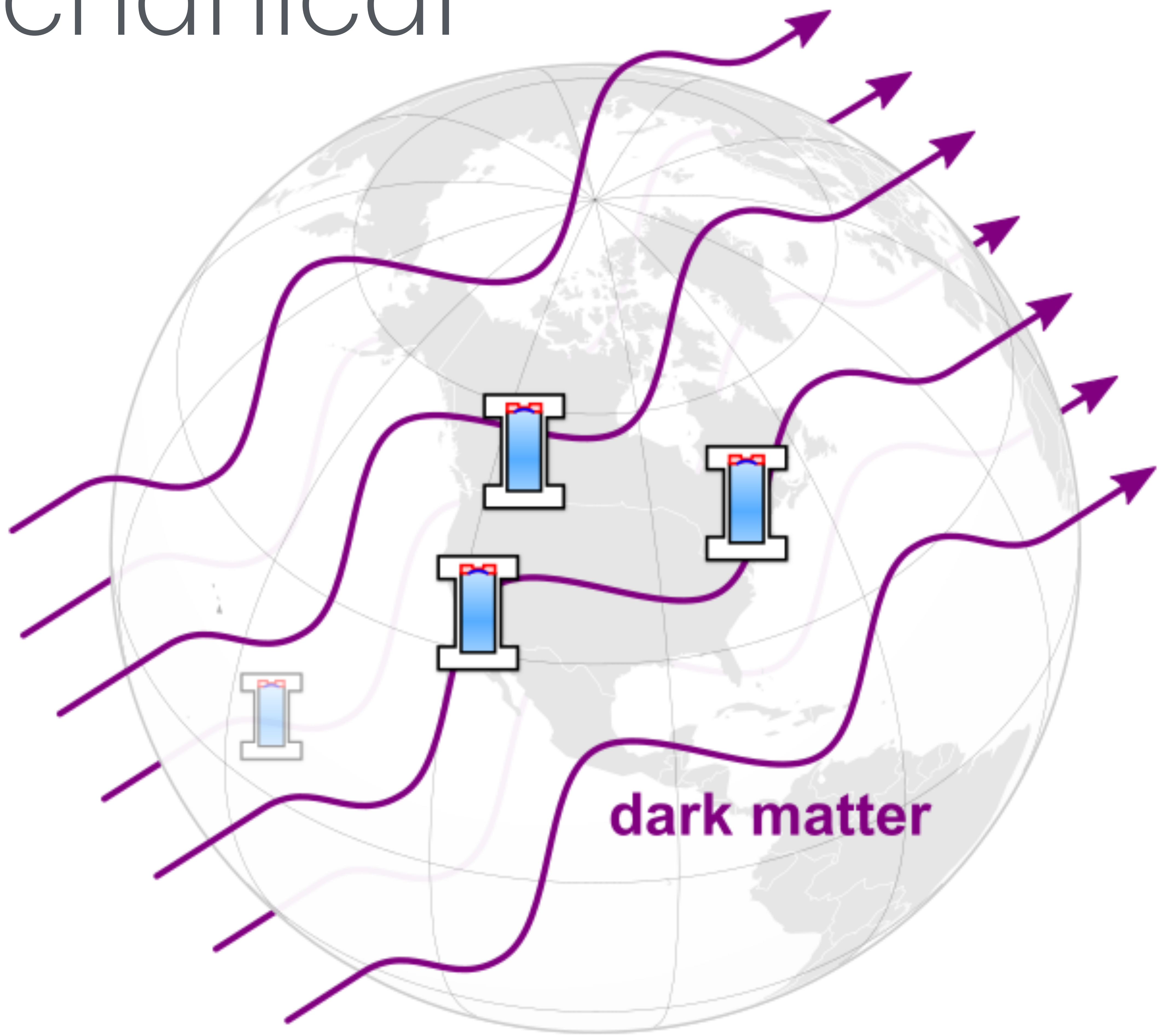
Search for ultralight dark matter using superfluid helium mechanical resonator



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Mathieu Juan (USherbrooke, Canada)

General **U**ltra-l**I**ght **N**ew **E**xciting d**A**rk matter **P**roject **I**n **G**alactic searches

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Mass, in electron volts (eV)
What Could Dark Matter Be?
10-21
10-18
10-15
10-12
10-9
10-6
10-3
1
10³
10⁶
10⁹
10¹²
10¹⁵
Electron mass
Proton mass
ULTRALIGHT DARK MATTER
Mass range
~10-22 eV to ~10-6 eV
Experiments
CASPEr, MAGIS-100
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PRIMORDIAL BLACK HOLES
Mass range
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SUB-GeV DARK MATTER
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SENSEI, TESSERACT

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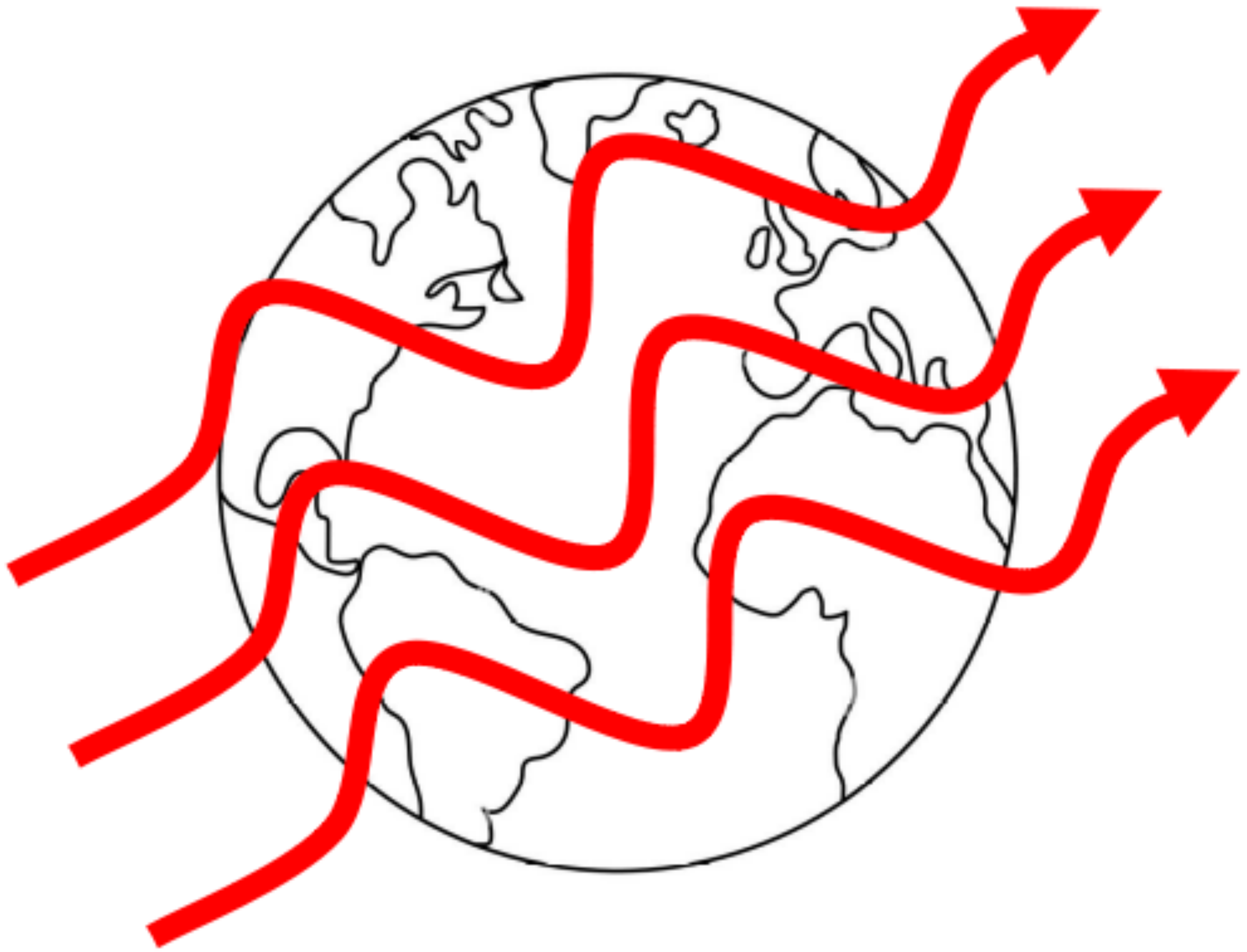
Ultralight Dark Matter (UDM)

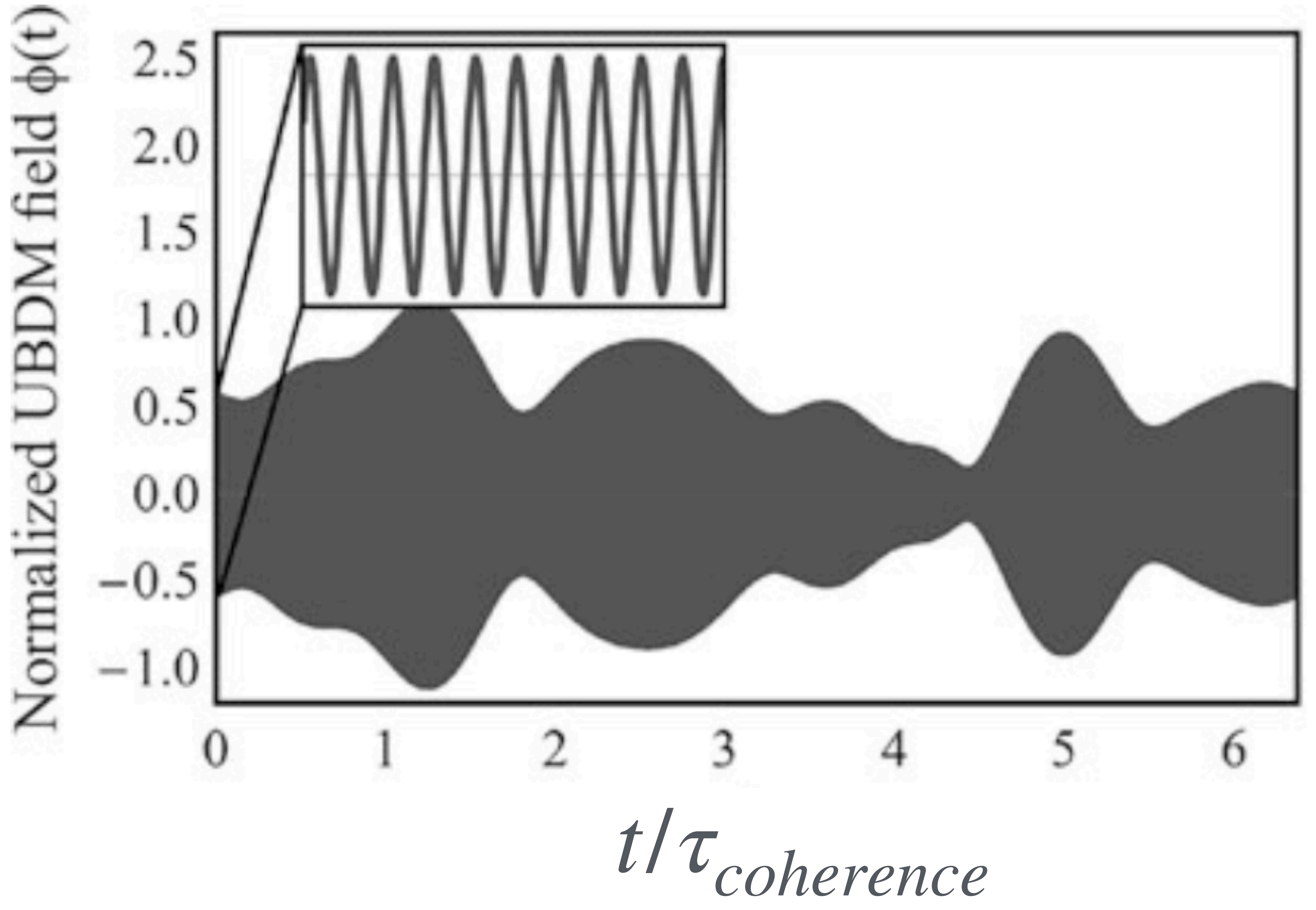
- Mass scale ~ pico-eV
- Assuming local DM density ~ 0.4 GeV/cm^3
  - Large occupation numbers == > boson
  - DM particles behave as a classical field
  - Can be a **scalar** or **vector** field



In this presentation, will focus on **scalar** UDM

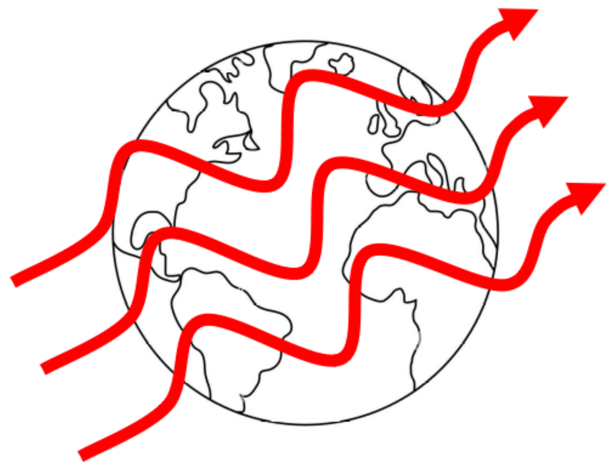
Ultralight Dark Matter (UDM)

- Search methods aimed at detecting coherent effects of UDM waves
  - Earth-size wavelength
  - Oscillation frequency ~ kHz
- Virialization
  - 1 ppm energy spread
  - Coherence time ~ 1 hour



D.F. Jackson Kimbal and K. van Bibber (Ed.), Springer International Publishing, April 2022

Scalar UDM

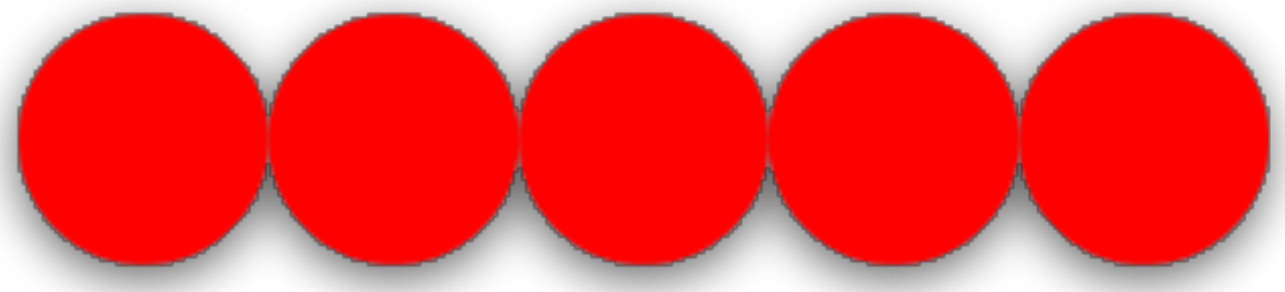


Dark matter may modulate the **atomic radius** via variations of "fundamental" constants

$$r \propto \frac{\hbar}{c m_e \alpha}$$

$$\alpha(t) = \alpha_0 \left[1 + d_e \frac{\sqrt{8\pi G_N \rho_{\mathrm{DM}}}}{m_\phi} \cos\left(\omega_{\mathrm{DM}}(t - \boldsymbol{v} \cdot \boldsymbol{x})\right) \right]$$

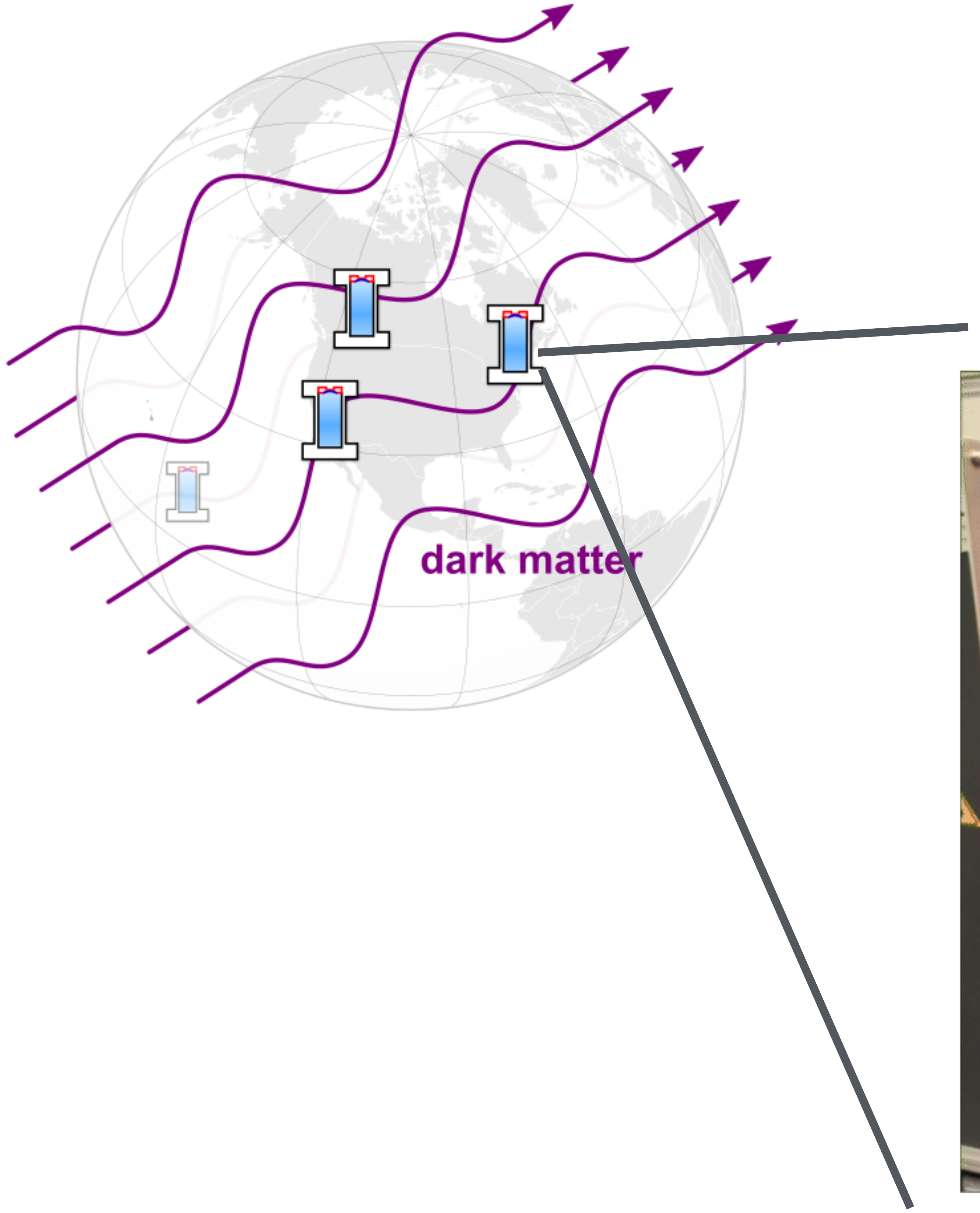
$$m_e(t) = m_{e,0} \left[1 + d_{m_e} \frac{\sqrt{8\pi G_N \rho_{\mathrm{DM}}}}{m_\phi} \cos\left(\omega_{\mathrm{DM}}(t - \boldsymbol{v} \cdot \boldsymbol{x})\right) \right]$$

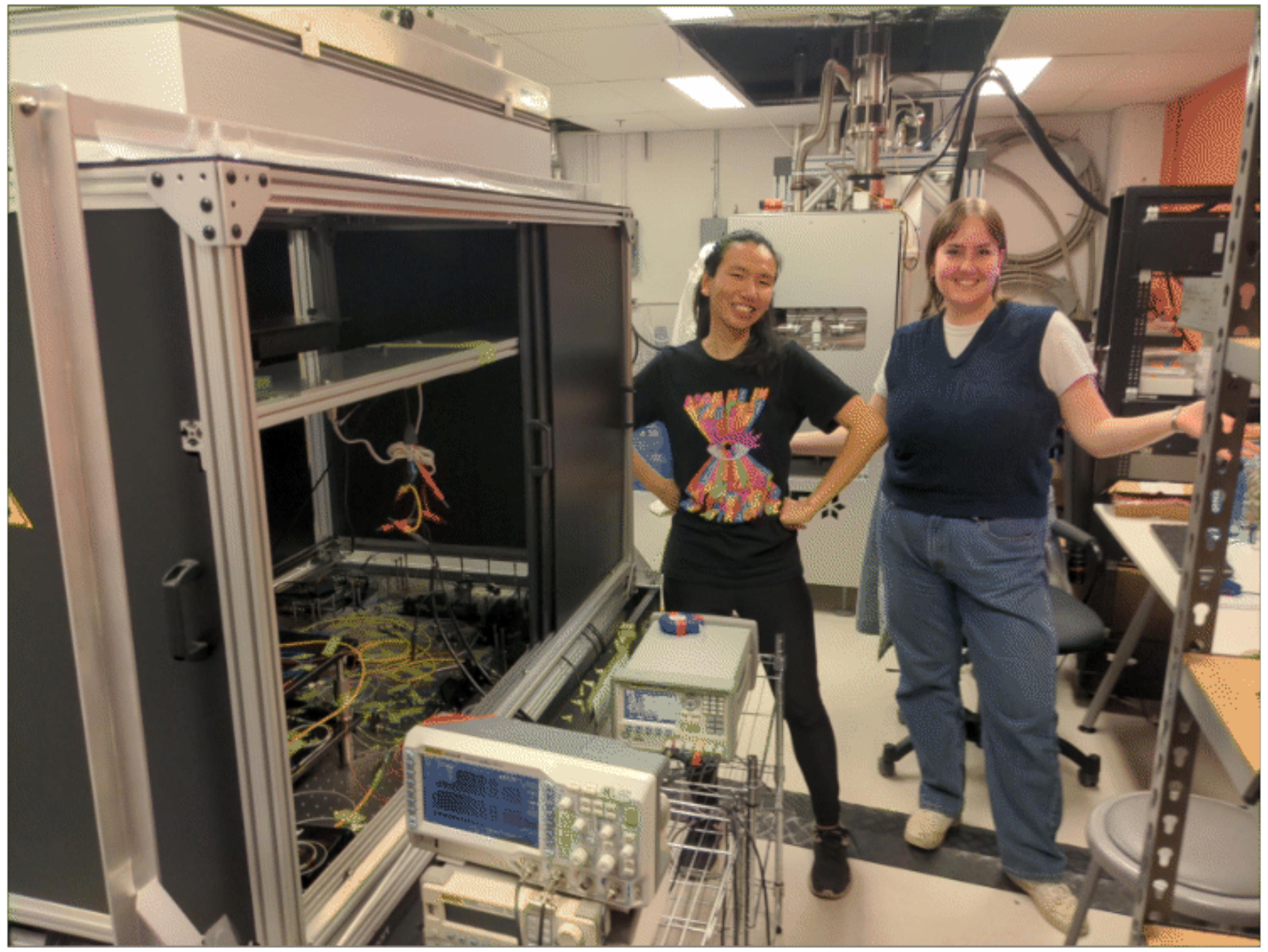


Arvanitaki et al. Phys. Rev. Lett. 116 (2016) 031102
Manley et al., Phys. Rev. Lett. 124 (2020) 151301

Scalar UDM

But the size of every atom is modulated!



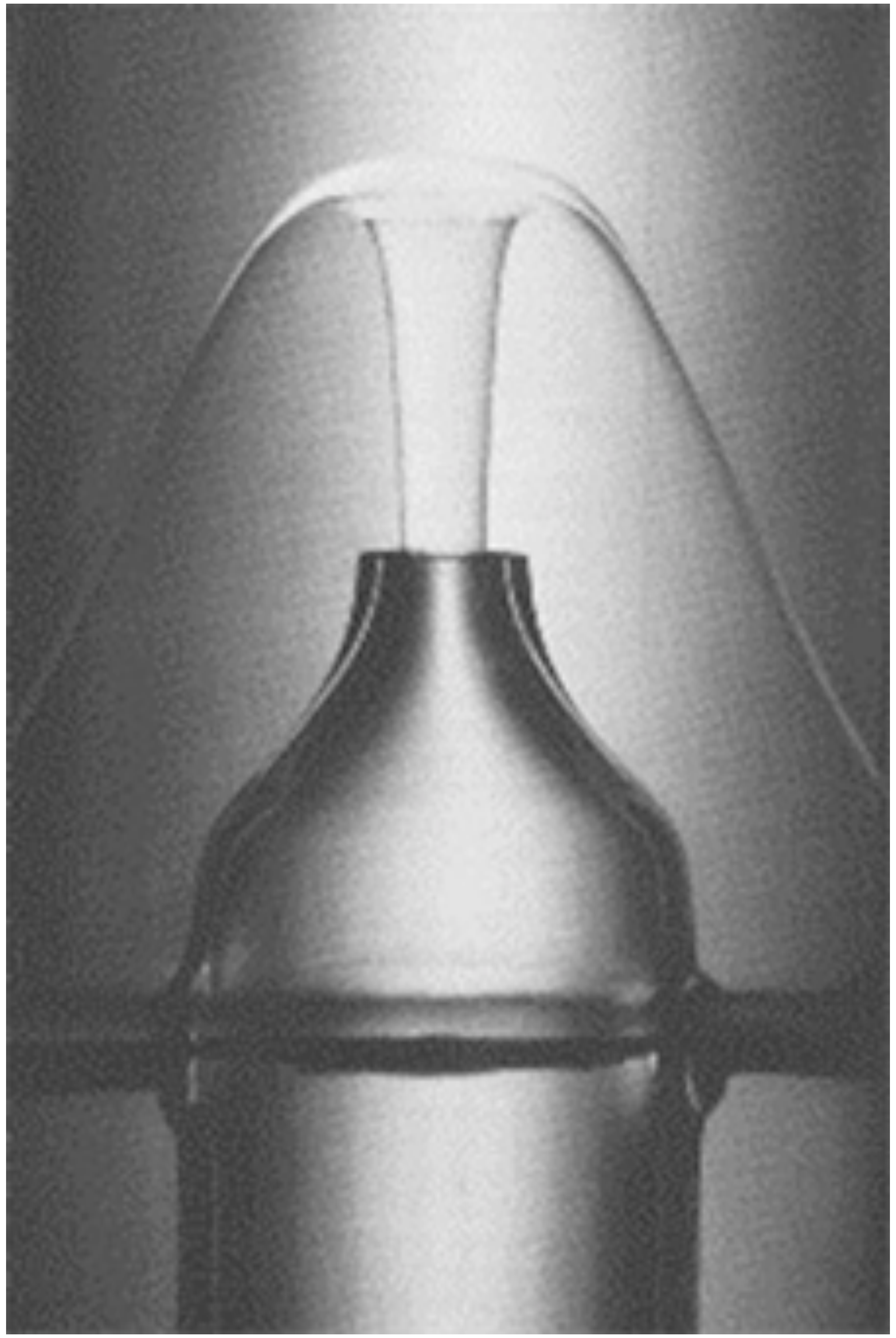


(Simulation!)

Superfluid Helium-4

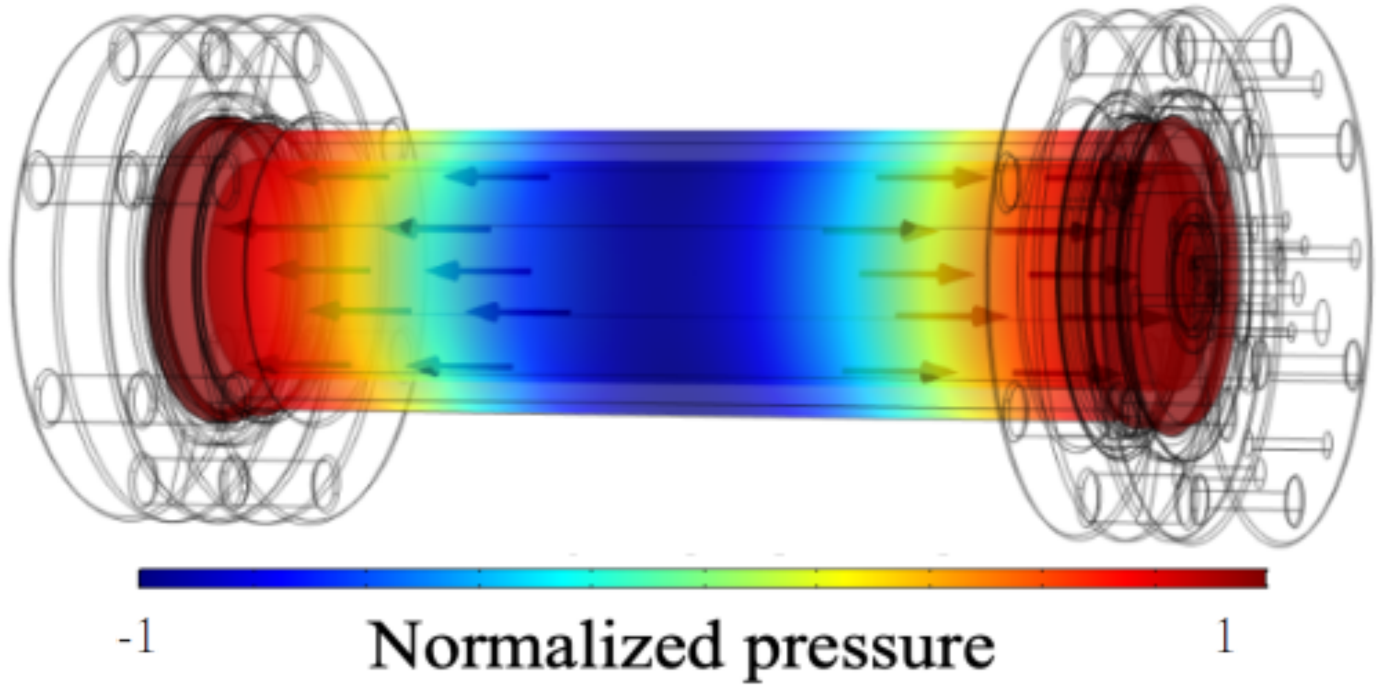
- **Extremely low thermal noise**
  - No viscosity
  - High mechanical quality ($Q > 10^8$)

- **Liquid at cryogenic temperature**
  - Resonator mass can fill any size
  - Resonances swept *in situ* by fill level or pressurization

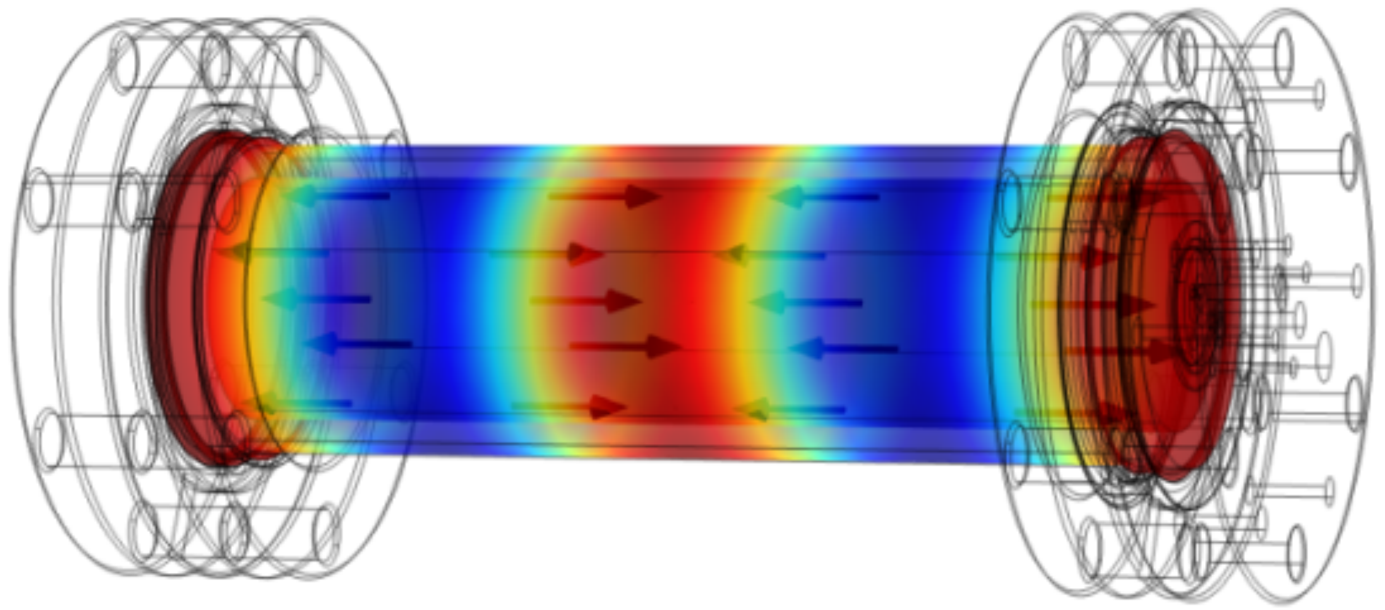


Sorongane, OJAppS 12 (2022) 1254

Superfluid "Weber Bar"



2nd mode



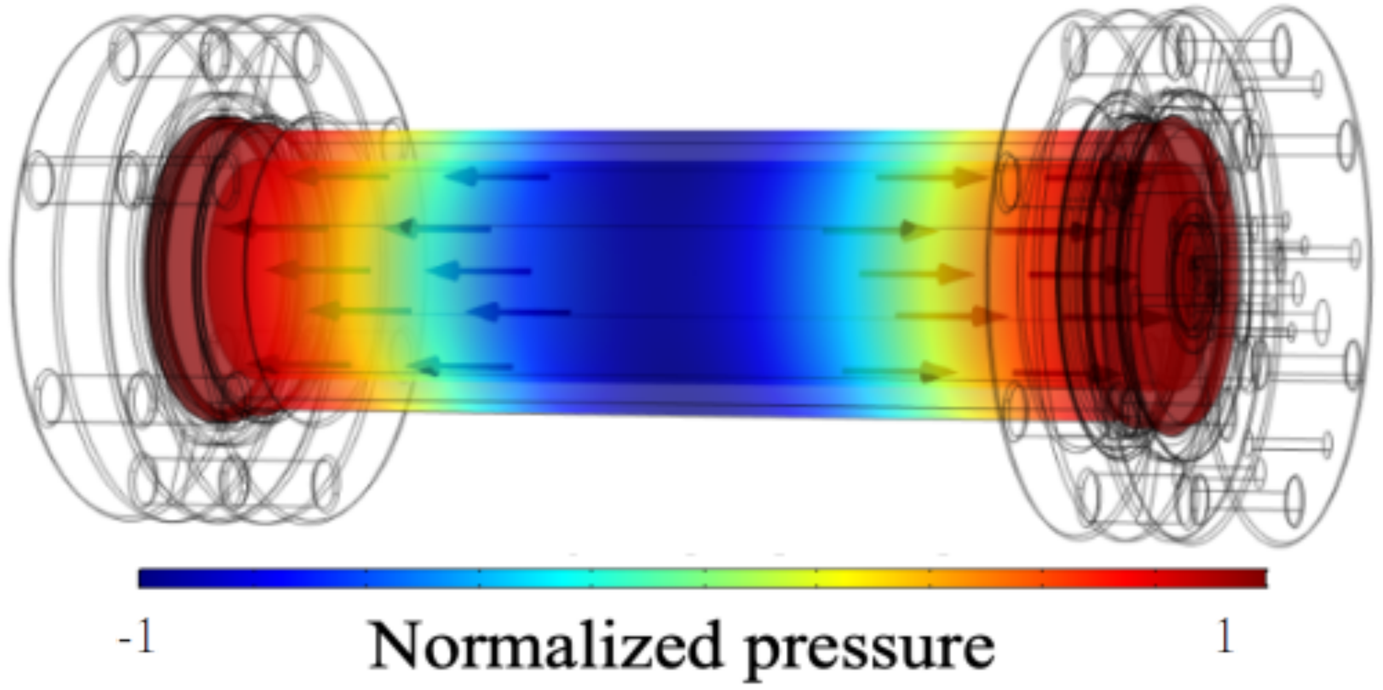
4th mode

Oscillatory UDM drive

- Same in pipe and helium
- **Differential response** creates pressure wave
- Uniform strain couples only to **breathing modes** (symmetry)

M. Herschel et al., PRD 109 (2024) 095011

Superfluid "Weber Bar"



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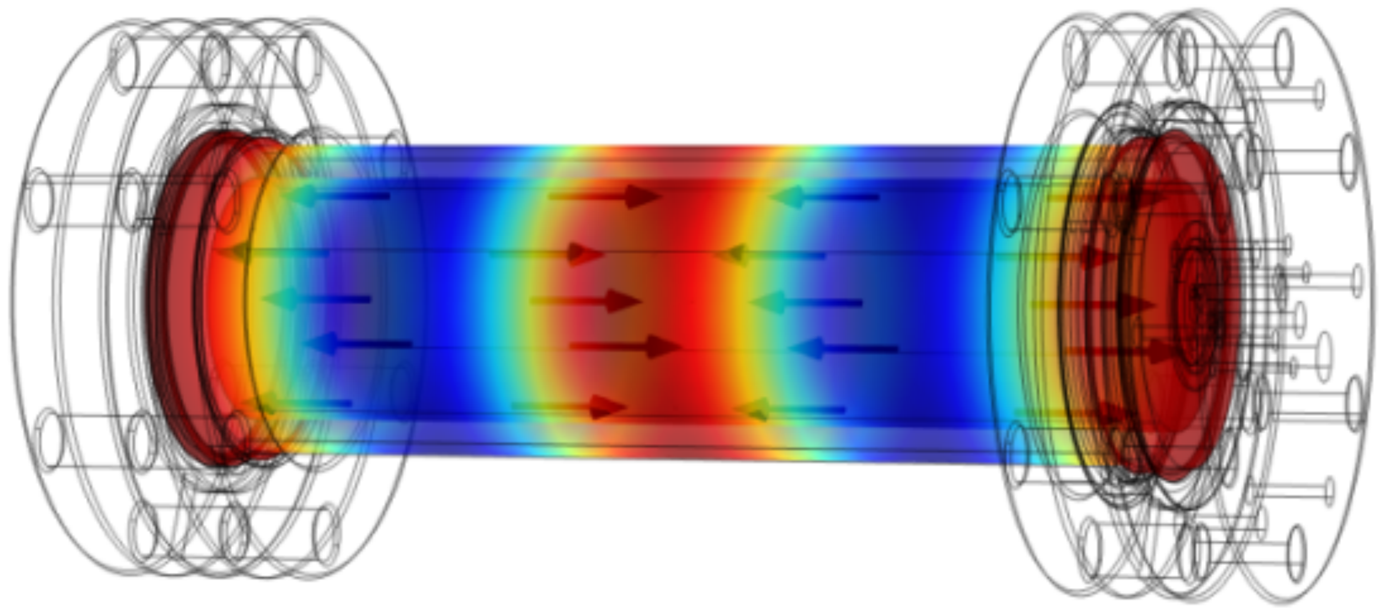


4th mode

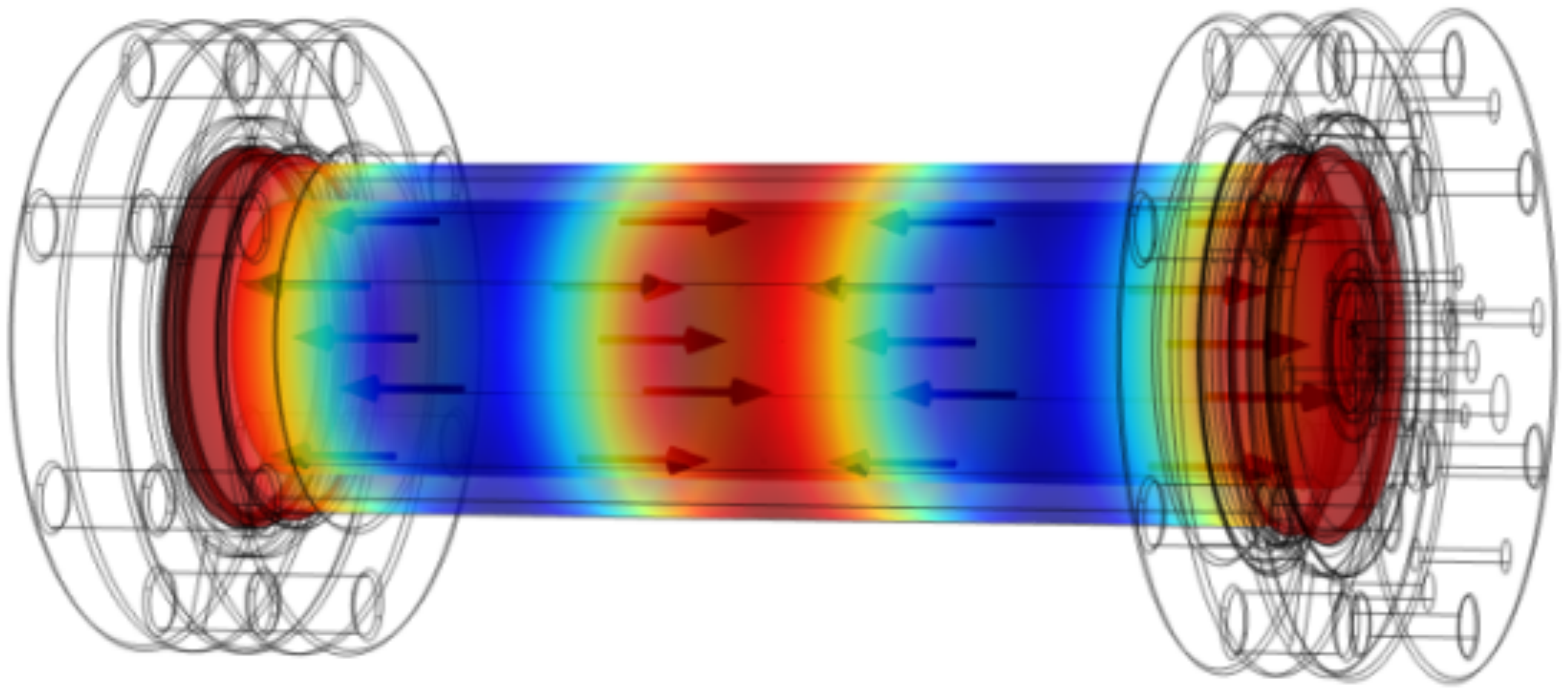
Finite-element simulation (COMSOL)

- Works
- Little intuition / guidance
- (So far) one mode at a time
- Slow (costly)

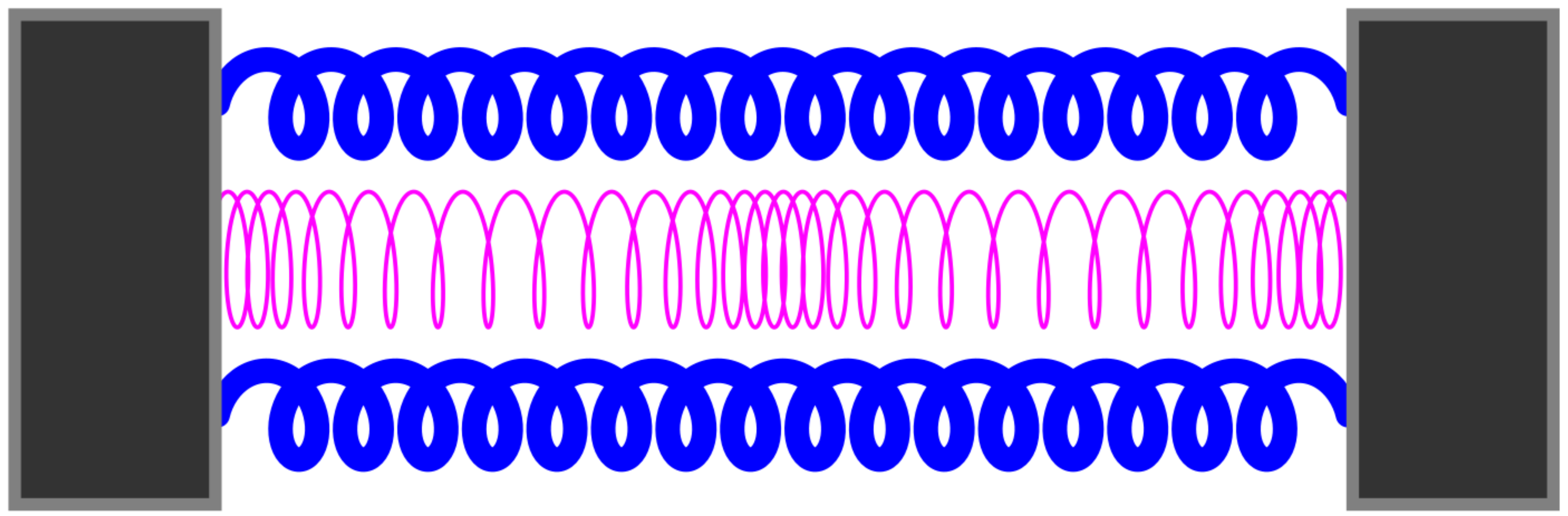
Simple analytical model

M. Herschel et al., PRD 109 (2024) 095011

Simple model for superfluid "Weber bar"

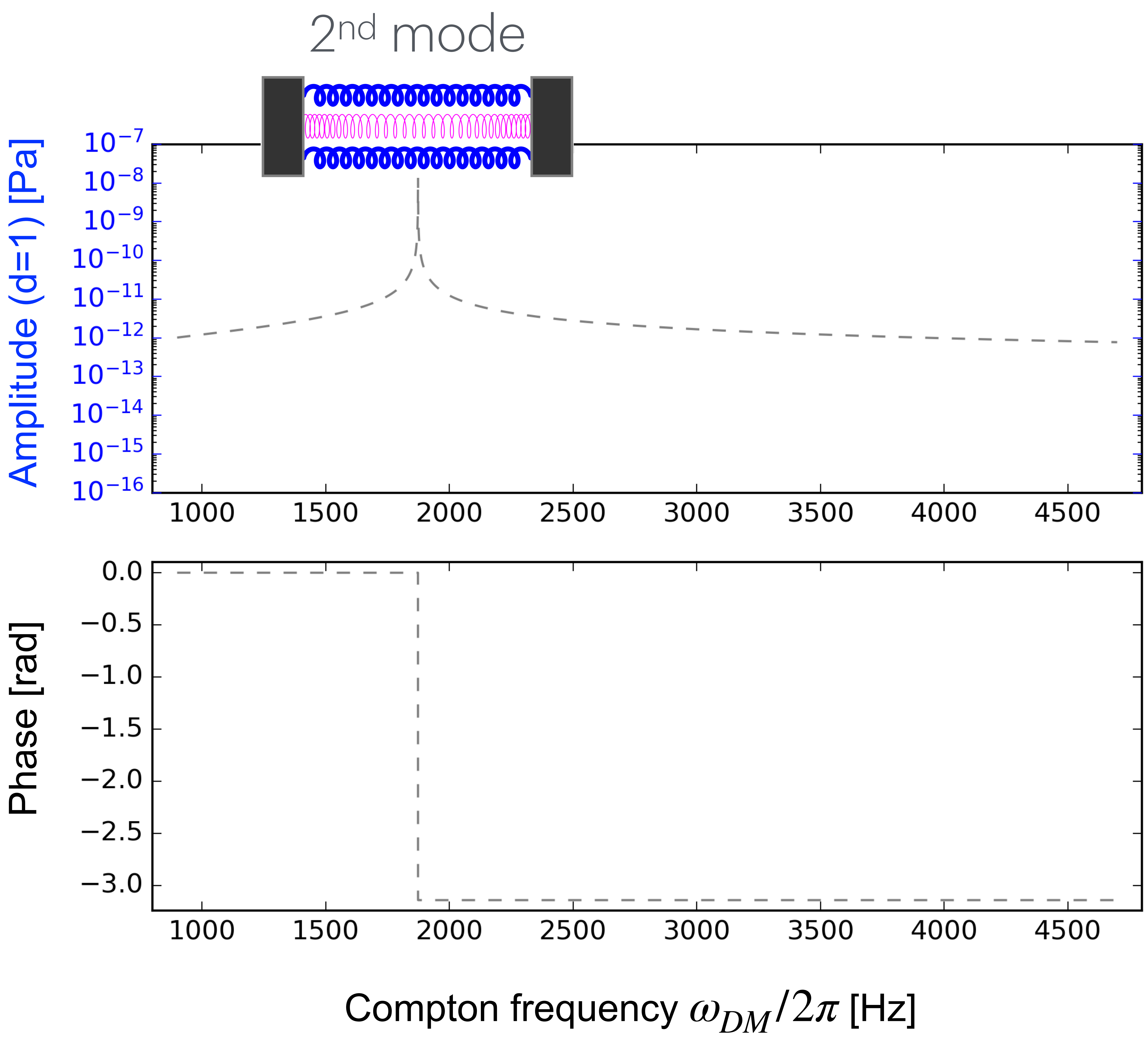


Longitudinal wave equation in **both**



- **Light, compressible superfluid**
- **Heavy, stiff pipe wall**
- **Rigid end cap mass (boundary)**

Mechanical Response to UDM (endcap pressure)



- **Pressure response** arises from **differential inertia** (pipe vs helium)

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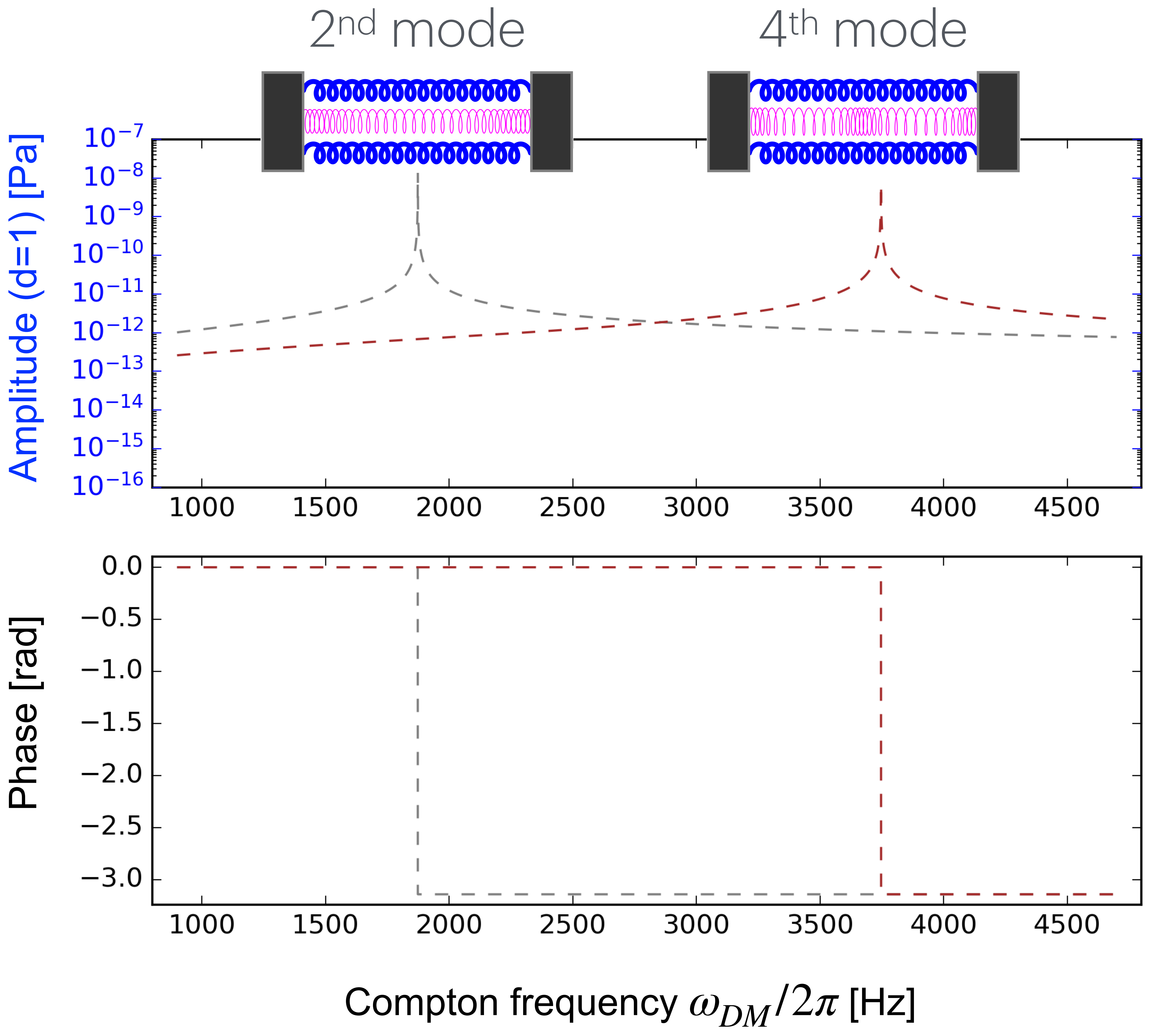

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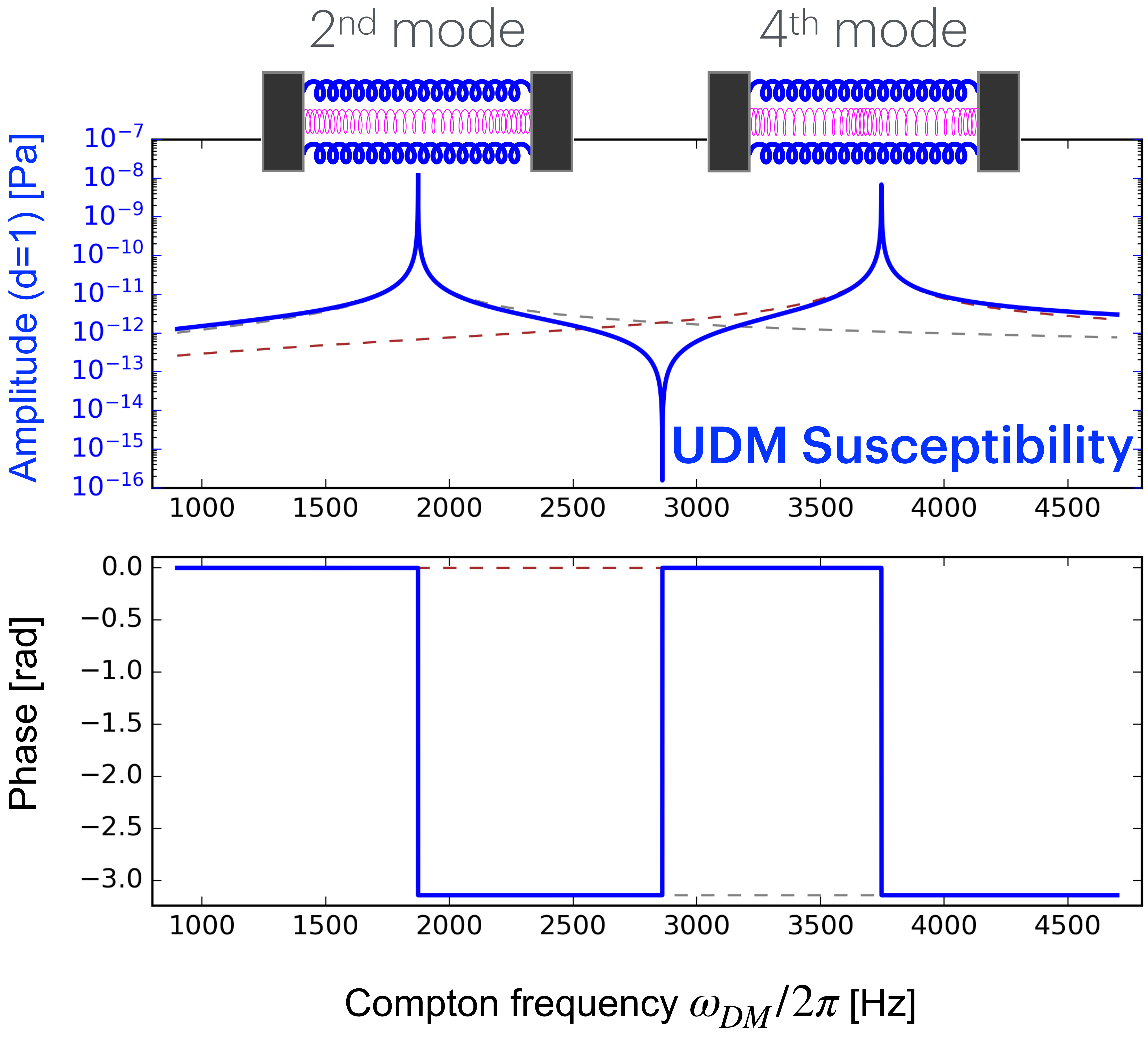

- **Pressure response** arises from **differential inertia** (pipe vs helium)
- **Antiresonances** from simultaneous drive of multiple modes

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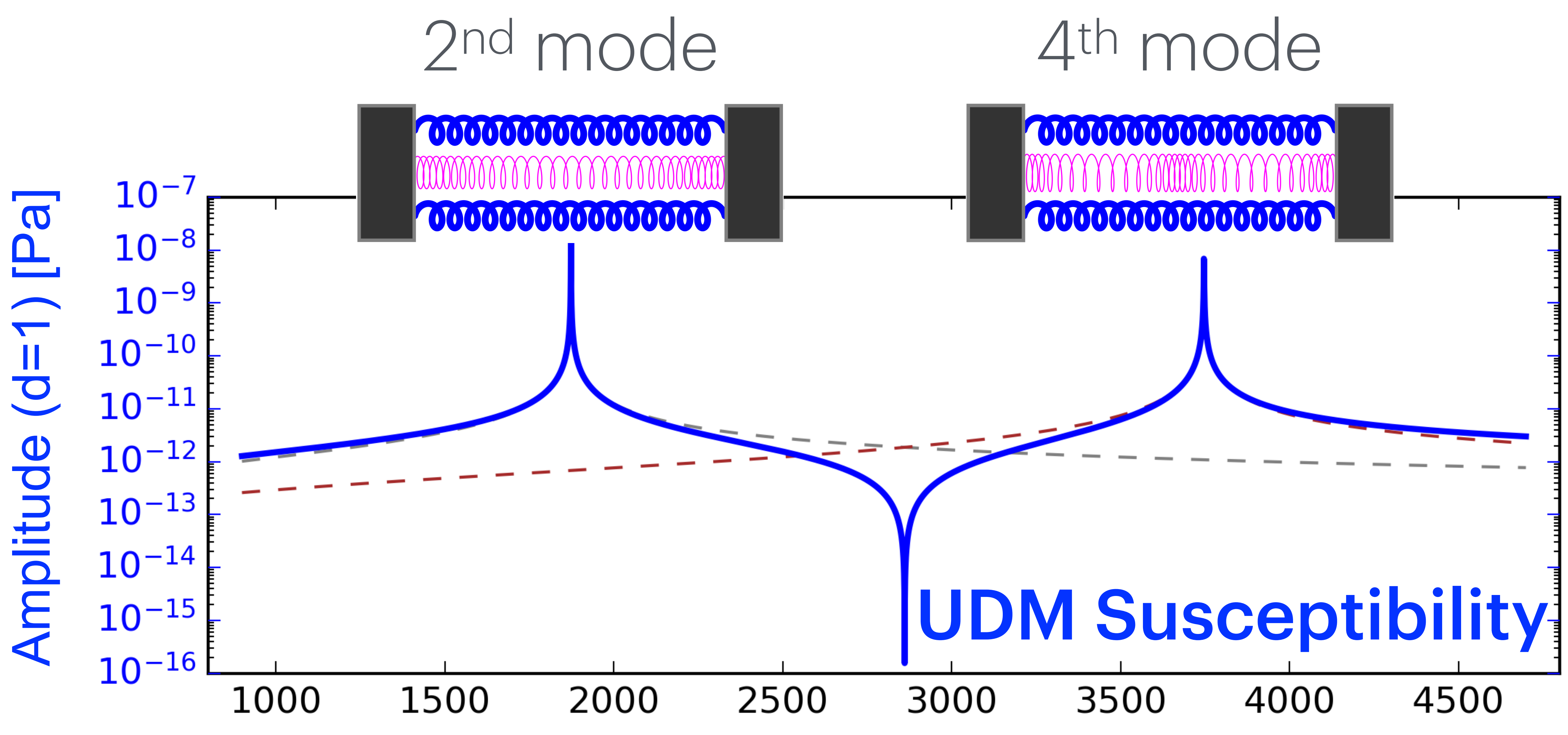

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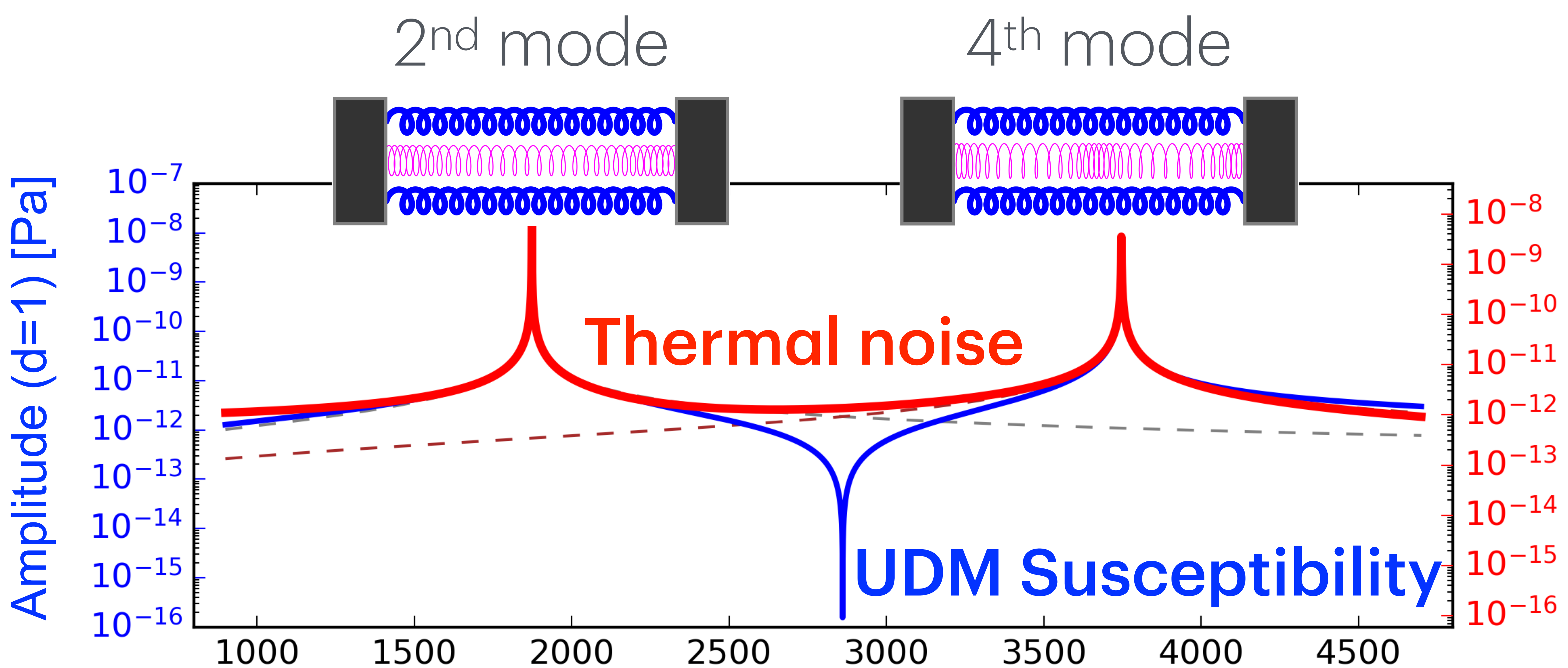
Signal validation!
(swept frequency)

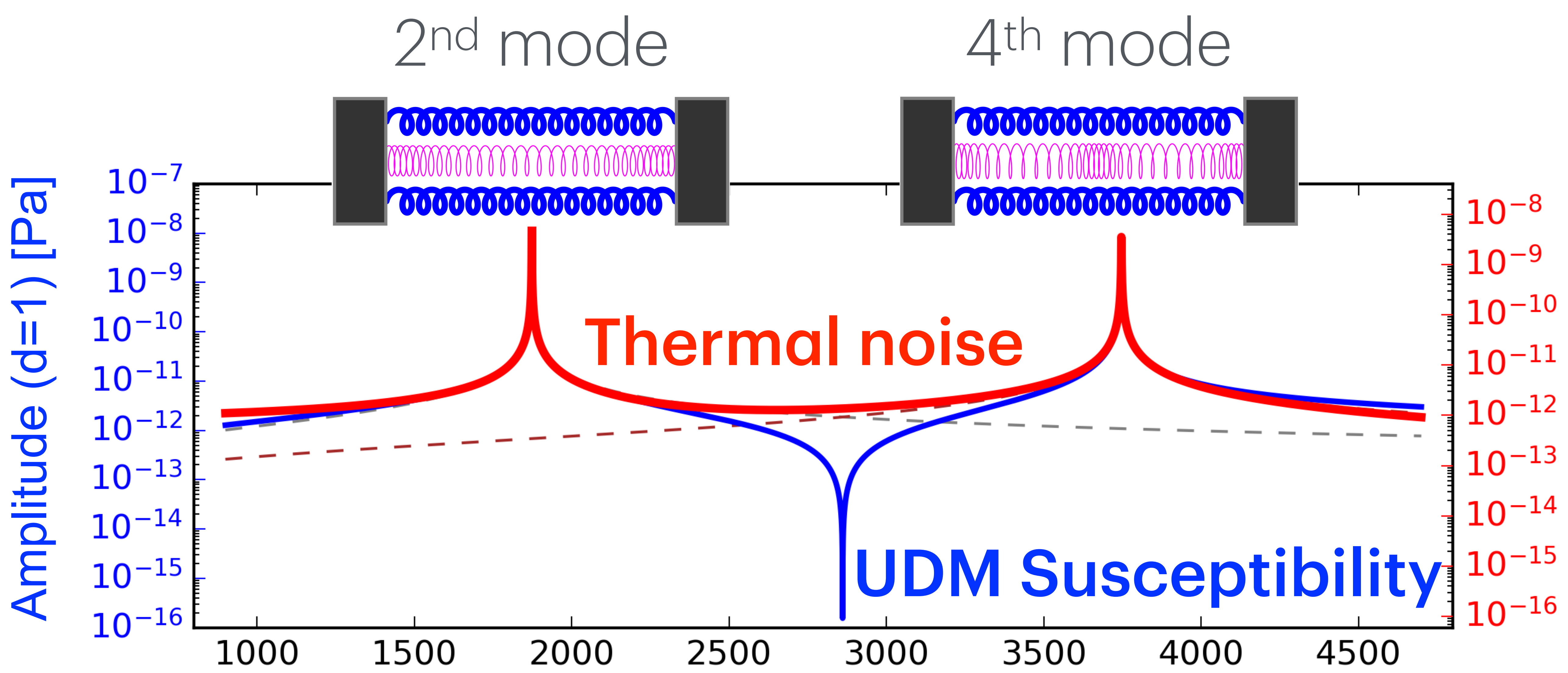
Mechanical Response to UDM (endcap pressure)



Thermal noise (incoherent)

- Resonant peaks
- No antiresonance

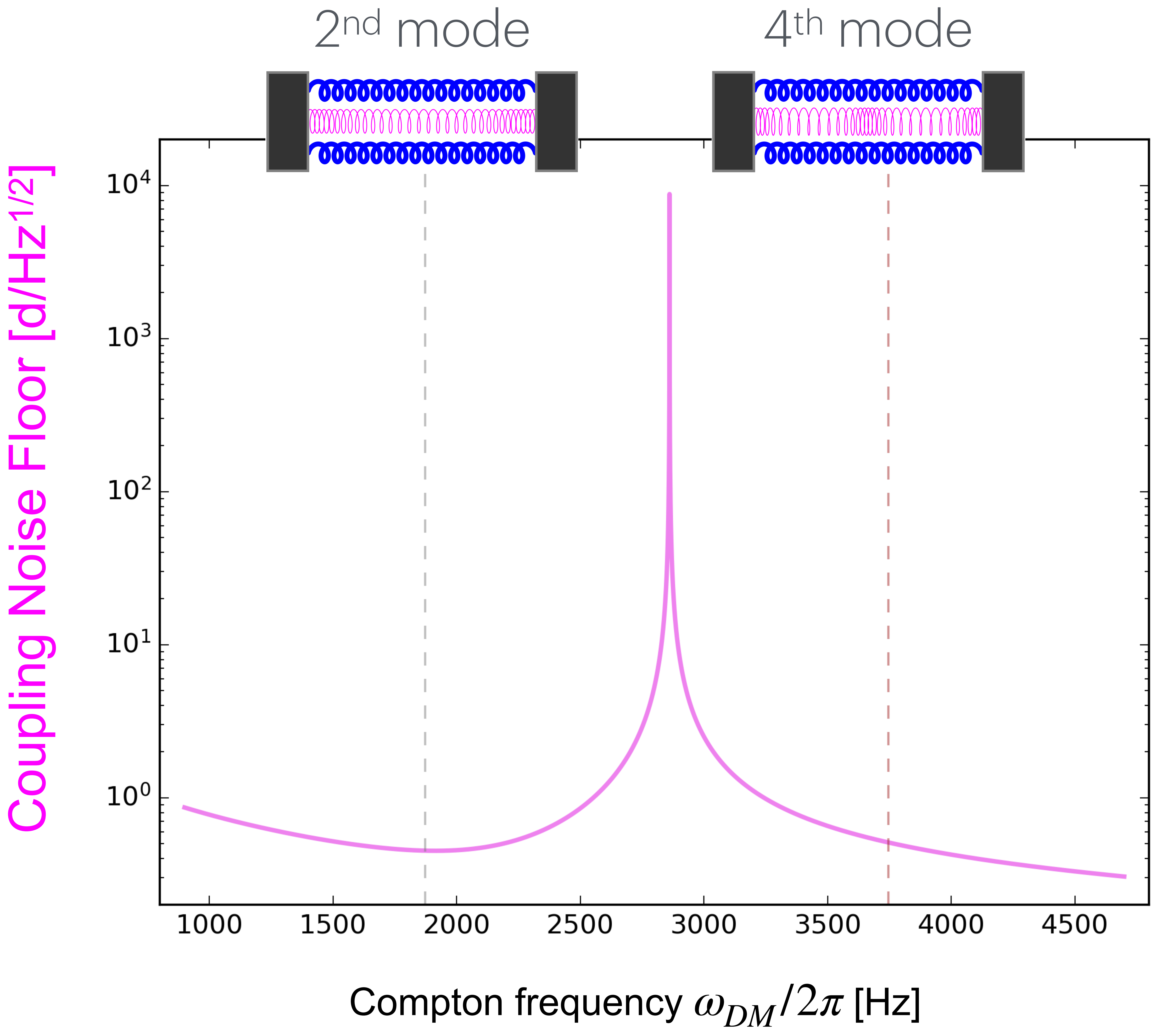
Mechanical Response to UDM (endcap pressure)



Converting measured signal to strain

- **Drive** = **motion** / **susceptibility**

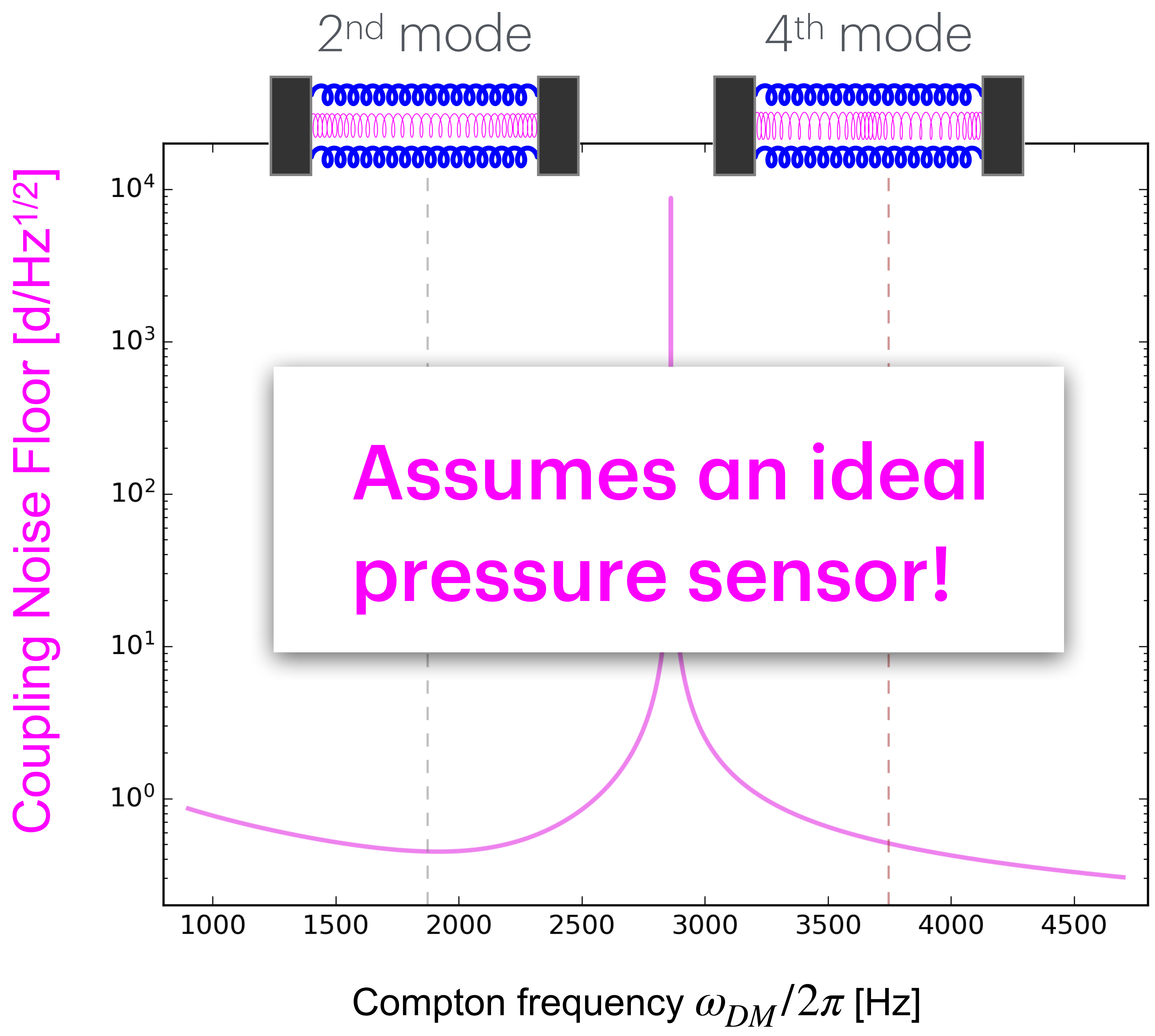
Mechanical Response to UDM (endcap pressure)



Converting measured signal to strain

- **Drive** = **motion** / **susceptibility**
- Resonances cancel
- Antiresonances = noise spikes

Mechanical Response to UDM (endcap pressure)



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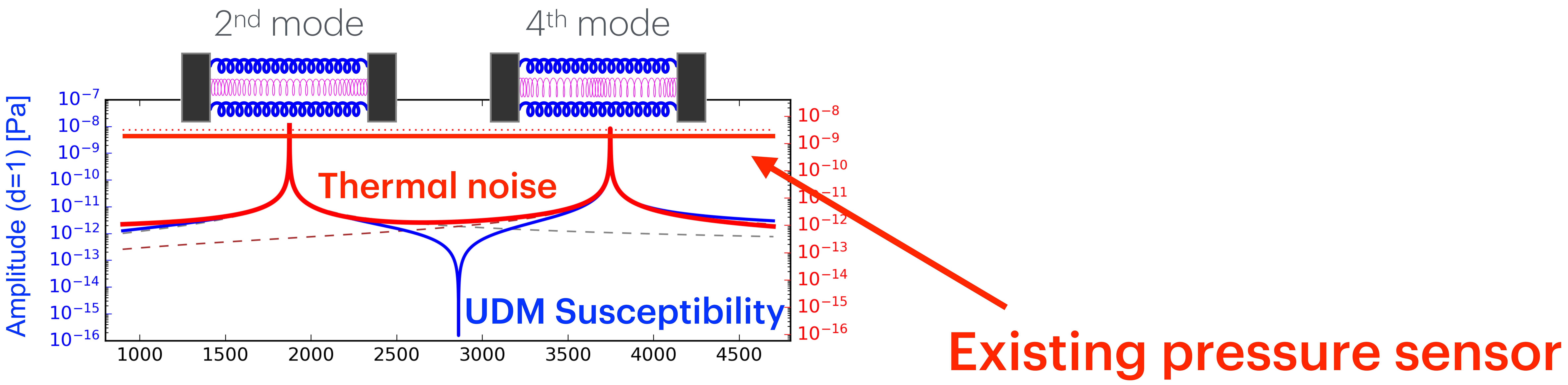
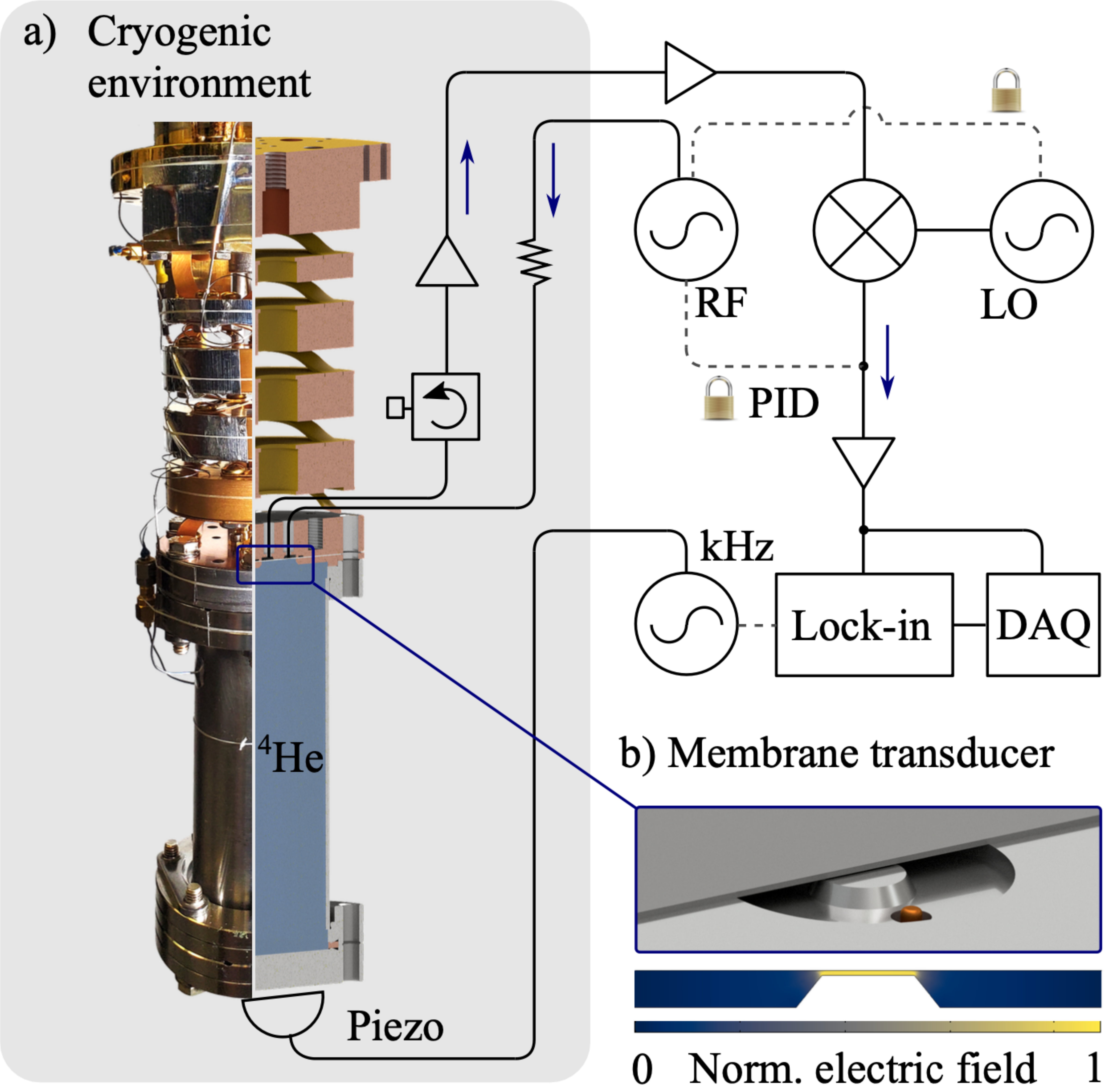


Helium ultraLIght dark matter Optomechanical Sensor (HeLIOS)



Existing pressure sensor

- 0.3-mm-thick niobium sheet
- Deflection capacitively coupled to superconducting microwave cavity
- **Helium thermal noise** (fundamental limit) visible only near resonance.

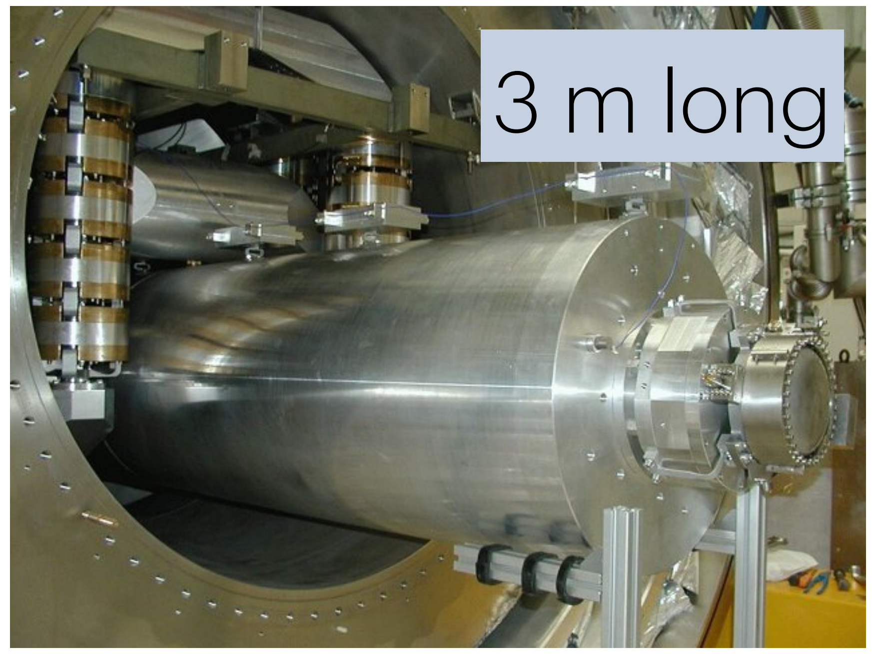
M. Herschel et al., PRD 109 (2024) 095011

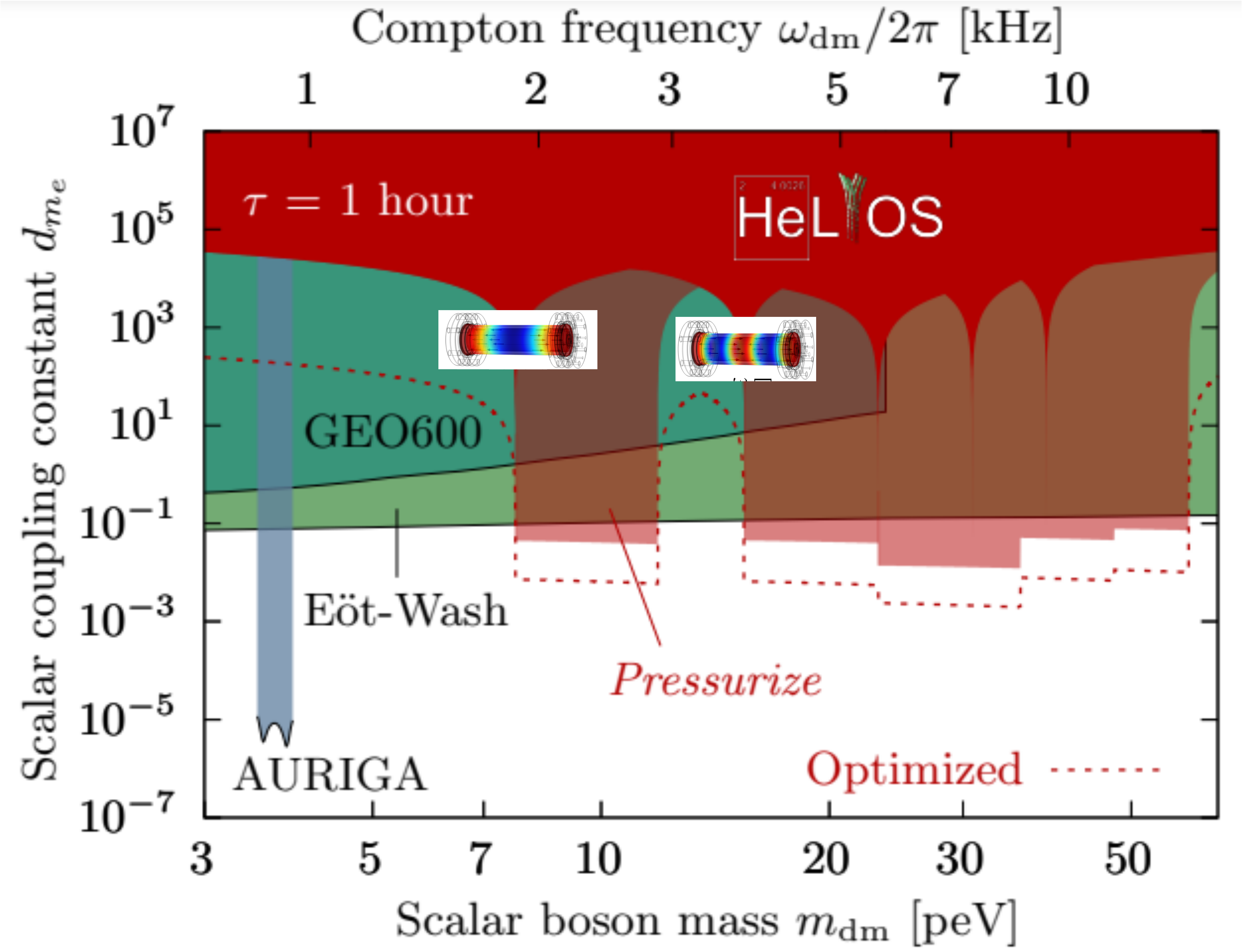
Helium ultra**LI**ght dark matter **O**ptomechanical **S**ensor (HeLIOS)

GEO600

EÖT-WASH

AURIGA





HeLIOS v1 (Sensitivity)

12 cm long

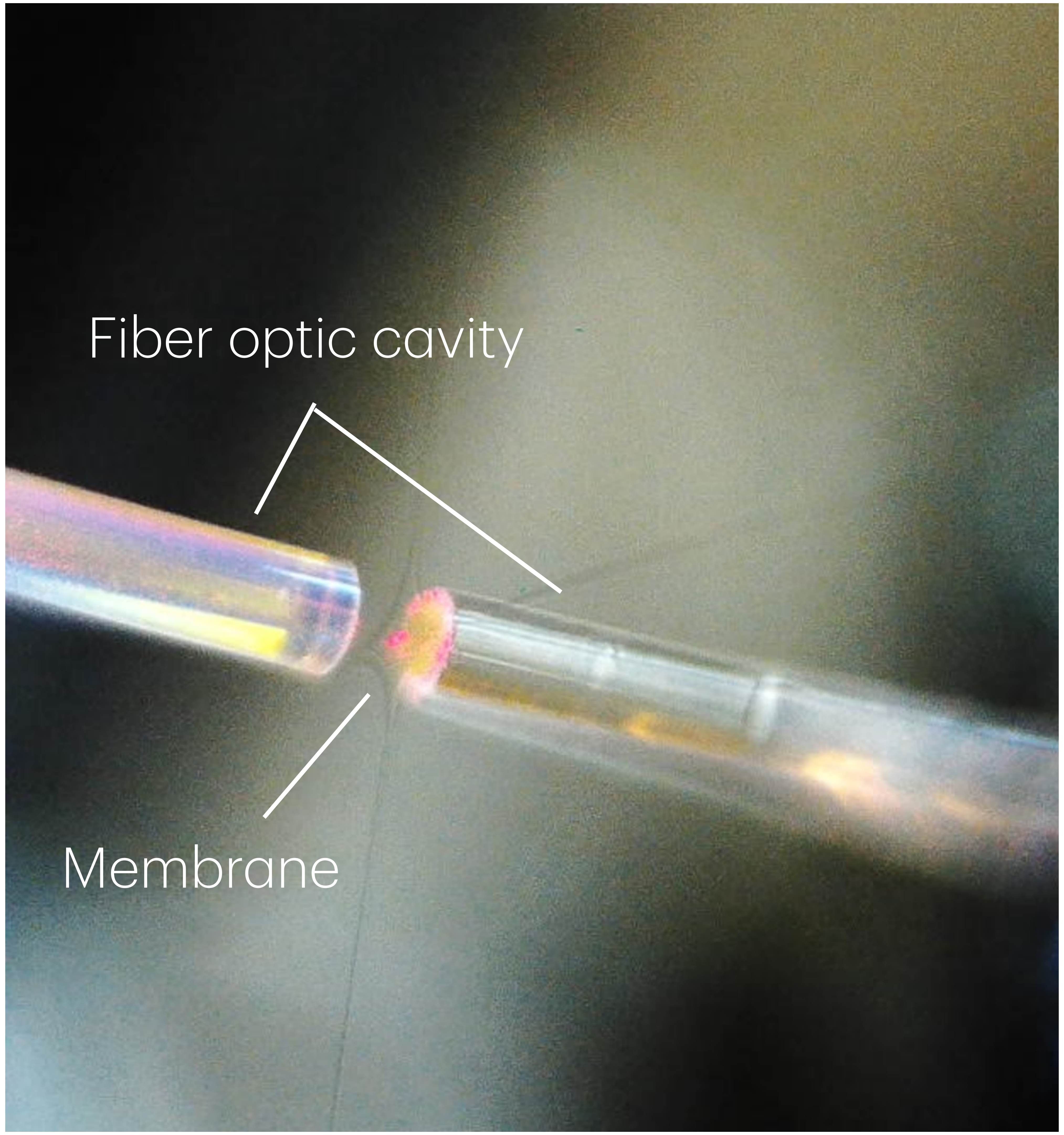
M. Herschel et al., PRD 109 (2024) 095011

Goal: Improved readout, ***broadband*** sensitivity

McGill

Quantum Optics & Sensing Lab
(**J. Sankey**, L. Childress)

Specialized in Quantum Optomechanics
100 Hz - 100 kHz



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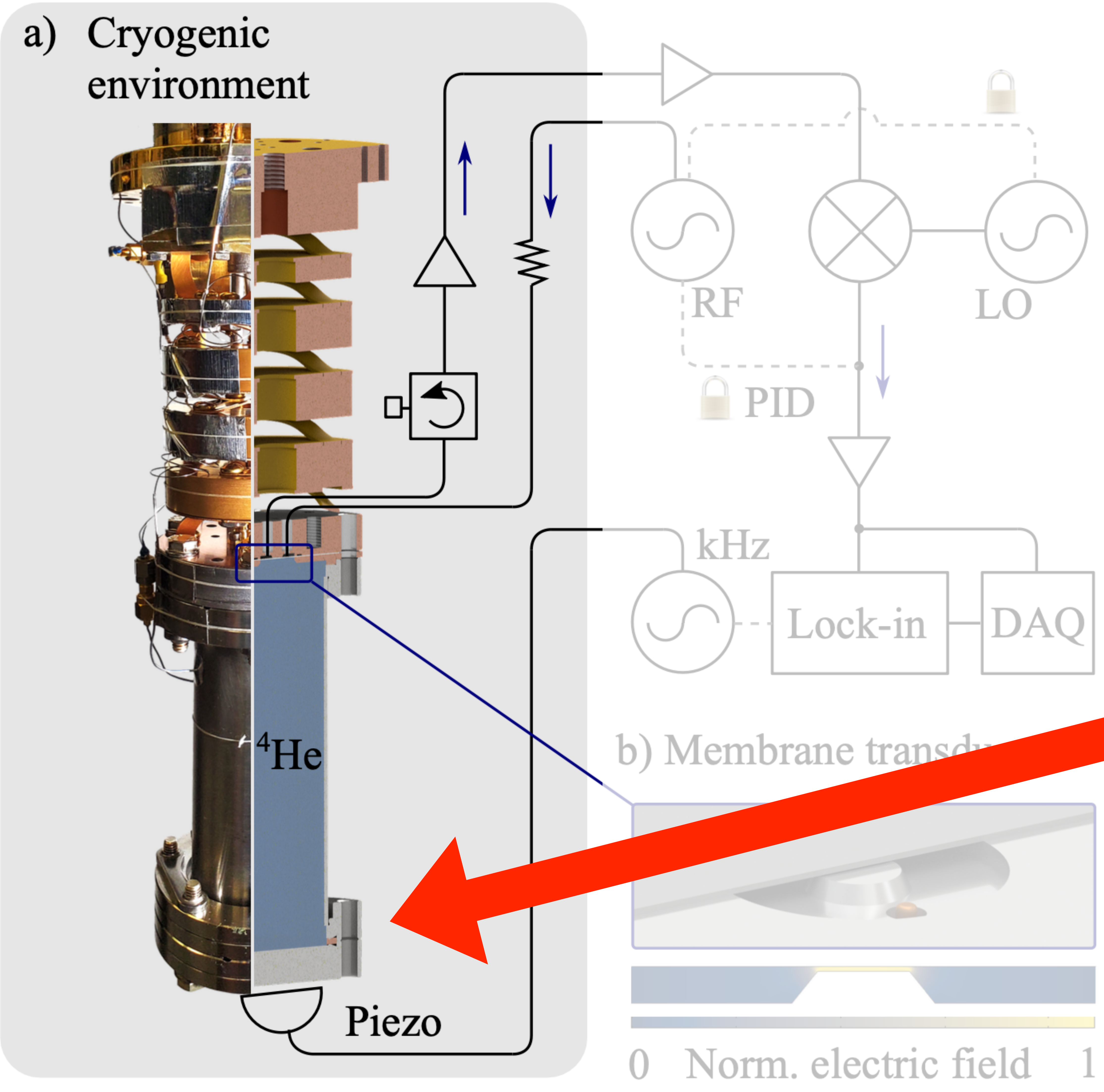
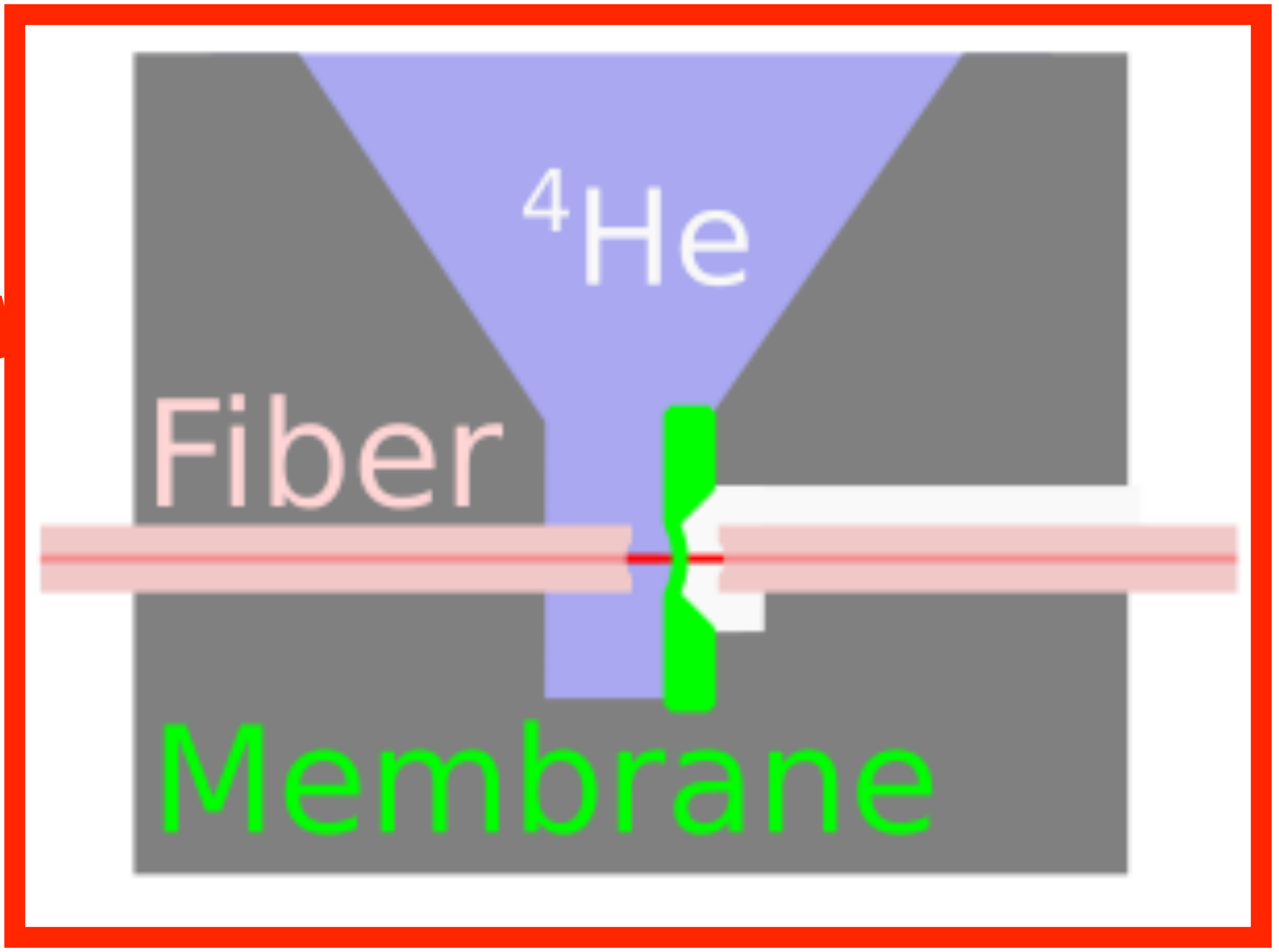


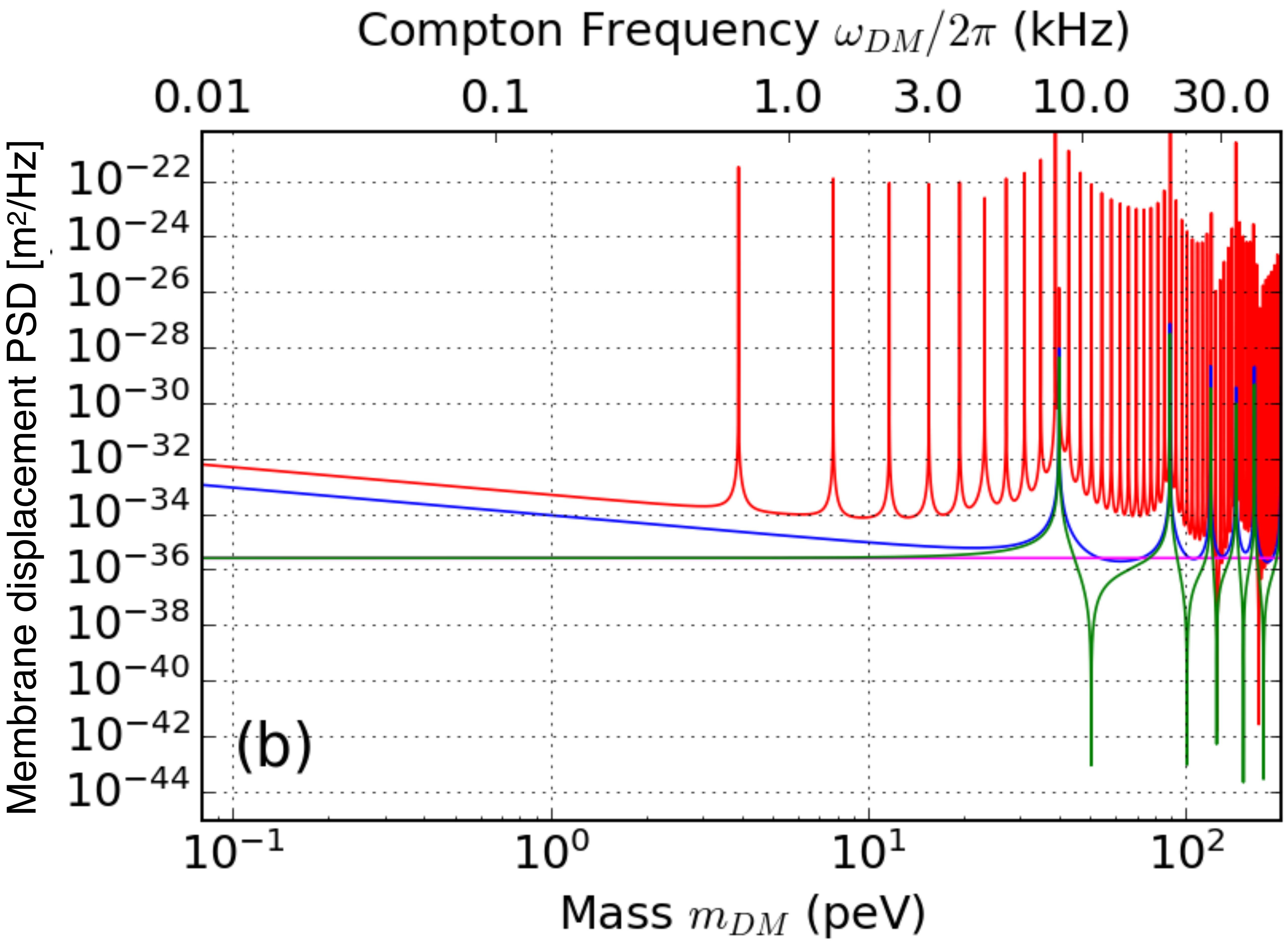
New pressure sensor

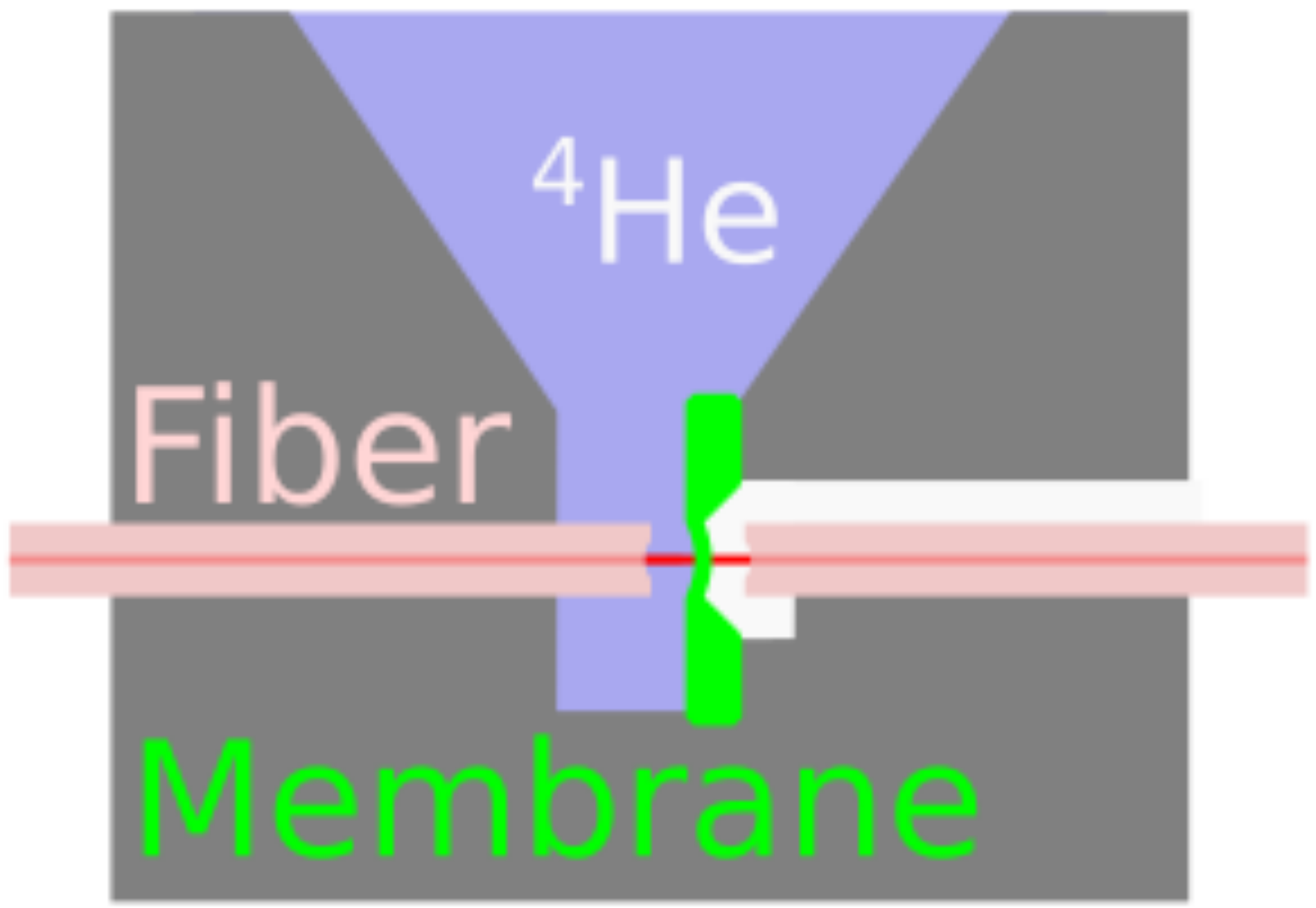
- 100-nm-thick SiN membrane
- Deflection measured with high-finesse fiber optic cavity
- No cry electronics / GHz coax cables



Noise budget with new pressure readout

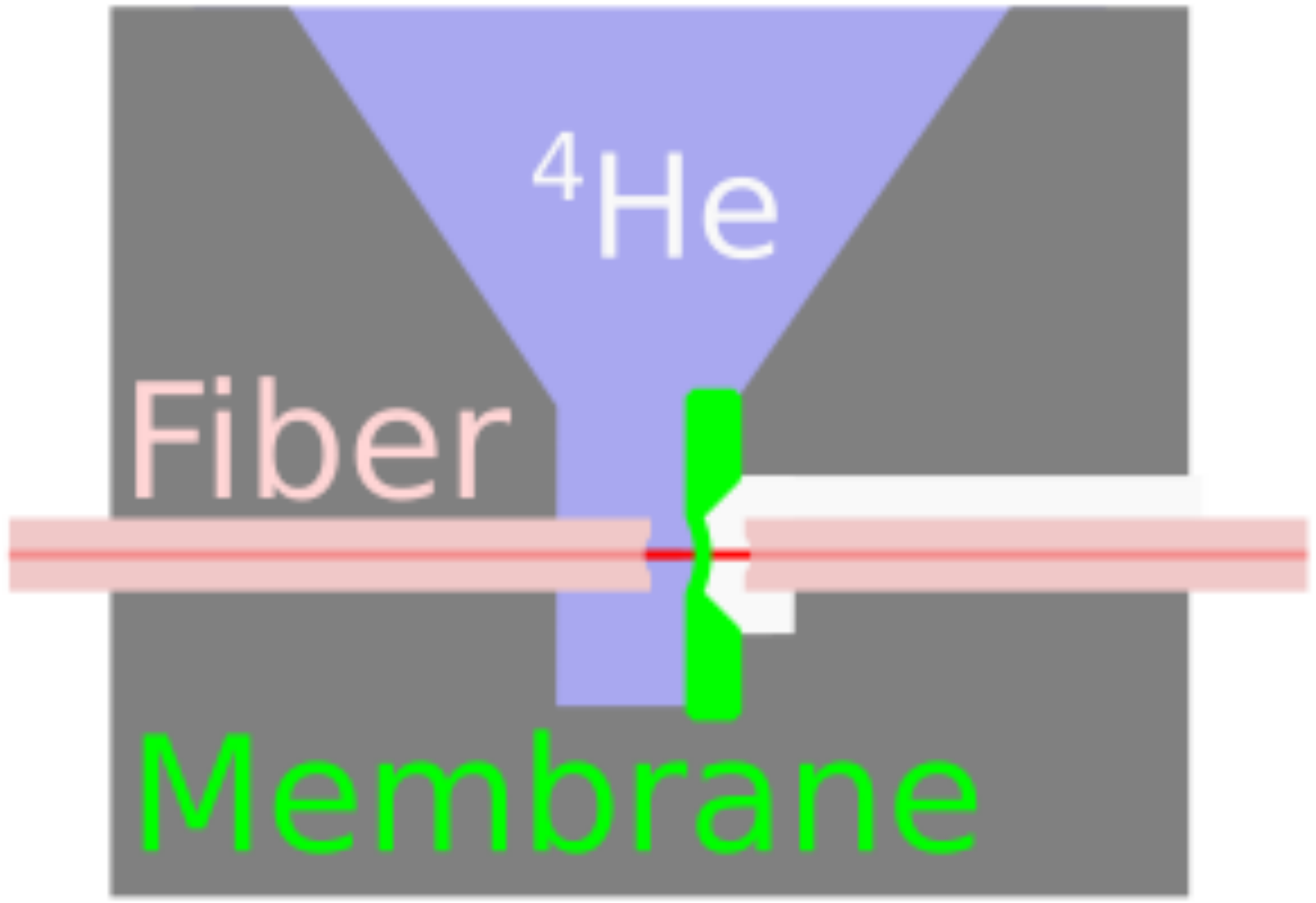
- Helium thermal noise (ultimate limit)
- Membrane thermal noise
- Readout quantum (shot) noise
- Quantum back-action

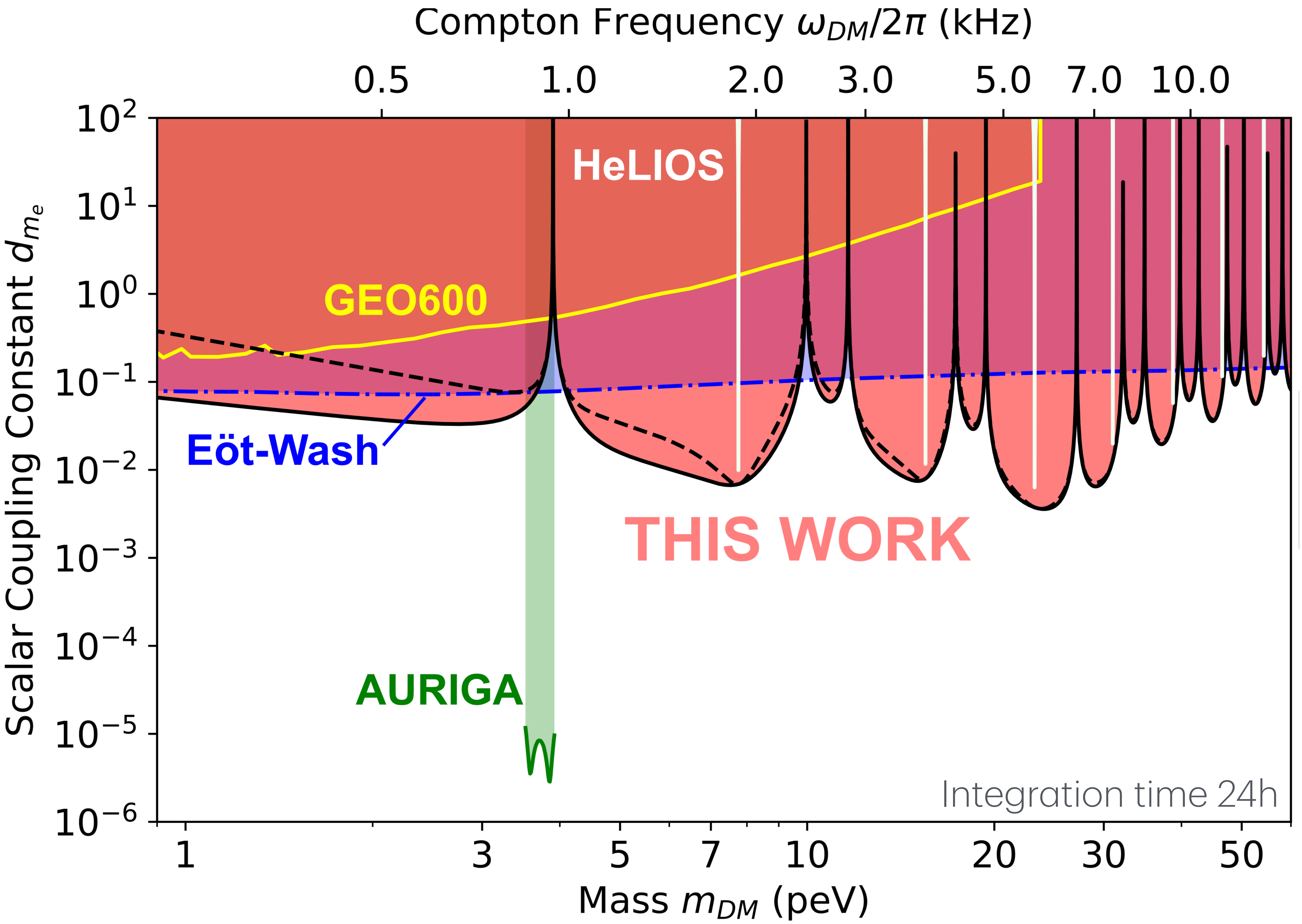




Scalar UDM (expected) sensitivity

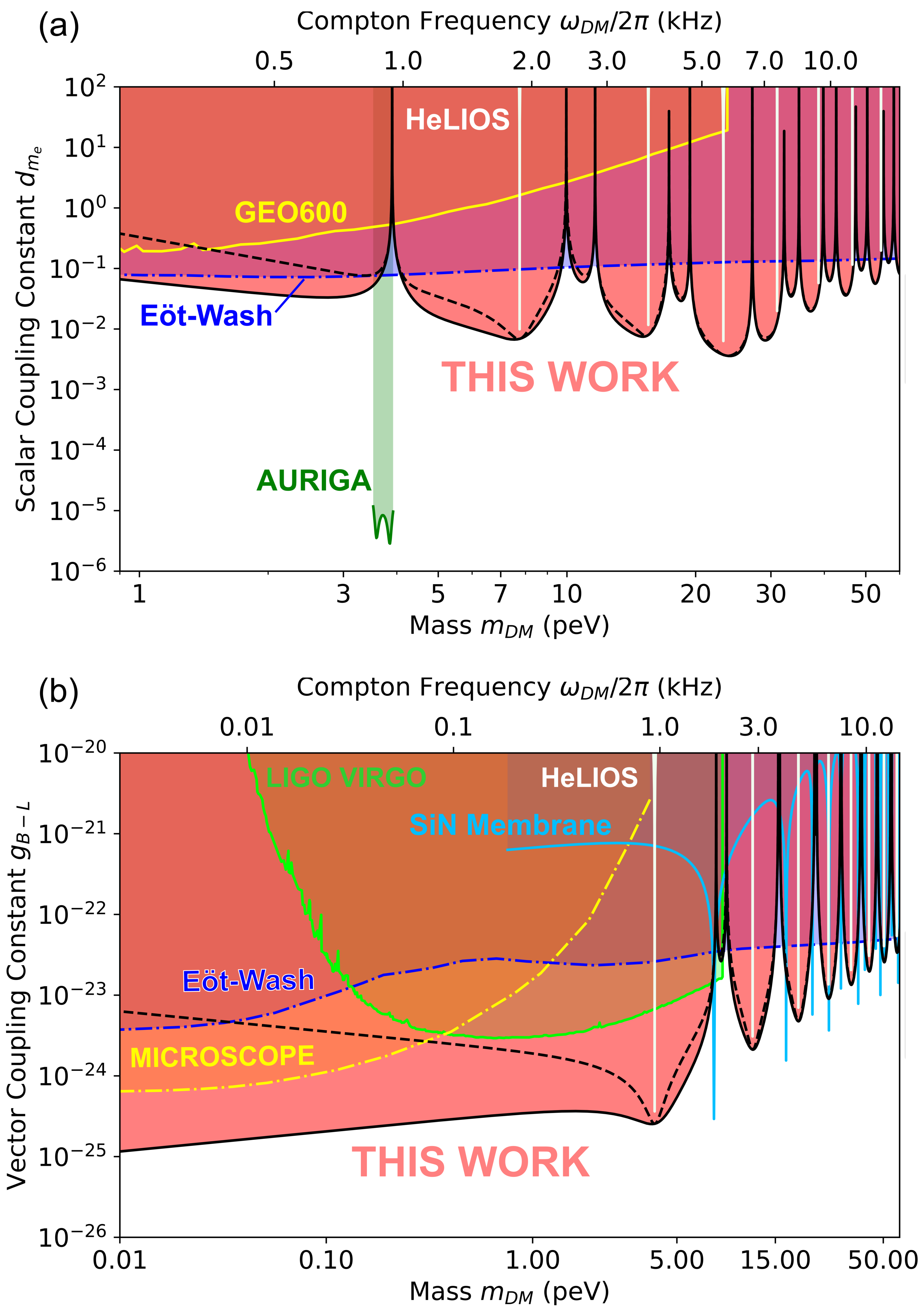
- Model quantitatively matches simulation
- World-leading sensitivity within 24h of data taking!



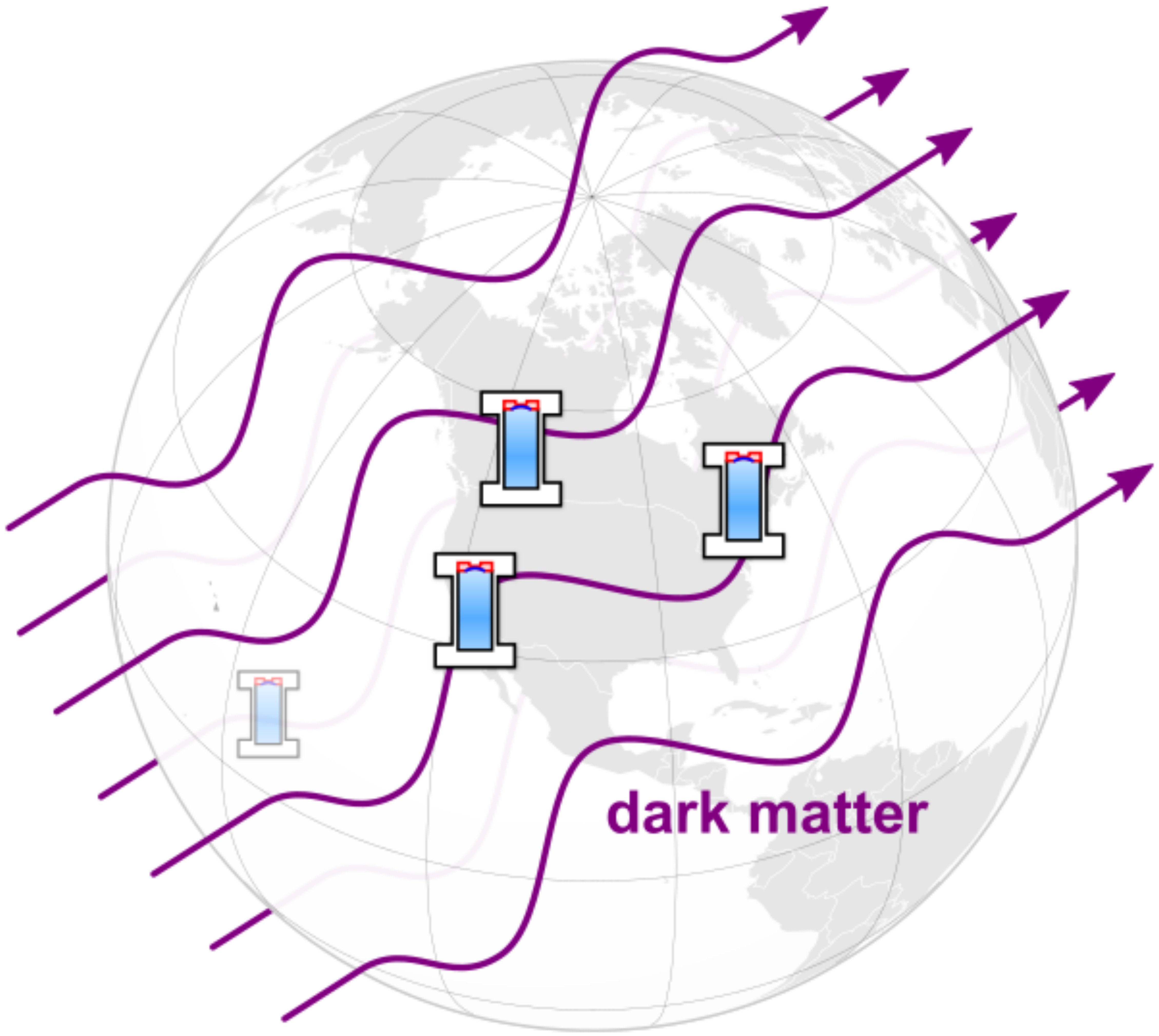


Summary

- Superfluid UDM detector concept
- Cavity-membrane readout for broadband response
- Swept-frequency antiresonance for signal validation
- Simultaneously sensitive to both **scalar** and **vector** UDM
- Simple analytical model can be used for detector optimization

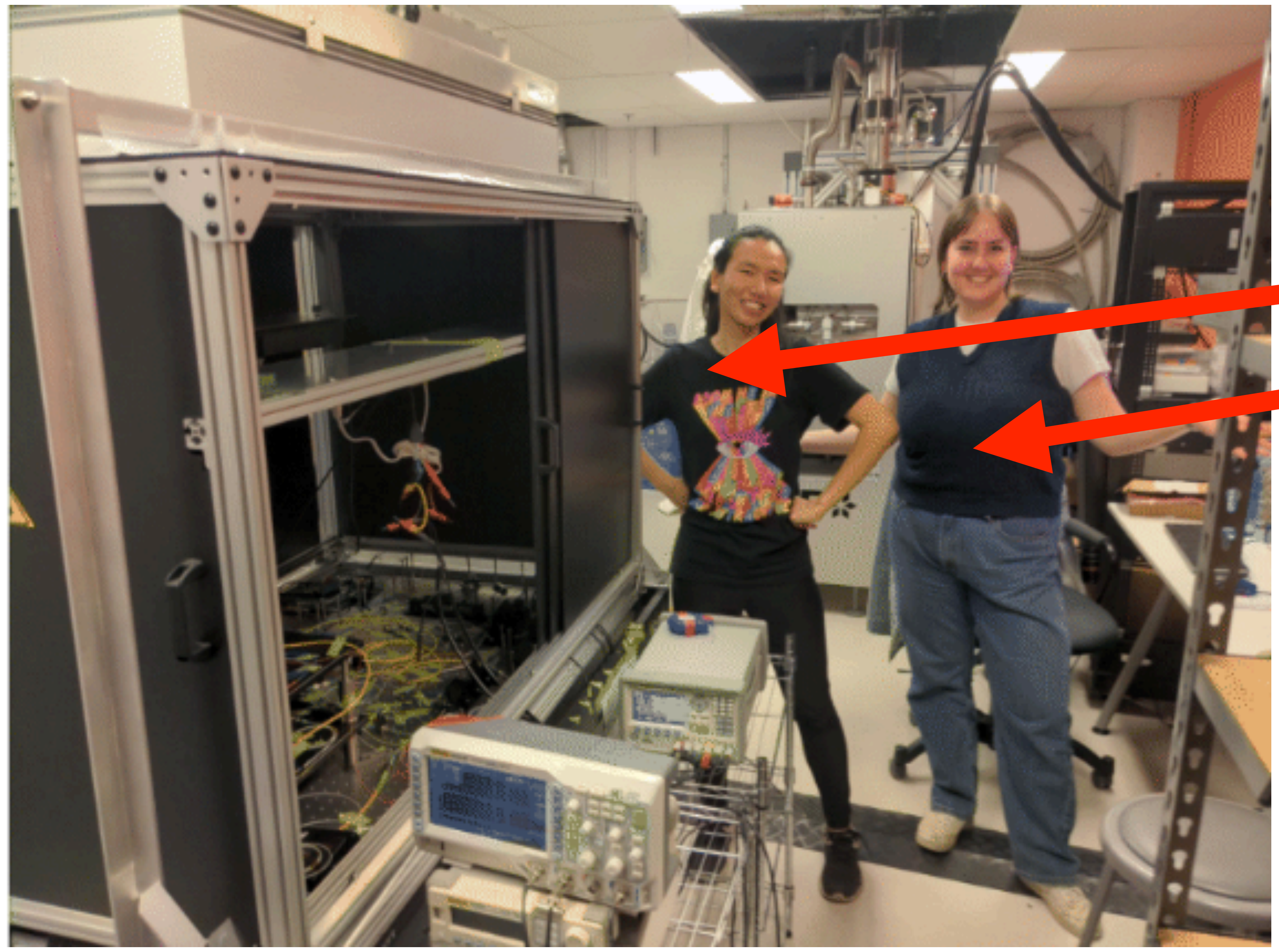


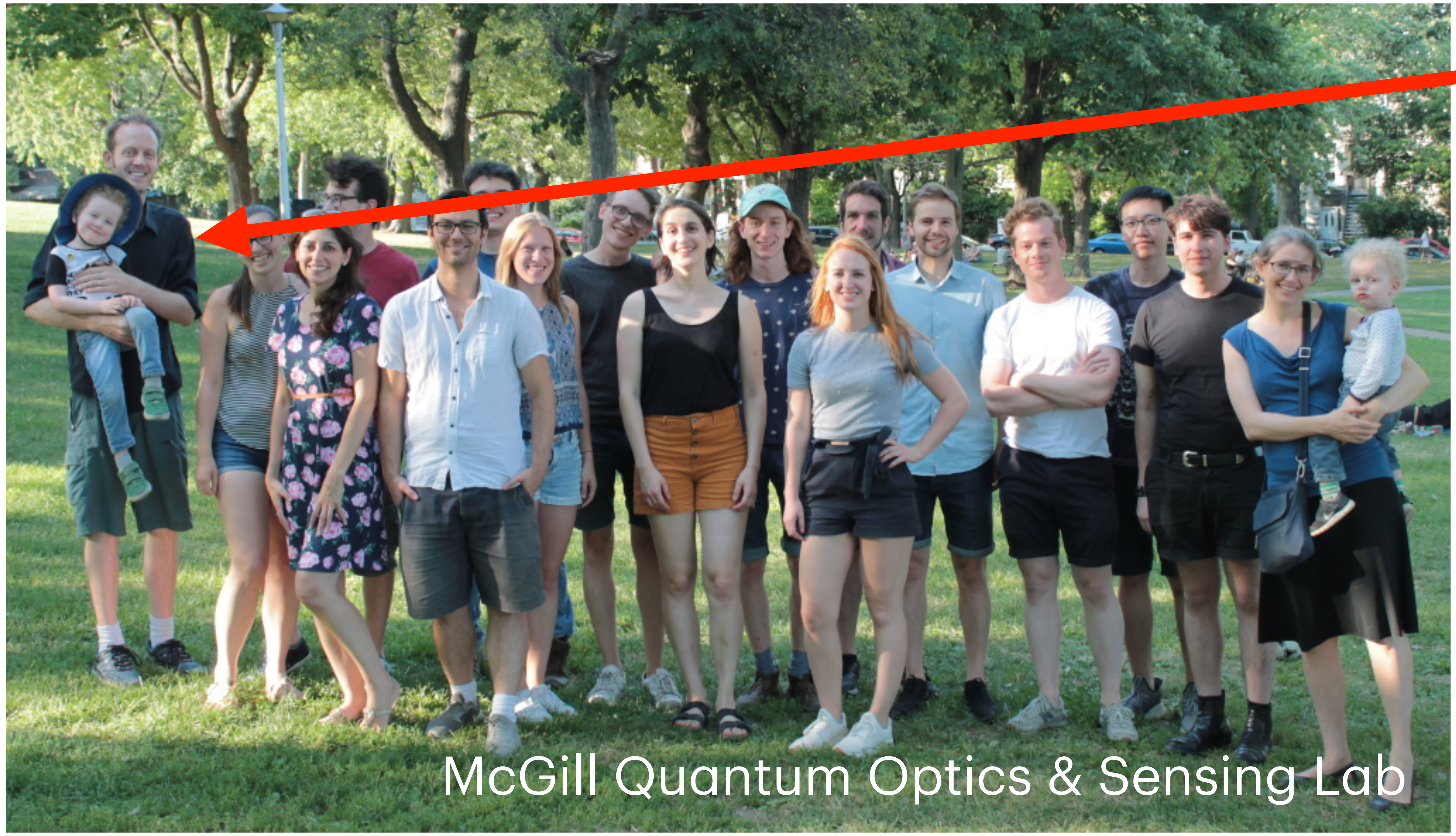
Long term vision



- Global network
  - Noise rejection
  - Directionality
- Scaling beyond “low-cost tabletop” (dreams?)

Team





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BACKUP

Parameters used for noise budget

HeLIOS & realistic parameters

Temperature	10 mK
Pipe material	stainless
Pipe length	12.7 cm
Pipe inner diameter	3.79 cm
End cap mass	0.6 kg
Pipe mode Q-factors	10^4
Helium mode Q-factors	10^7
Membrane width	15 mm
Membrane thickness	100 nm
Membrane stress	400 MPa
Membrane mode Q-factors	10^6
Cavity finesse	30,000
Input power	10 microwatts

Vector UDM

Dark matter may also be a *vector* field that

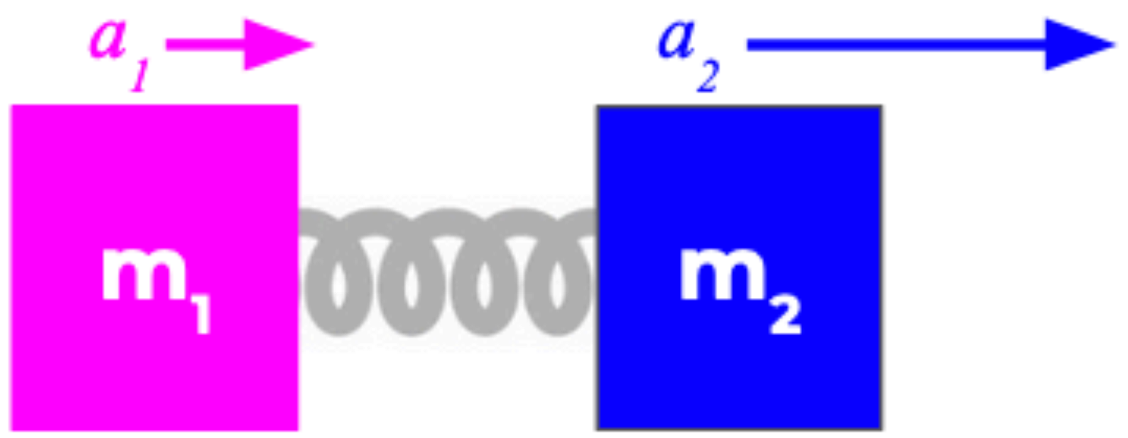
- accelerates material according to "barion minus lepton" number (i.e., A-Z)
- produces differential acoustic signal in composite systems

unitless coupling constant we wish to constrain

$$a(t, \boldsymbol{r}) \approx g_{\text{B-L}} \left(1 - \frac{Z}{A}\right) \sqrt{\frac{2e^2 c^2 \rho_{\text{DM}}}{\epsilon_0 m_{\text{n}}^2}} \cos\left(\omega_{\text{DM}} t - \boldsymbol{k} \cdot \boldsymbol{r}\right)$$

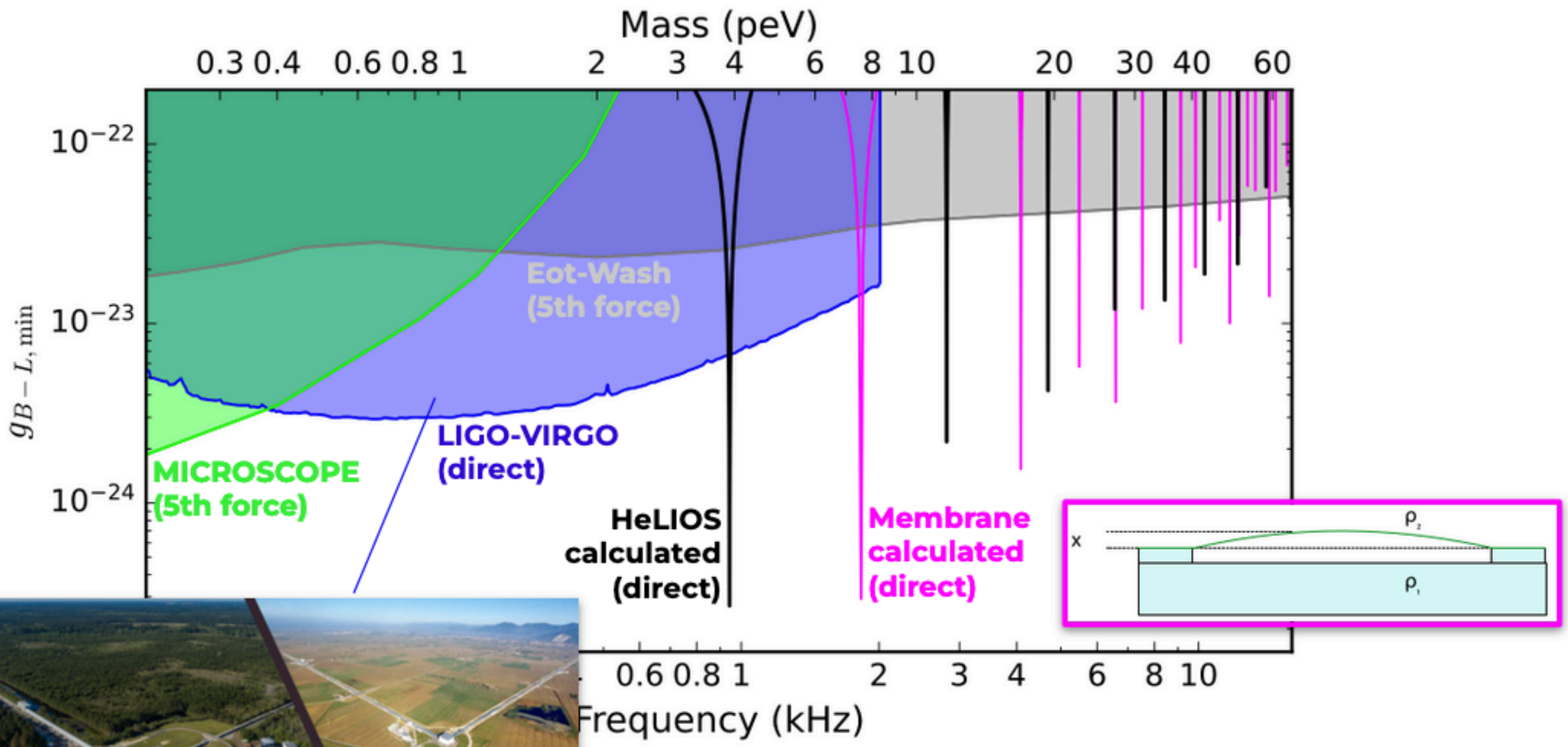
material-dependent

acceleration of a single nucleon from DM

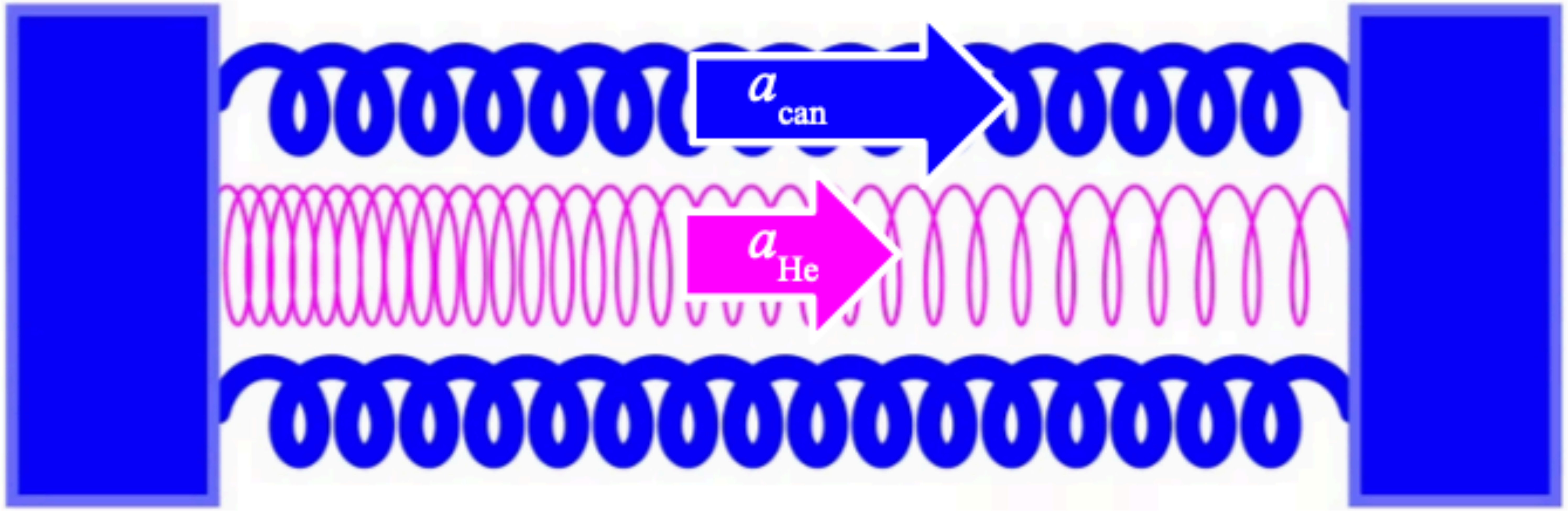


Graham *et al*, Phys. Rev. D **93**, 075029 (2016)
Manley *et al*, Phys. Rev. Lett. **126**, 061301 (2021)

Vector UDM existing constraints



Mechanical response to vector UDM



Differential acceleration induces "sloshing"

- Couples to *odd* "sloshing" modes
- Does *not* couple to even "breathing" modes
- Nonzero susceptibility at low frequency

What Do (We Think) We Know About Dark Matter?

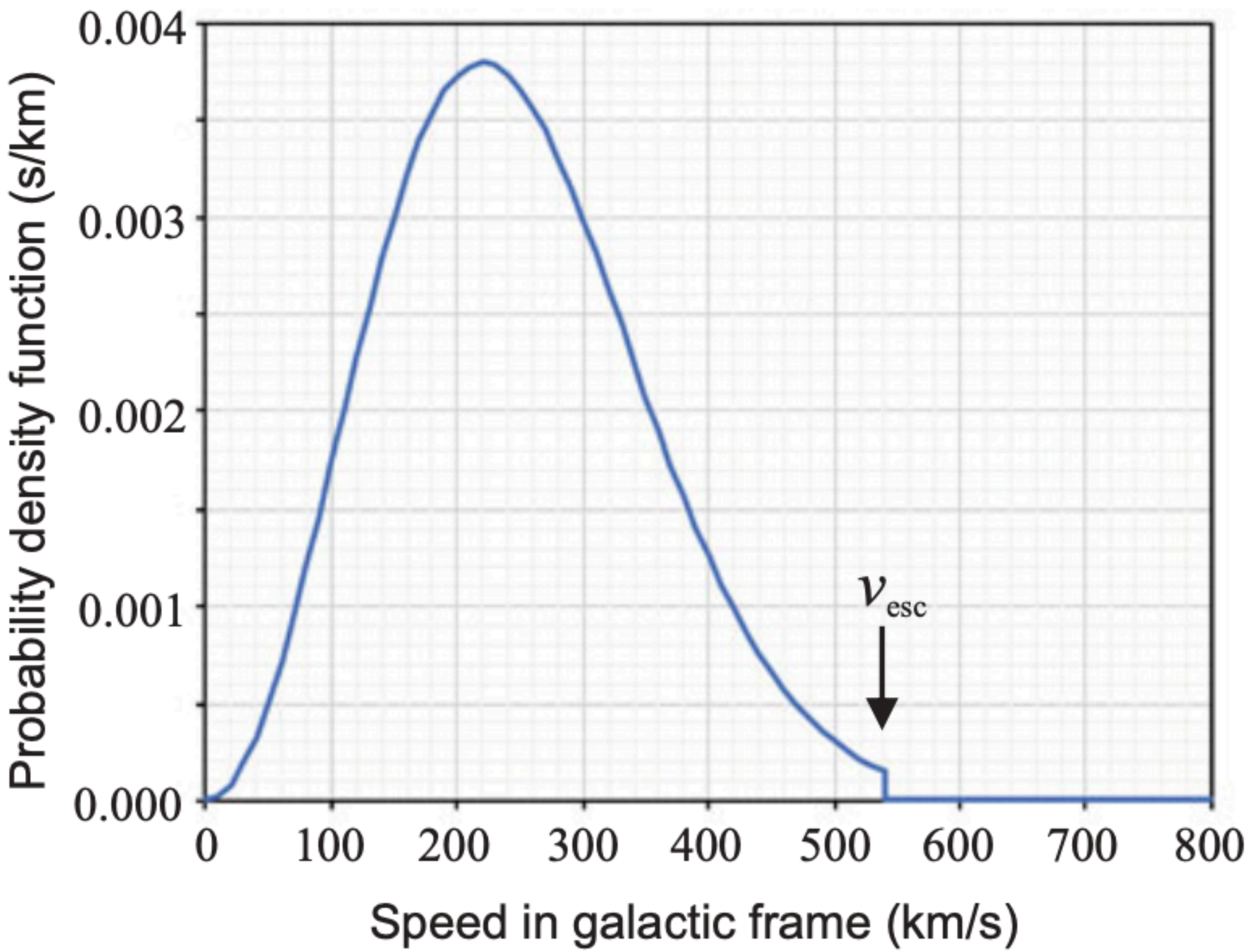
- **Has a gravitational mass**
- Is stable or long-lived
- Must be neutral (to be “dark”)
- Is not predominantly made of known Standard Model particles
- Is predominantly nonrelativistic (cold enough to clump)
- Is distributed in large "halos" around galaxies, far beyond visible matter
- Has local density ~ 0.4 GeV/cm^3 (~ 1 hydrogen atom per few cm^3)

What Do (We Think) We Know About Dark Matter?

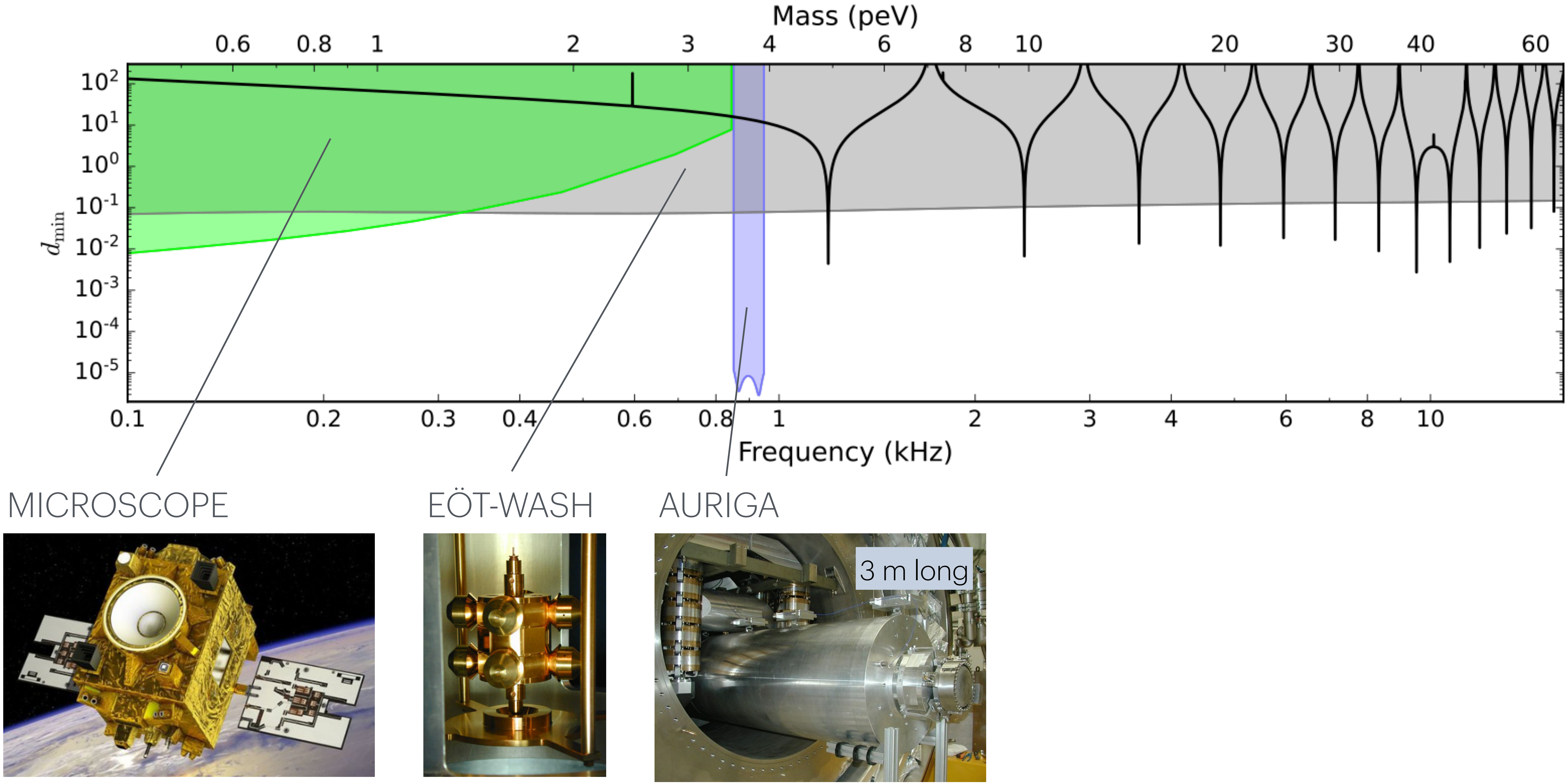
Standard Malo Model (SHM)

- Isotropic velocity distribution (w/r to galactic frame)

- (mostly) virialized.



Constraints on Scalar UDM



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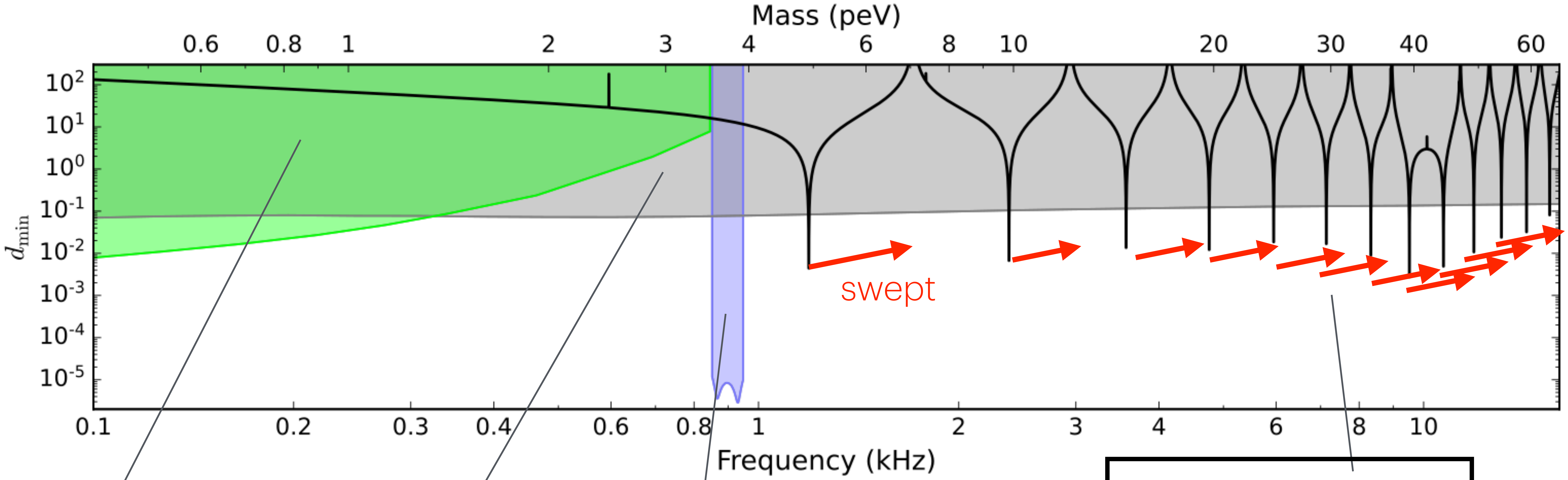
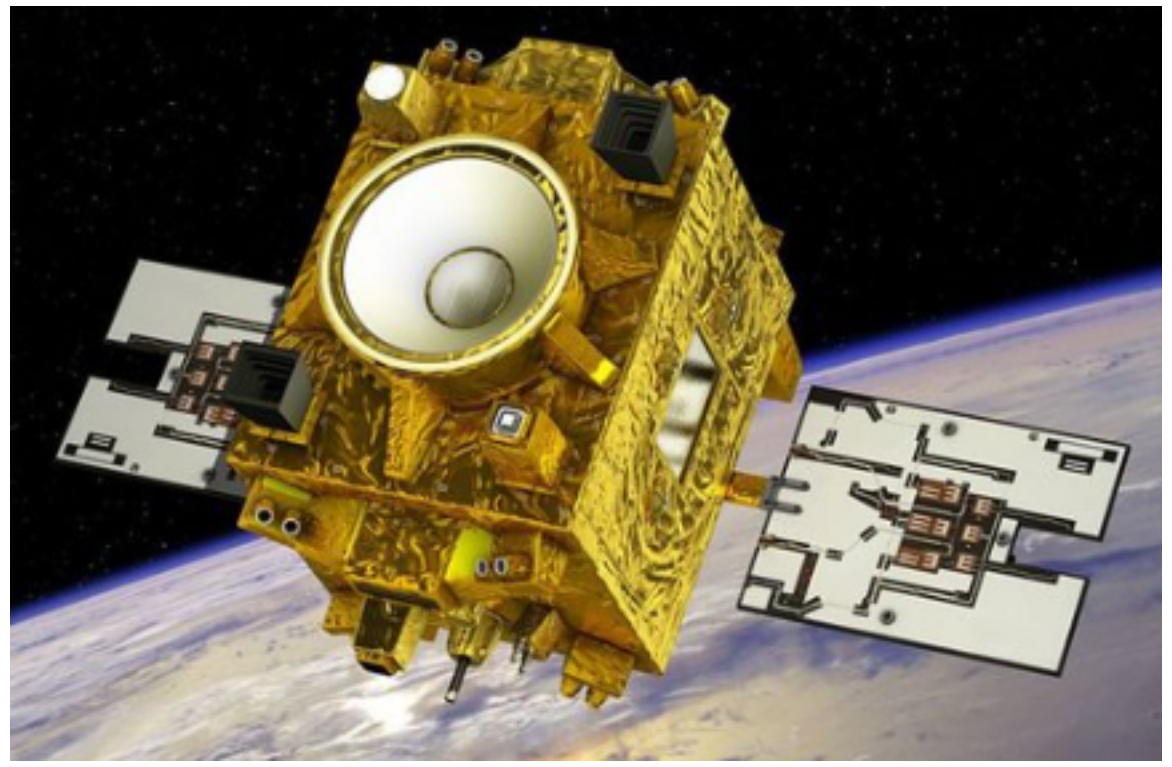


MICROSCOPE



EÖT-WASH

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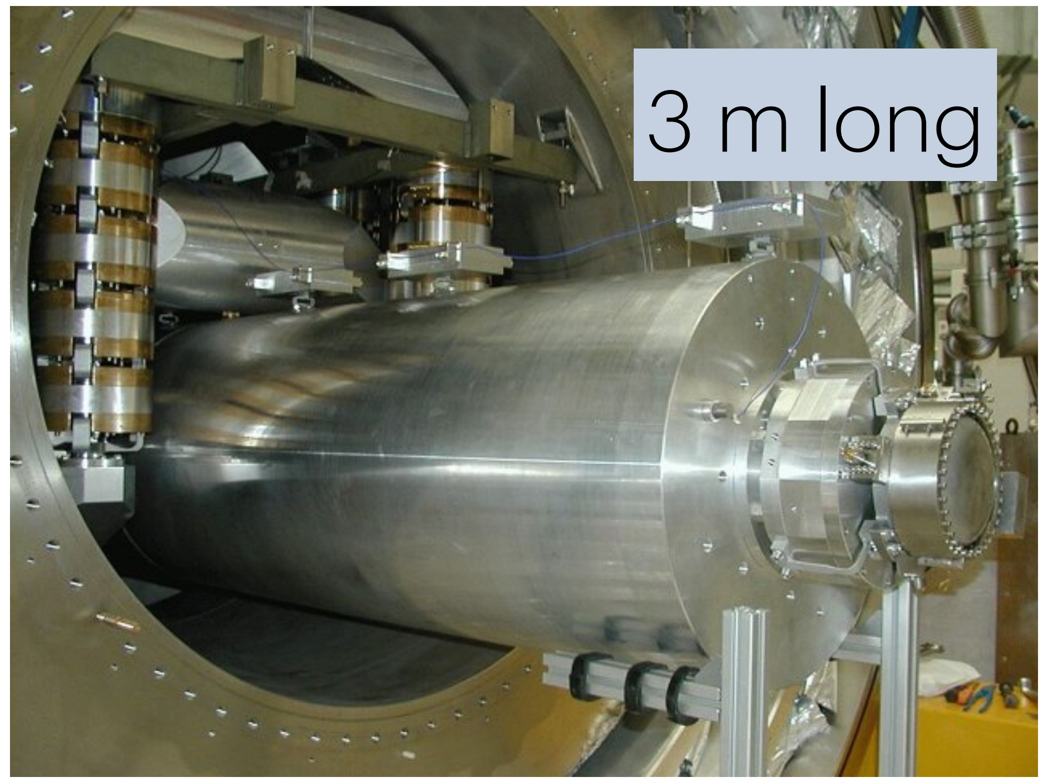

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(Sensitivity)

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