducer



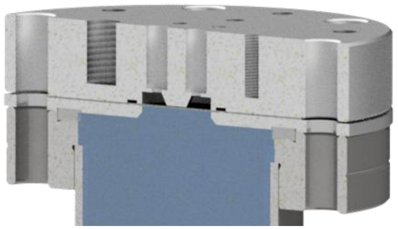


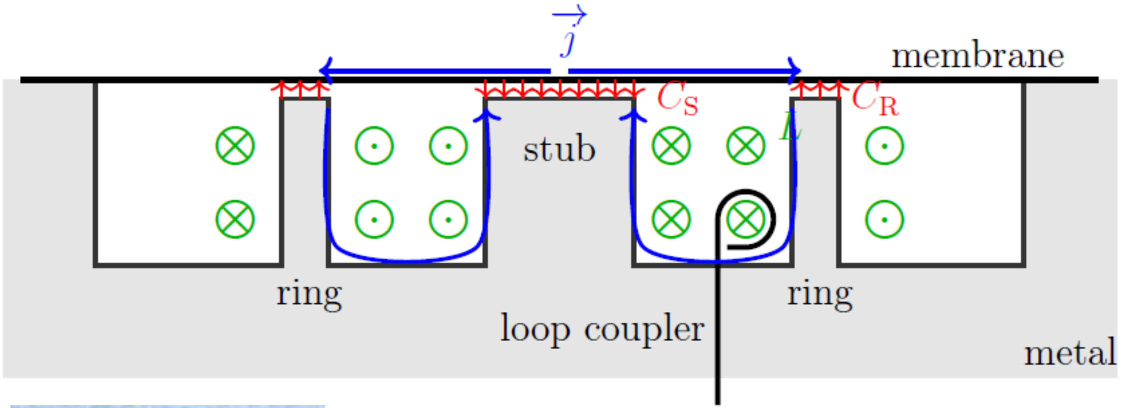
HeLIOS Microwave Optomechanical Transducer

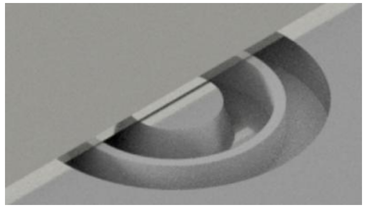


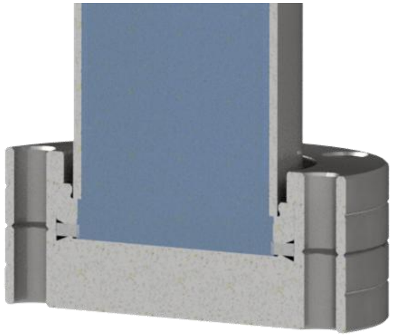


Microwave Transducer

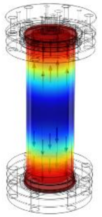


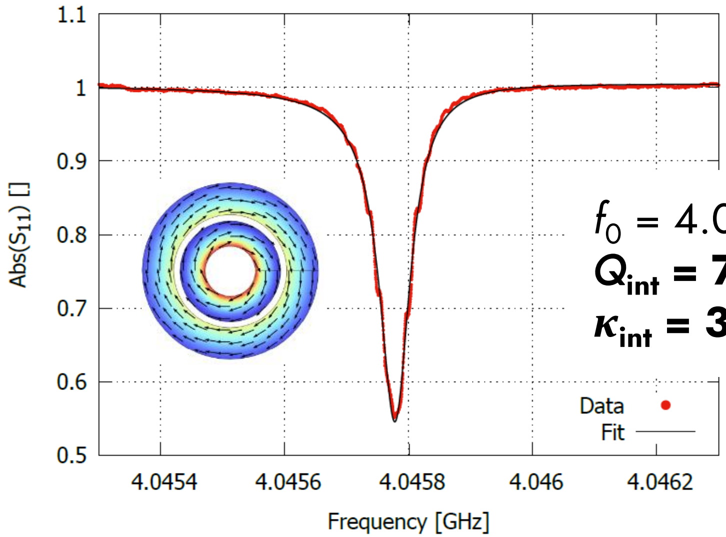




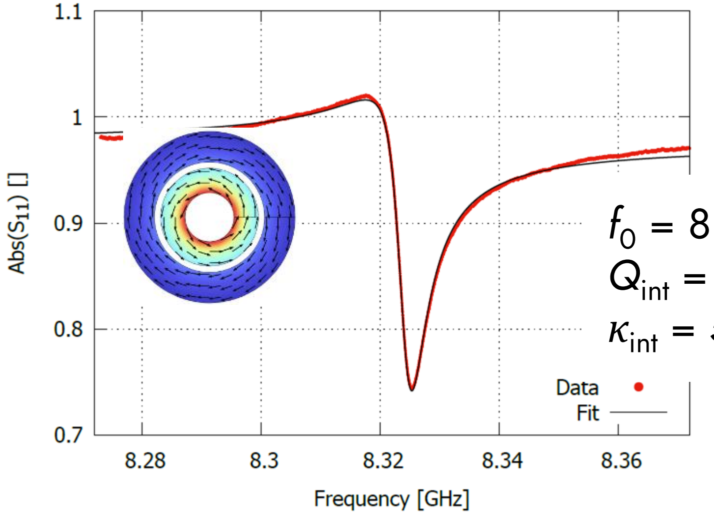


HeLIOS Microwave Optomechanical Transducer



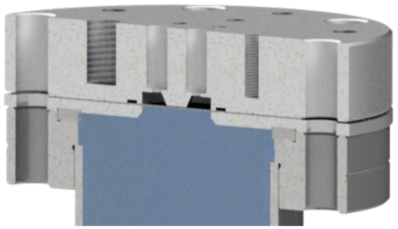


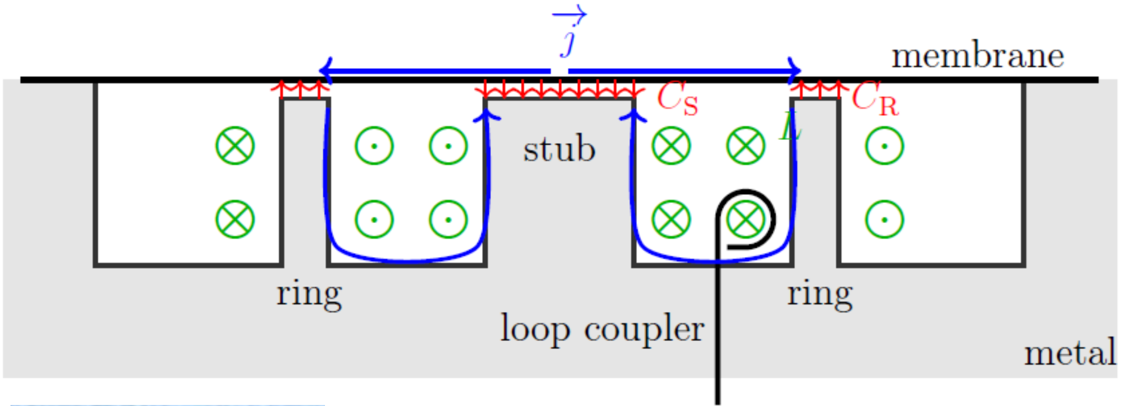
f_0 = 4.05 GHz
Q_{int} = 74800
κ_{int} = 340 kHz

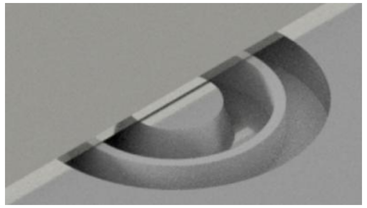


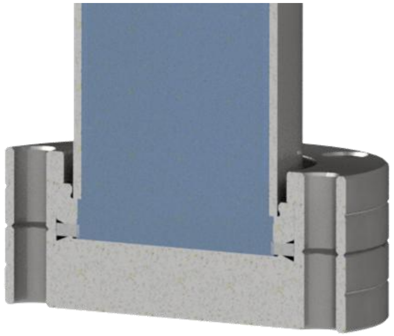
f_0 = 8.32 GHz
Q_{int} = 1650
κ_{int} = 5.04 MHz

Microwave Transducer

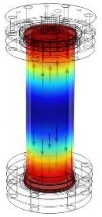






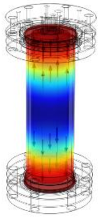


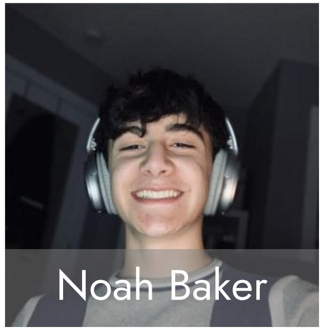
Superfluid UDM Detector

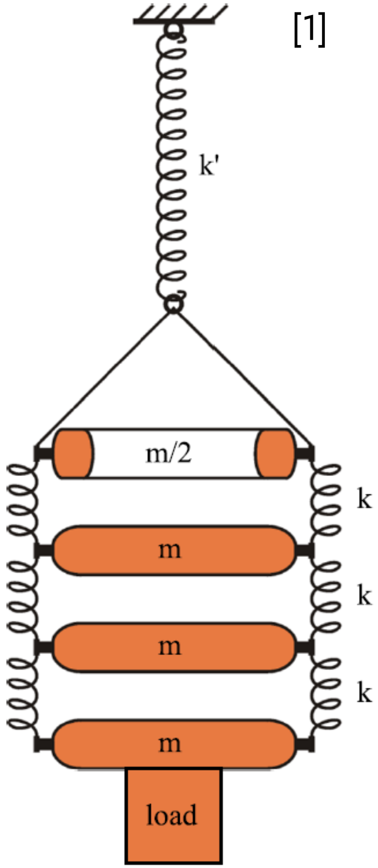


Vibration
solation

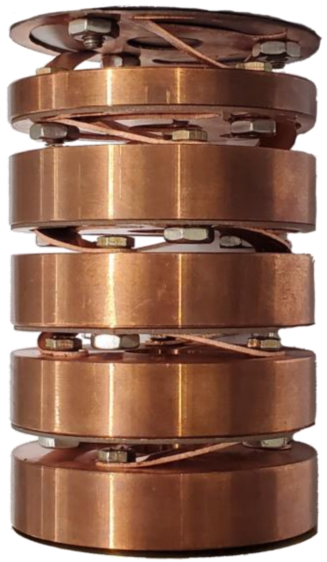
Superfluid UDM Detector







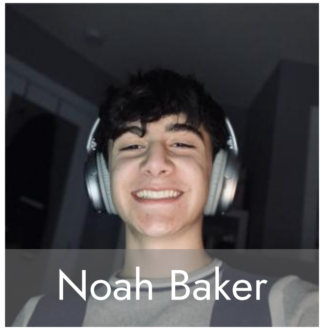
[1]

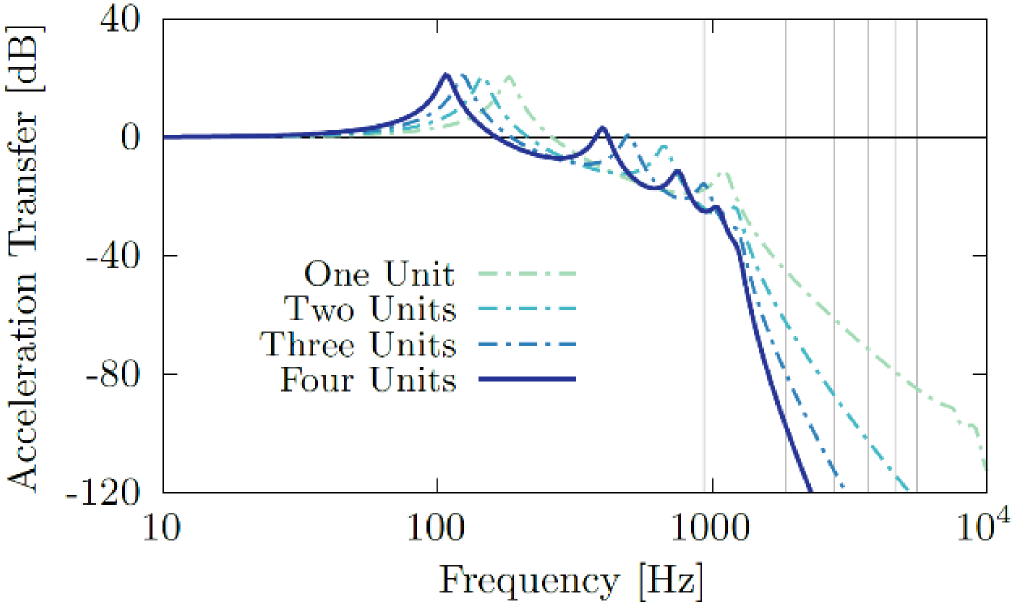


Vibration solation

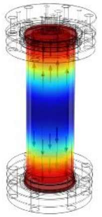
[1] M. de Wit, G. Welker, K. Heeck, F. M. Buters et al., *Rev. Sci. Instrum.* 90, 015112 (2019).

Superfluid UDM Detector





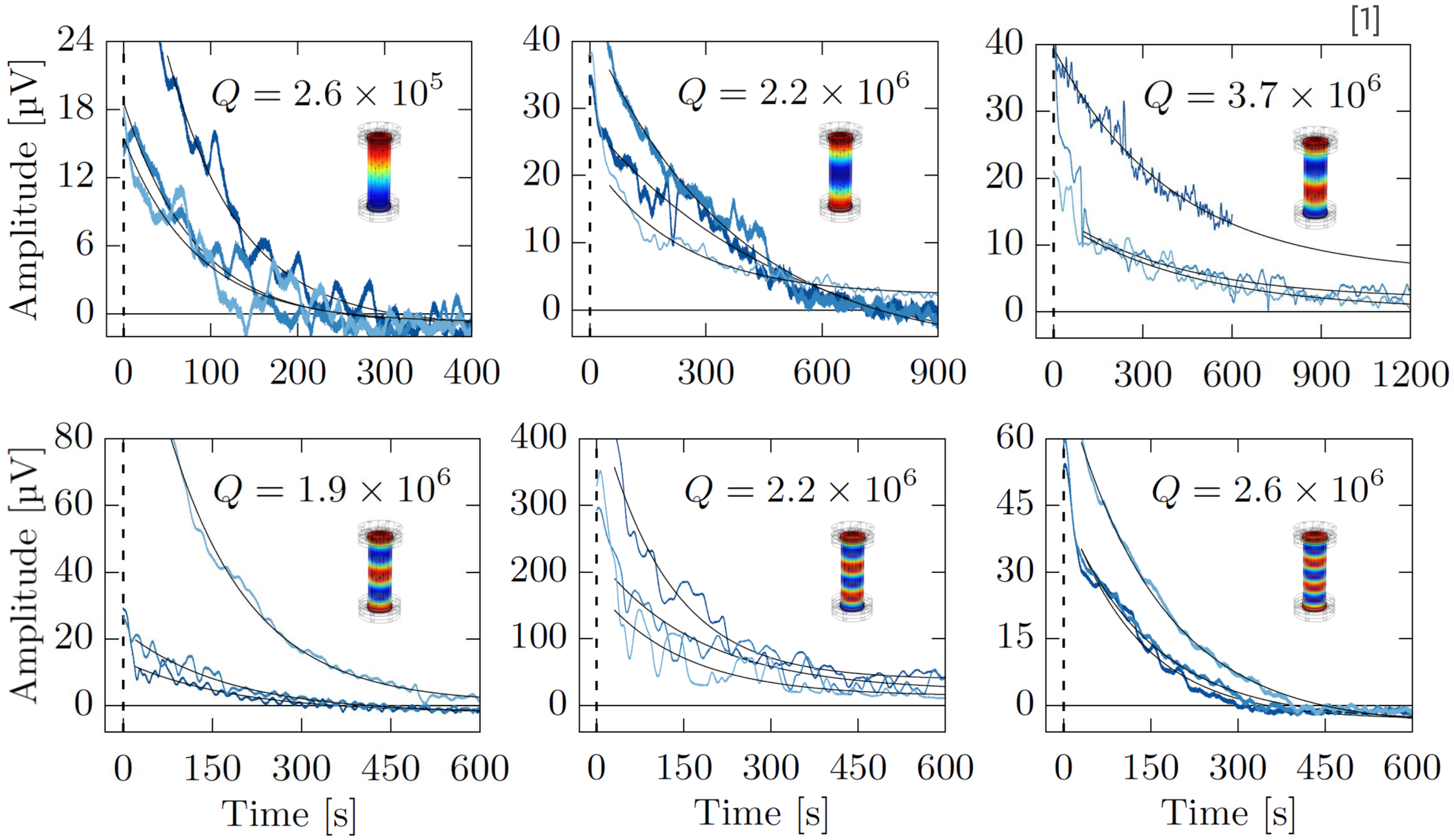
[2]

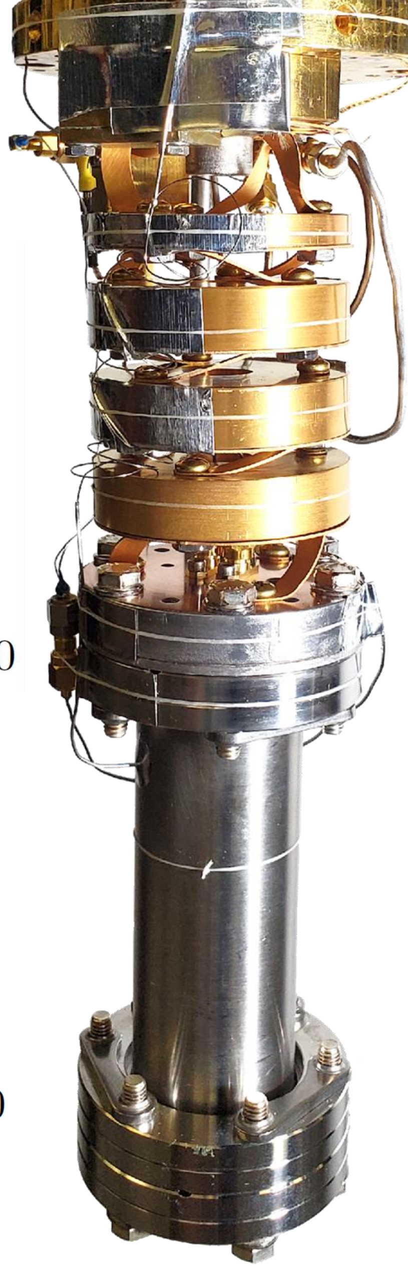


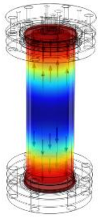
Vibration solation

[2] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

HeLIOS – First Prototype





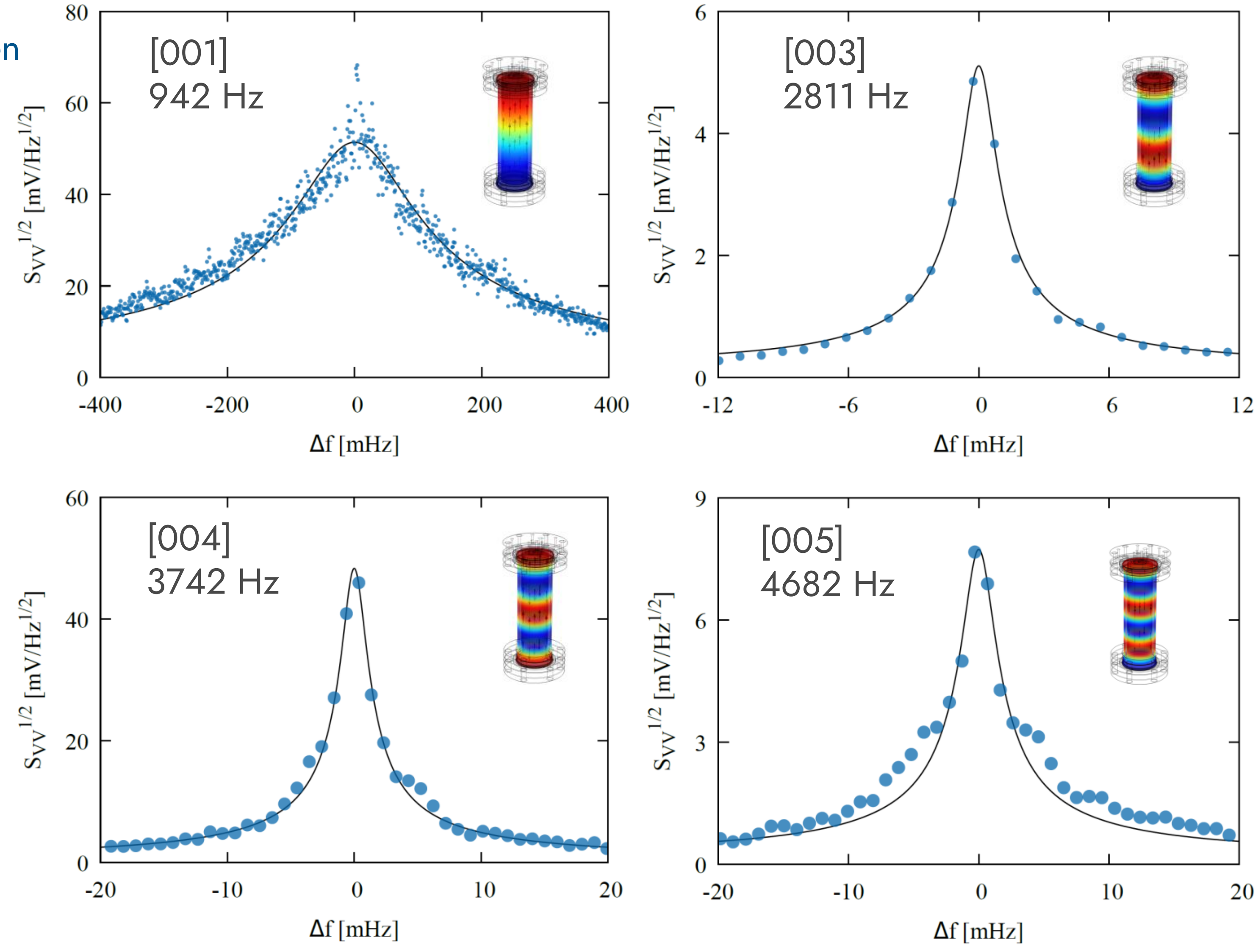


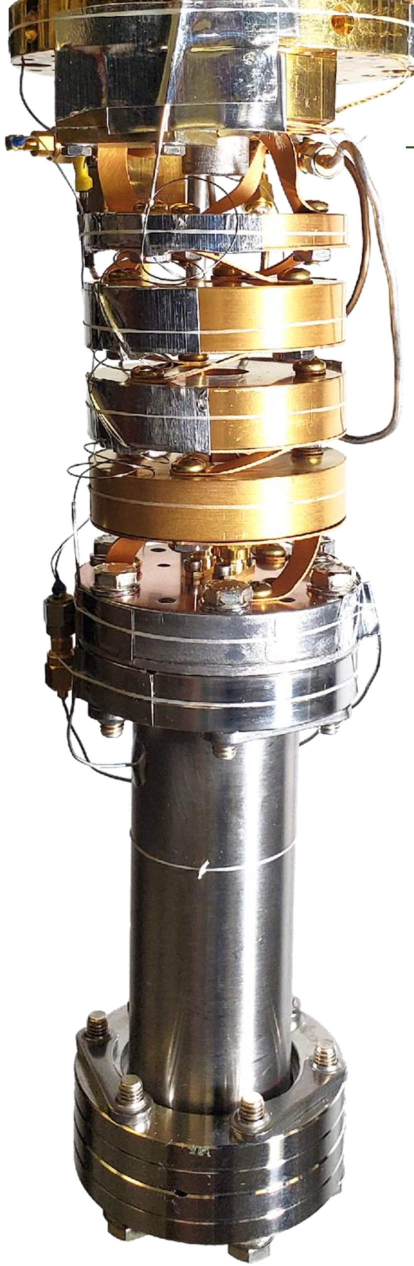
20 mK
70–170 mbar

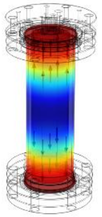
[1] **M. Hirschel**, V. Vadakkumbatt, N. P. Baker, F. M. Schweizer, J. C. Sankey, S. Singh & J. P. Davis, *PRD* 109, 095011 (2024).

HeLIOS – First Prototype

Undriven



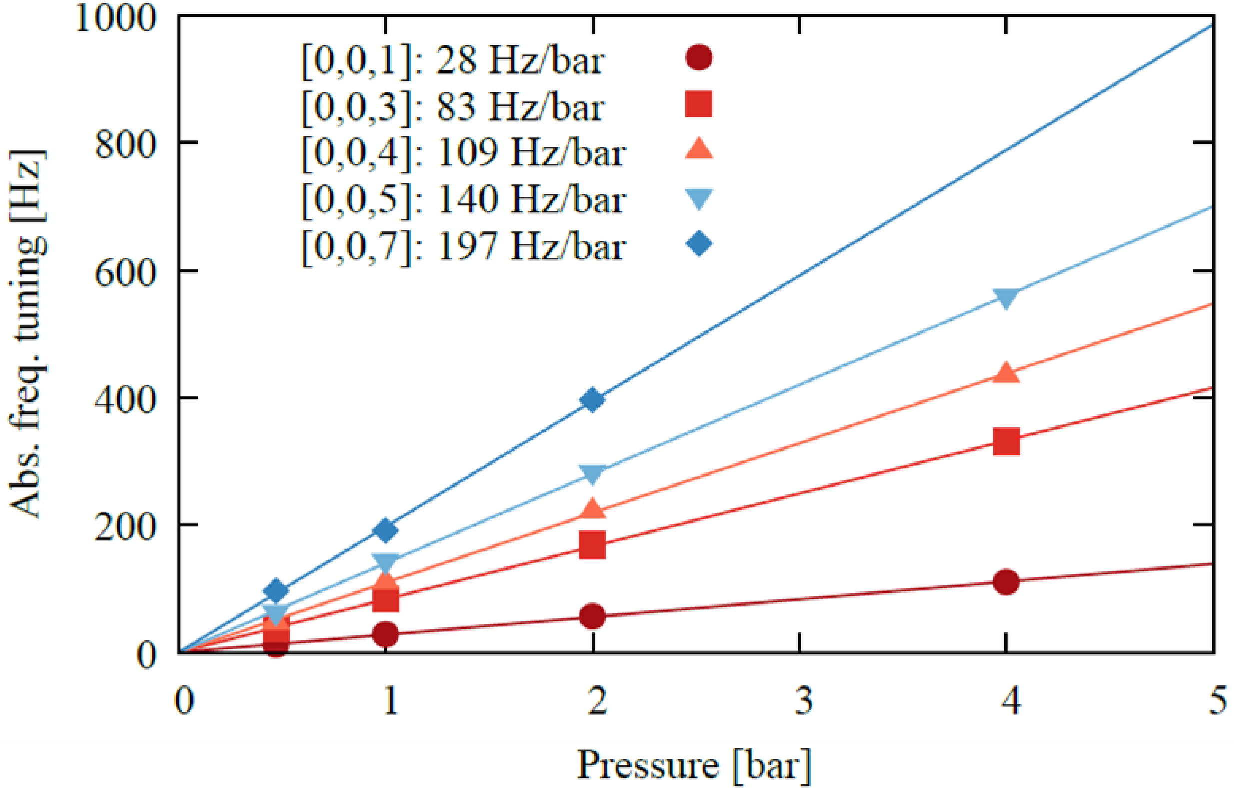


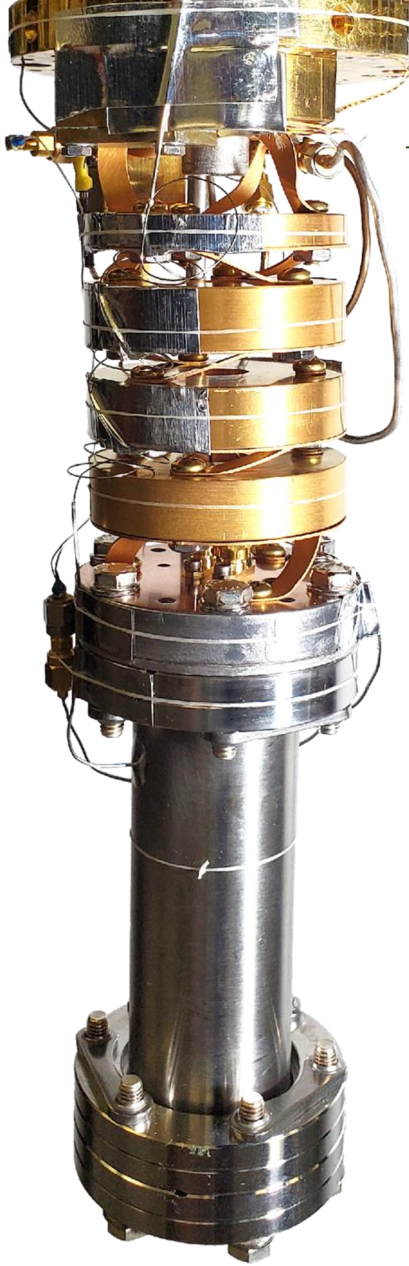


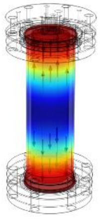
15 mK
470 mbar

HeLIOS – First Prototype

Undriven





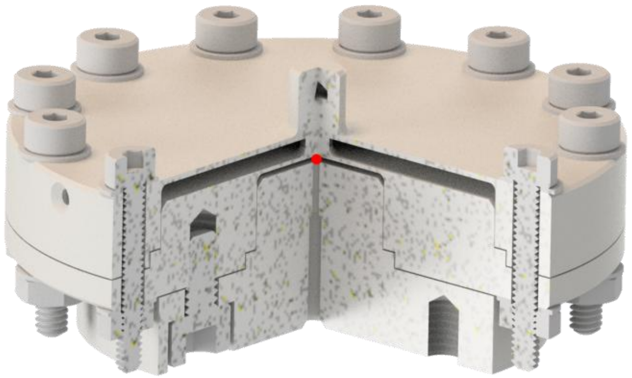


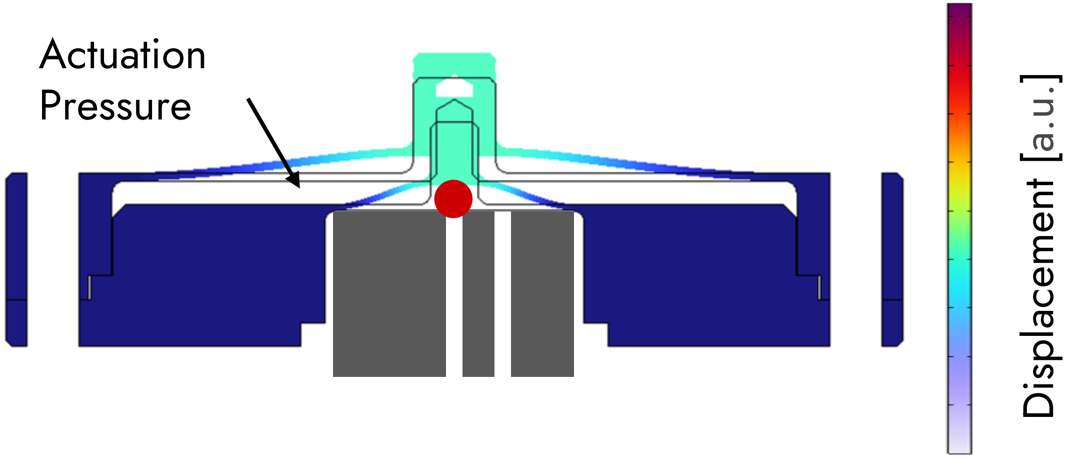
100 mK
0–4 mbar

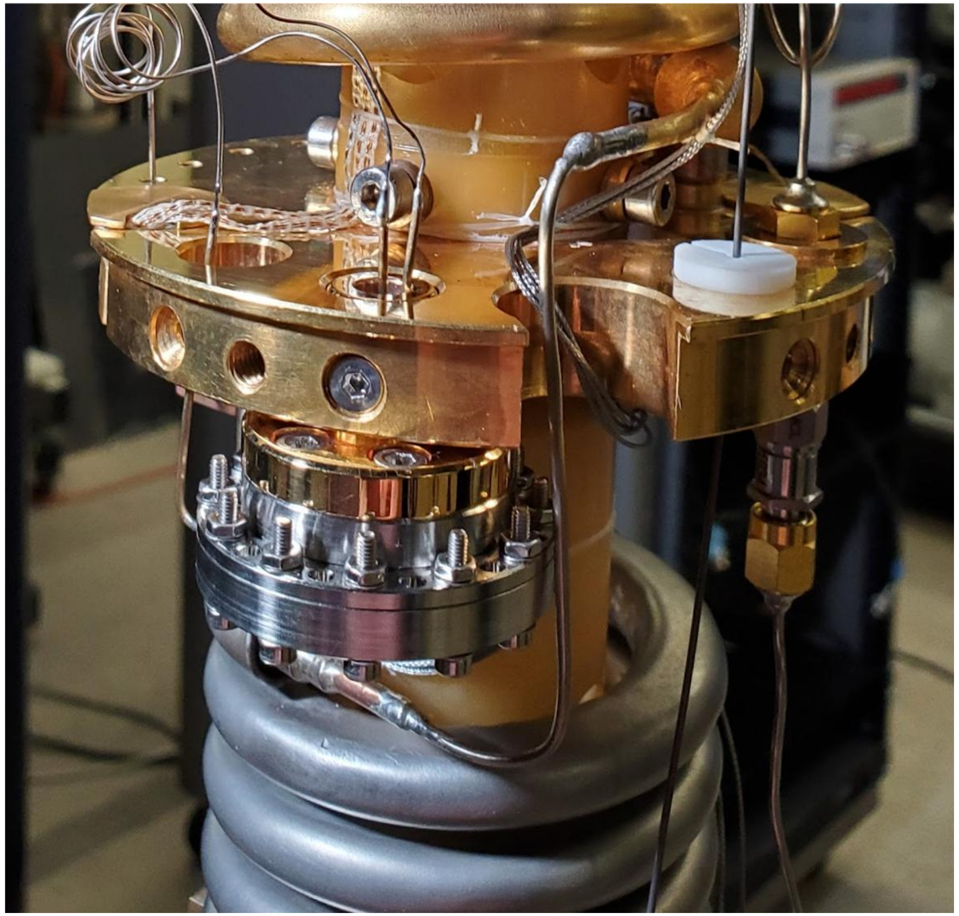
HeLIOS – Next Generation

Superfluid valve [1]

ZERO POINT CRYOGENICS





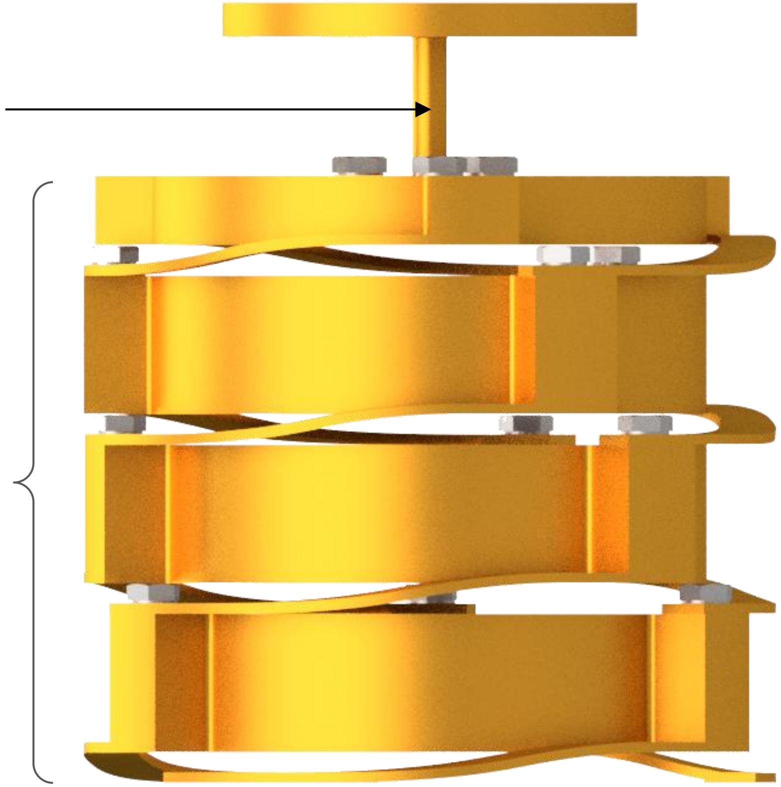


[1] Dotsenko & N. Mulders, *J. Low Temp. Phys.* 134, 443-446 (2004).

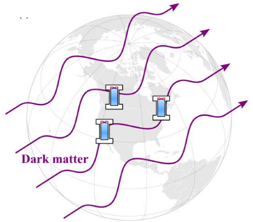
HeLIOS – Next Generation

Rod stage
Brass
Single pendulum for x-y isolation

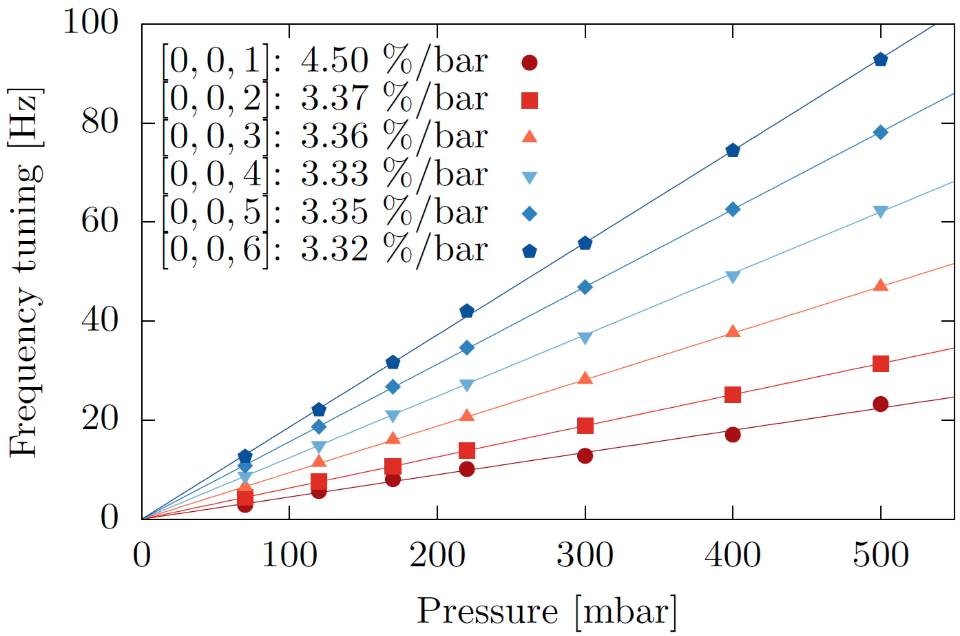
Cantilever column
Brass
4x mass-spring filter
for z-isolation



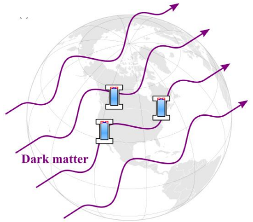
HeLIOS – Next Generation



Parametric Amplification
(Thermomechanical Noise Squeezing)



HeLIOS – Next Generation



Parametric Amplification
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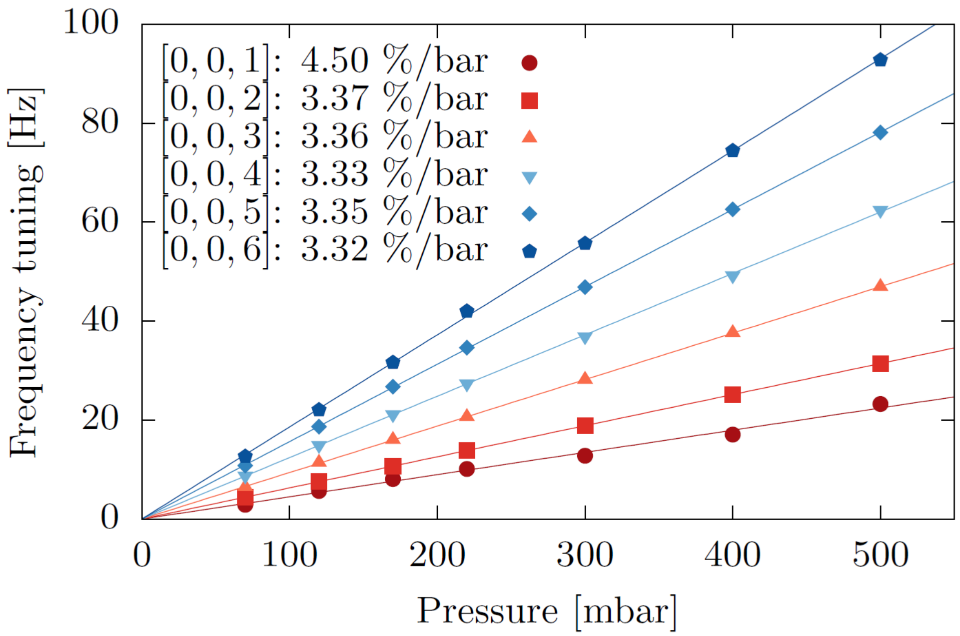
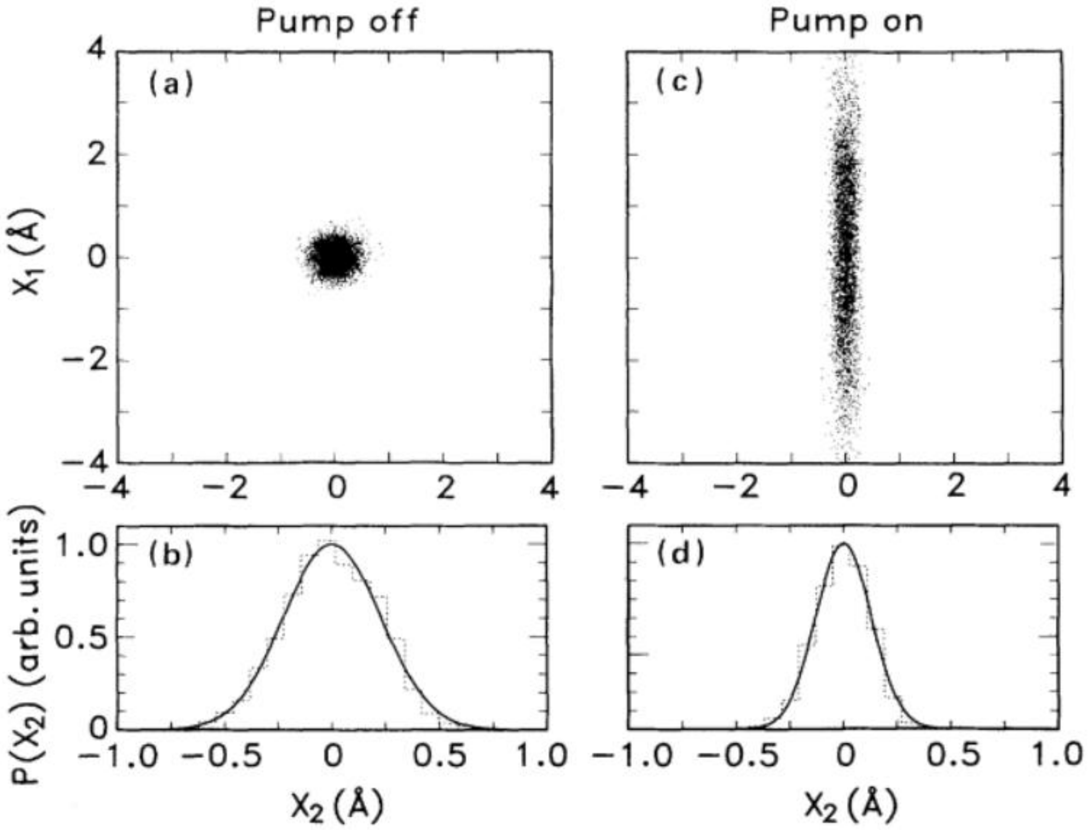


$2\Omega_n$ pump



[1]

[1] D. Rugar & P. Grütter, *PRL* 67, 699 (1991).