

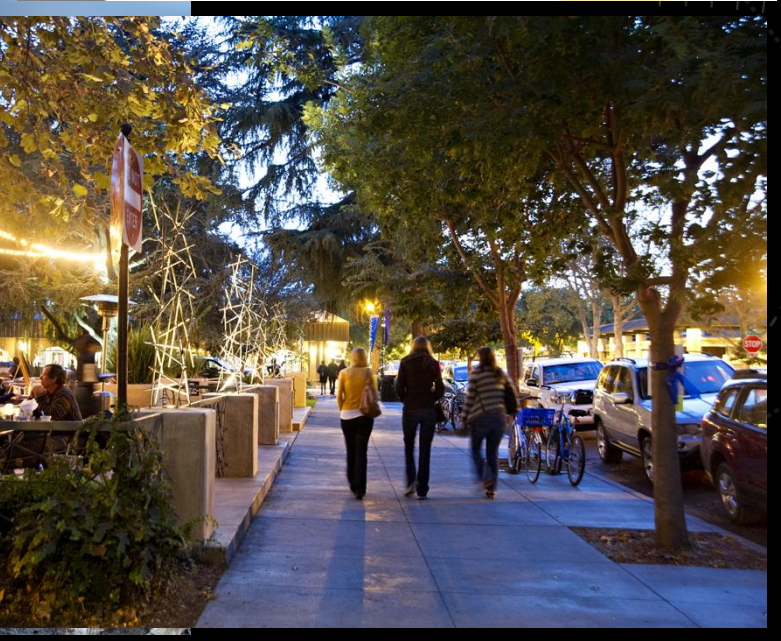
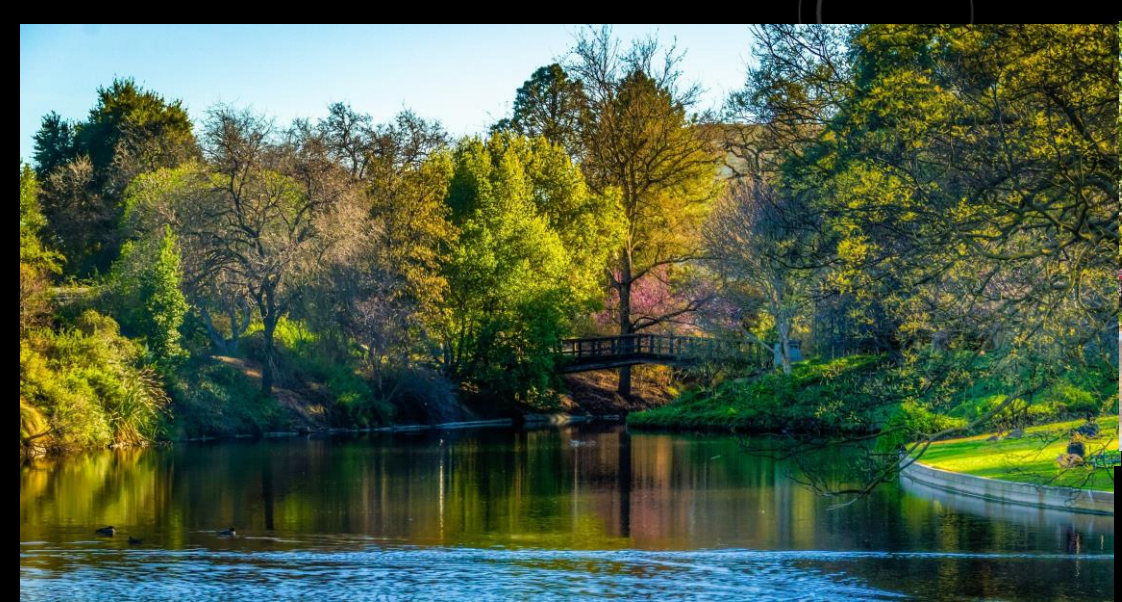


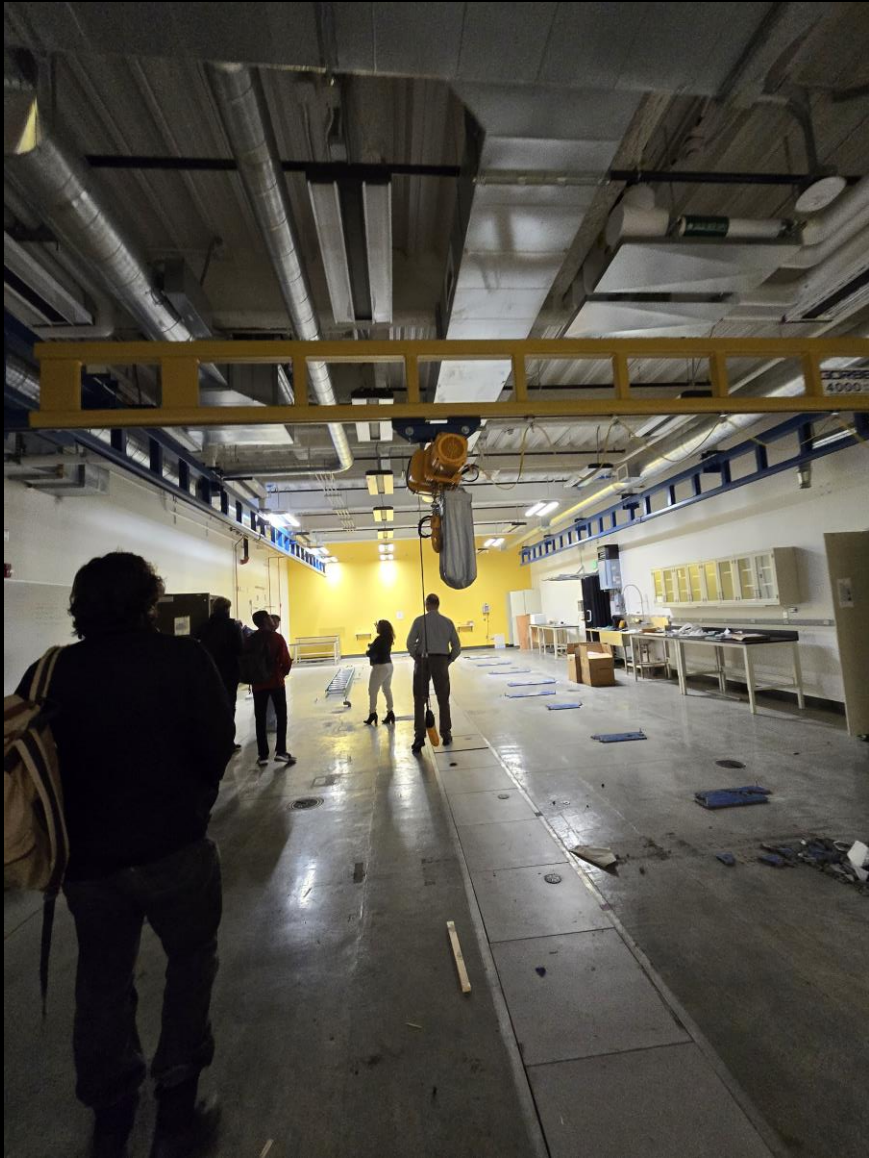
PROBING LIGHT AND ULTRALIGHT BOSONS THROUGH A VARIETY OF PRECISION MEASUREMENTS

NANCY AGGARWAL, UNIVERSITY OF CALIFORNIA, DAVIS

BICOQ 2026

JUN 17, 2026



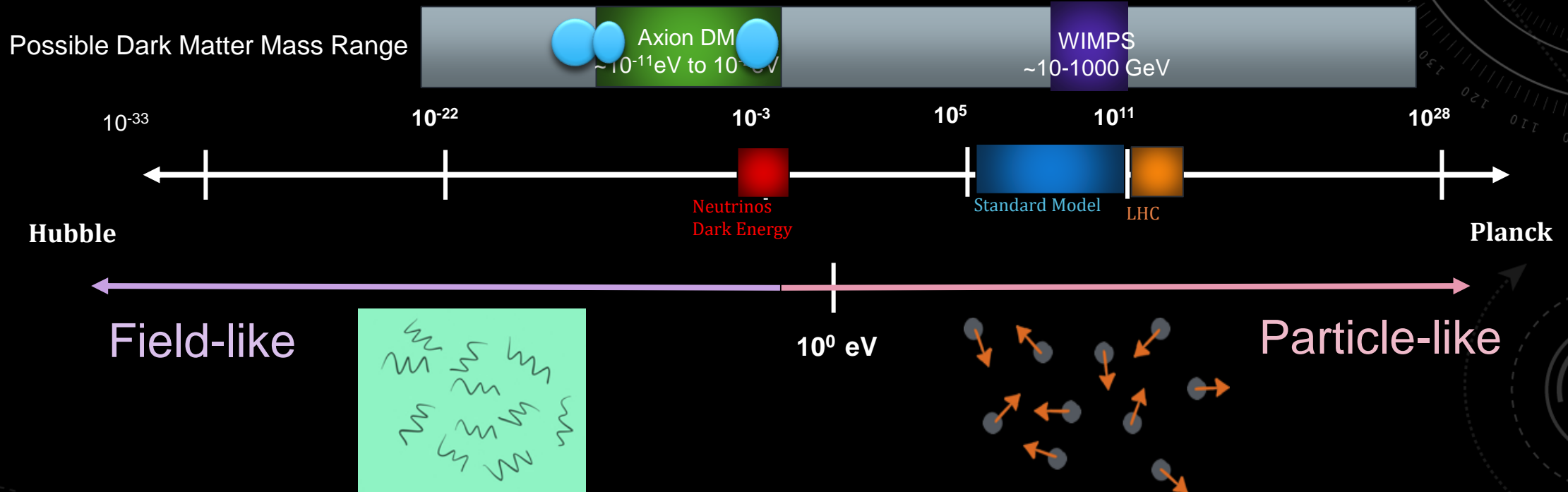


- **UC Davis:** Jackson Larsen, Dillon Goulart, Elmar Herzig, Jonathan Varghese, Anjani Gadkari, Akilan Babu, Isa Khalak, Rohan Patel
- **Northwestern University:** Andrew Geraci, Vicky Kalogera, George Winstone, Aaron Wang, Shelby Klomp, Jacob Sprague, Shefaq Elahi
- **Caltech:** Andrew Laeuger
- **MIT:** Evan Hall, Swadha Pandey
- **PTB Berlin:** Wolfgang Killian
- **Clarkson University:** Shane Larson
- **U of Washington:** Masha Baryakhtar
- **Stanford:** Mae Teo, Aharon Kahputalnik

Open PhD and Postdoc positions at UC Davis!

LIGHT AND ULTRALIGHT BOSONS

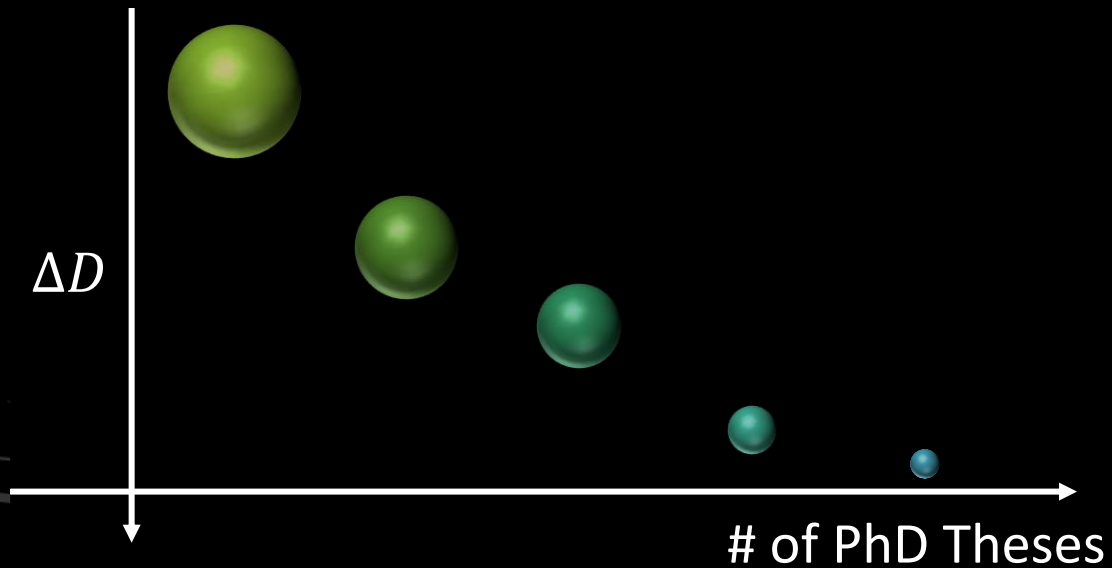
Beyond the Standard Model Physics | Strong CP violation (axion) | Dark matter candidates



Exploring ultralight bosons connects fundamental theory, cosmology, and lab-based precision measurements

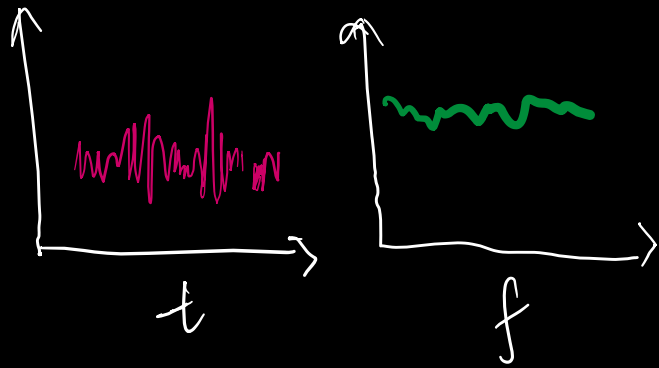
PRECISION MEASUREMENTS KEY TO:

- probe deeper into the universe via really faint GWs
- look for dark matter candidates like WIMPs and axions
- new physics at low-energy lab scales
- Also: GWs emitted by dark matter?

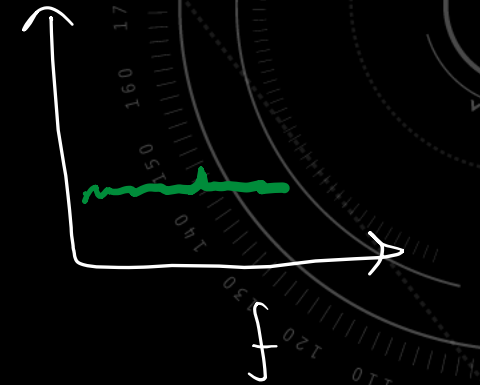
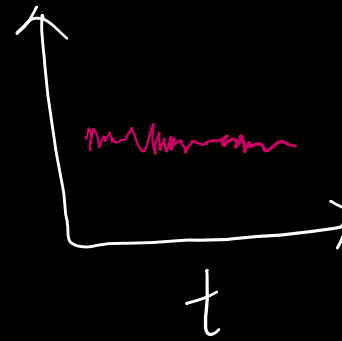
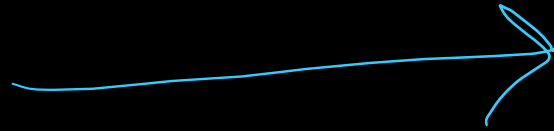


$$D \pm \Delta D$$

PRECISION MEASUREMENTS

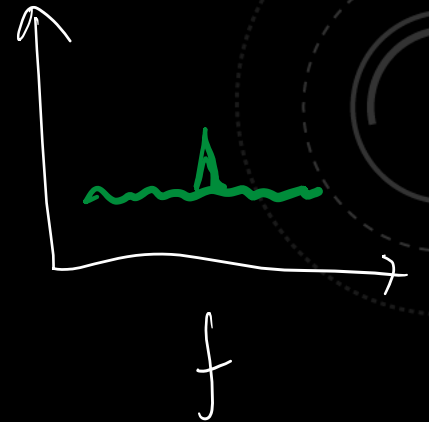
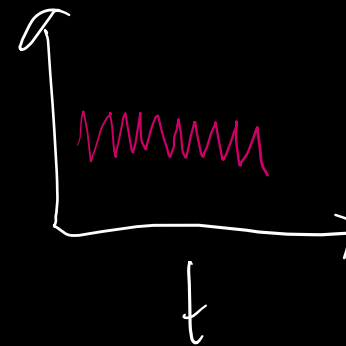
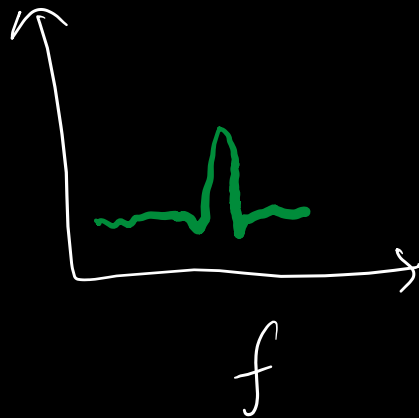
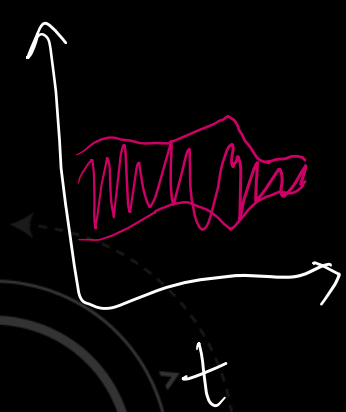


Reduce Noise



Amplify Signal

Lock-in / Matched filtering



TODAY'S TALK

m [eV]	10^{-14}	10^{-11}	10^{-9}	10^{-6}	10^{-3}
f [Hz]	10^{-14}	10^{-11}	10^{-10}	10^8	10^{11}
λ [m]	10^7	10^4	10^3	10^0	10^{-3}

ULTRALIGHT
DILATONIC
SCALAR
DARK
MATTER
SEARCHES
WITH LIGO

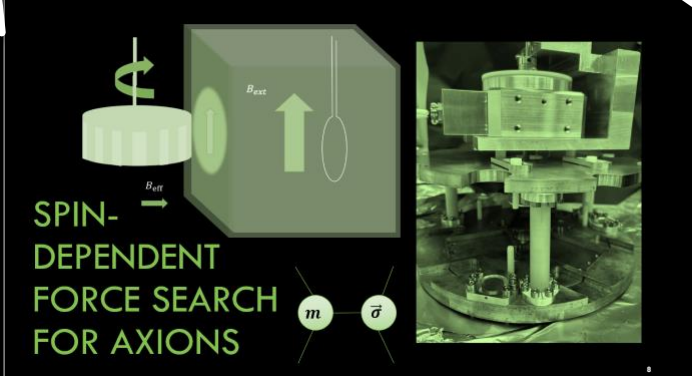


L = 4 km
P = 1MW

DM TELEVISION
Dark Matter TEsts using
LEVIitated Sensor
Interferometer
Observatory Network

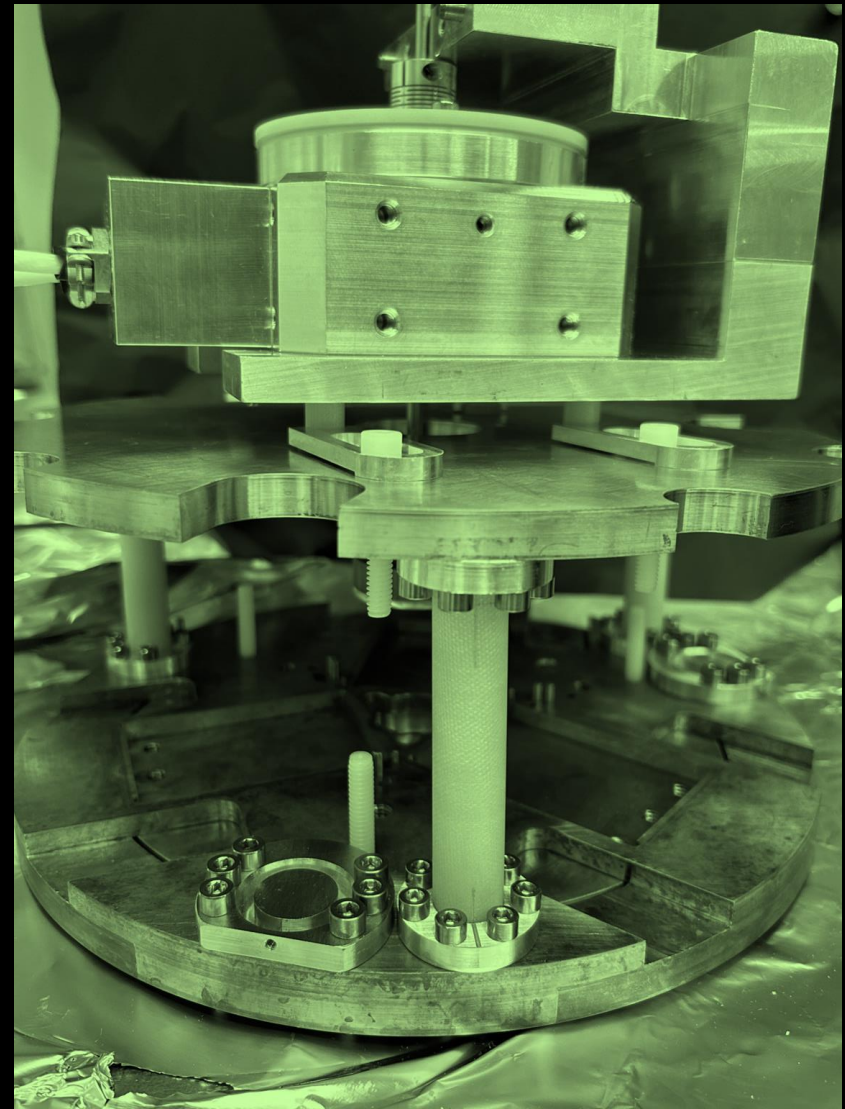
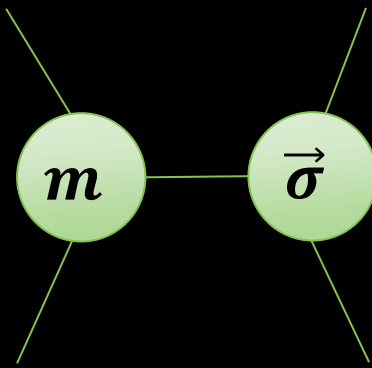
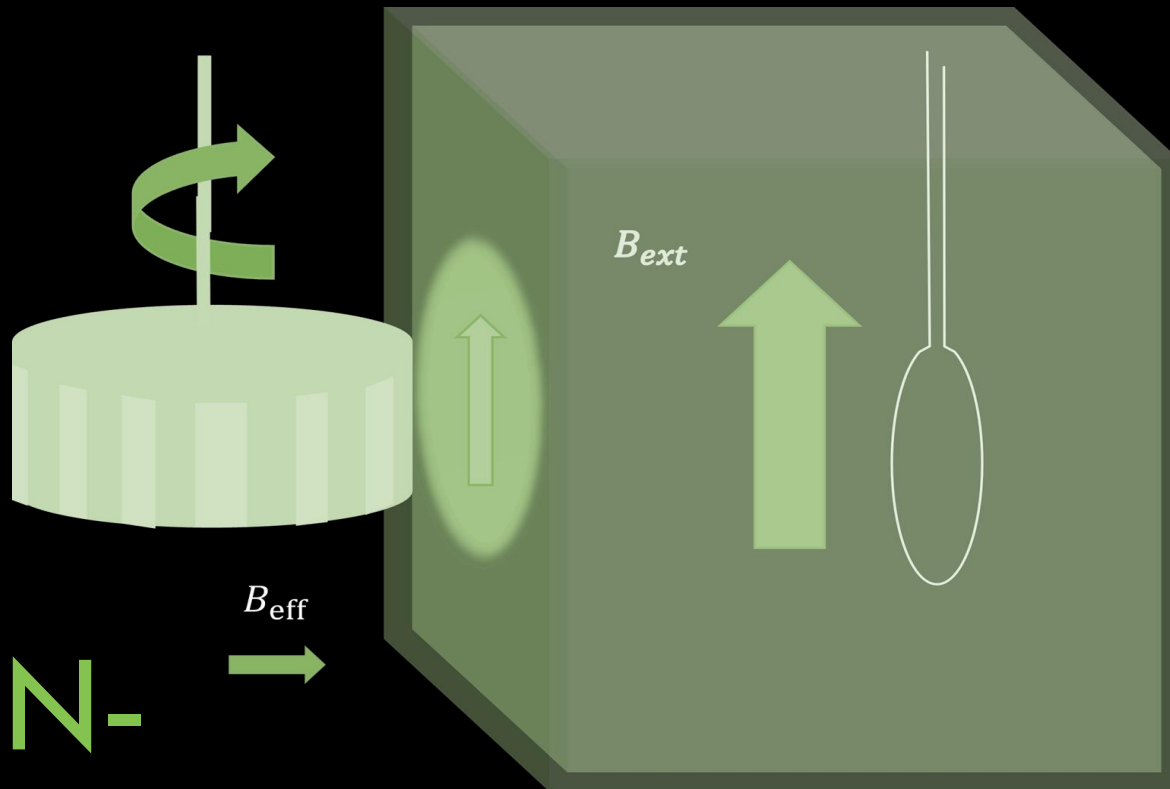


SPIN-
DEPENDENT
FORCE SEARCH
FOR AXIONS



B_{eff}
 m $\vec{\sigma}$

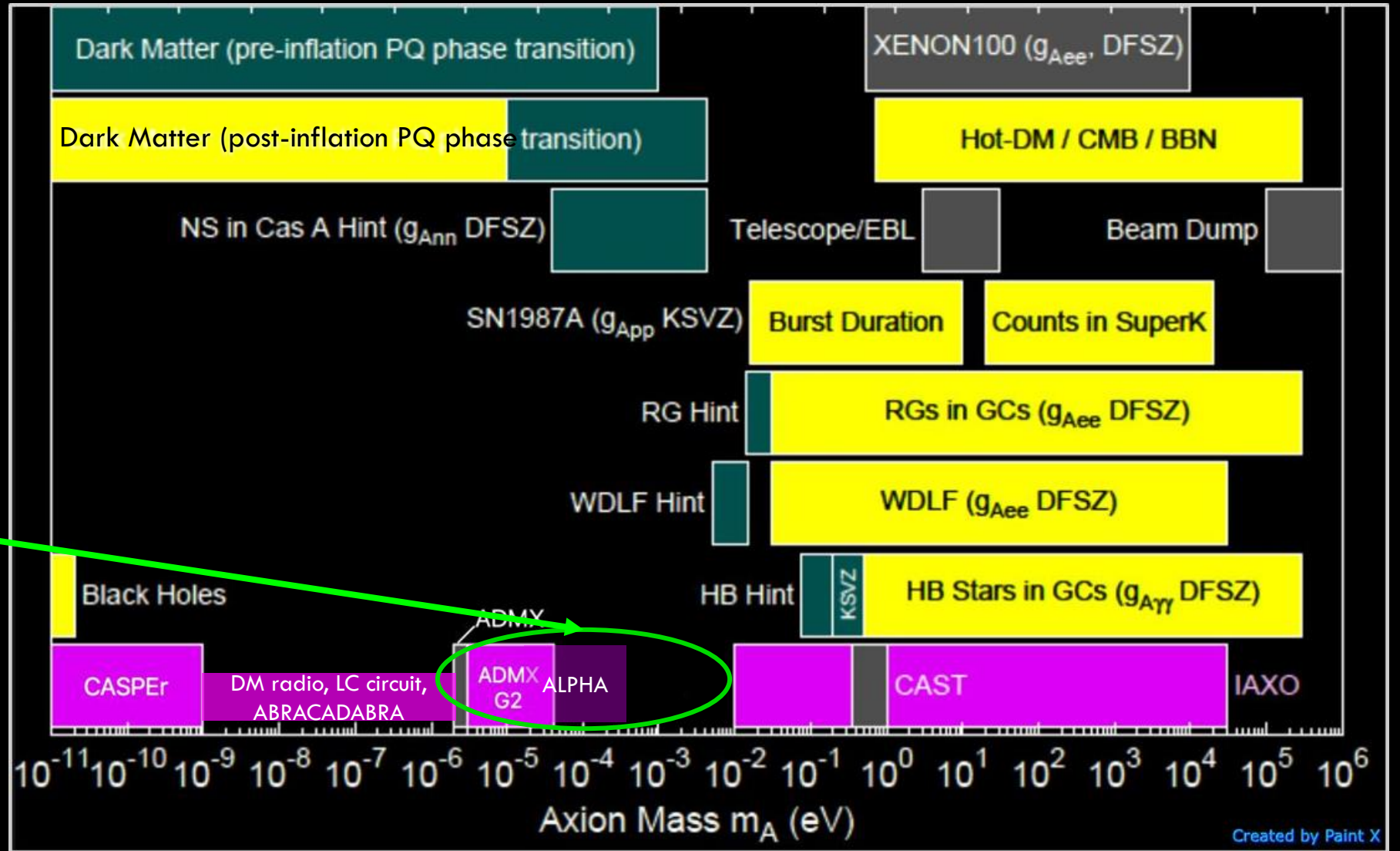
SPIN- DEPENDENT FORCE SEARCH FOR AXIONS



AXION PARAMETER SPACE - MASS

- Astrophysical Bounds
- Hints
- Experimental Bounds
- Current Experiments

ARIADNE



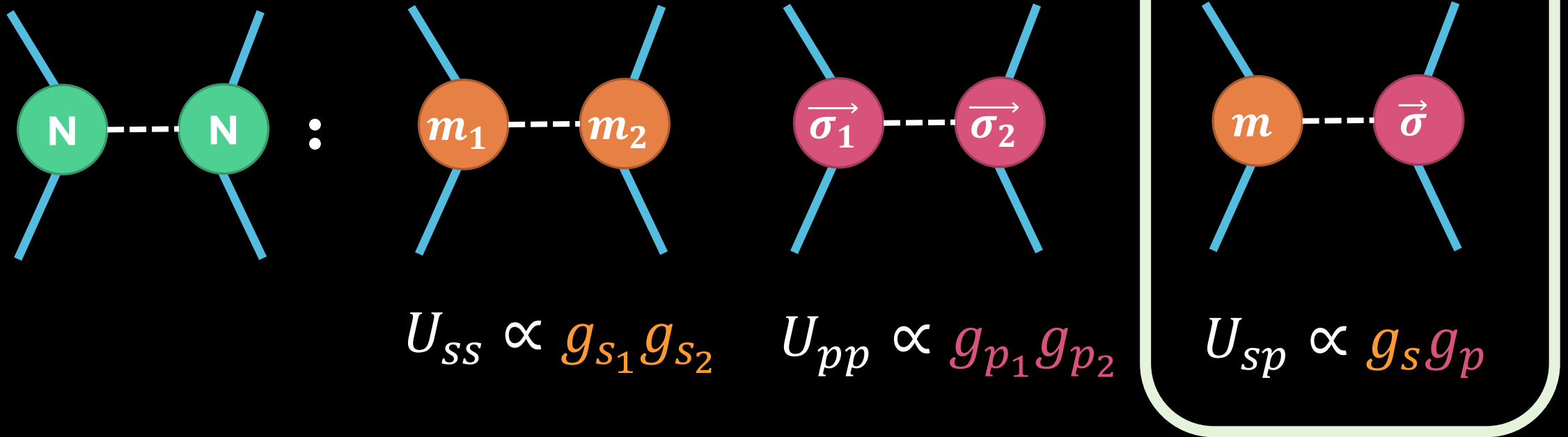
Created by Paint X

AXION PARAMETER SPACE – SOURCE AND COUPLING

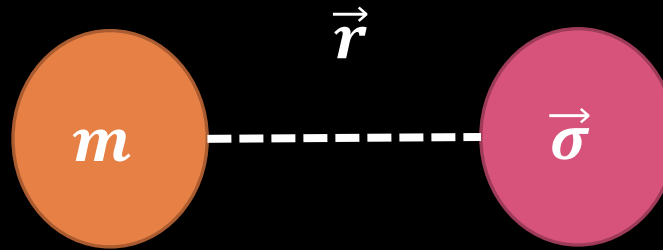
Source	Coupling		
	Photons	Nucleons	Electrons
Dark Matter (Cosmic) axions	ADMX, HAYSTAC, DM Radio, LC Circuit, ABRACADABRA MADMAX, Orpheus	CASPEr	QUAX
Solar axions	CAST IAXO		
Lab-produced	Light-shining-thru-walls (ALPS, ALPS-II)	ARIADNE	

Only experiment to directly test for nuclear couplings mediated by QCD axion in the lab

AXION-MEDIATED INTERACTIONS BETWEEN NUCLEONS



MONOPOLE-DIPOLE FORCES DUE TO AXION

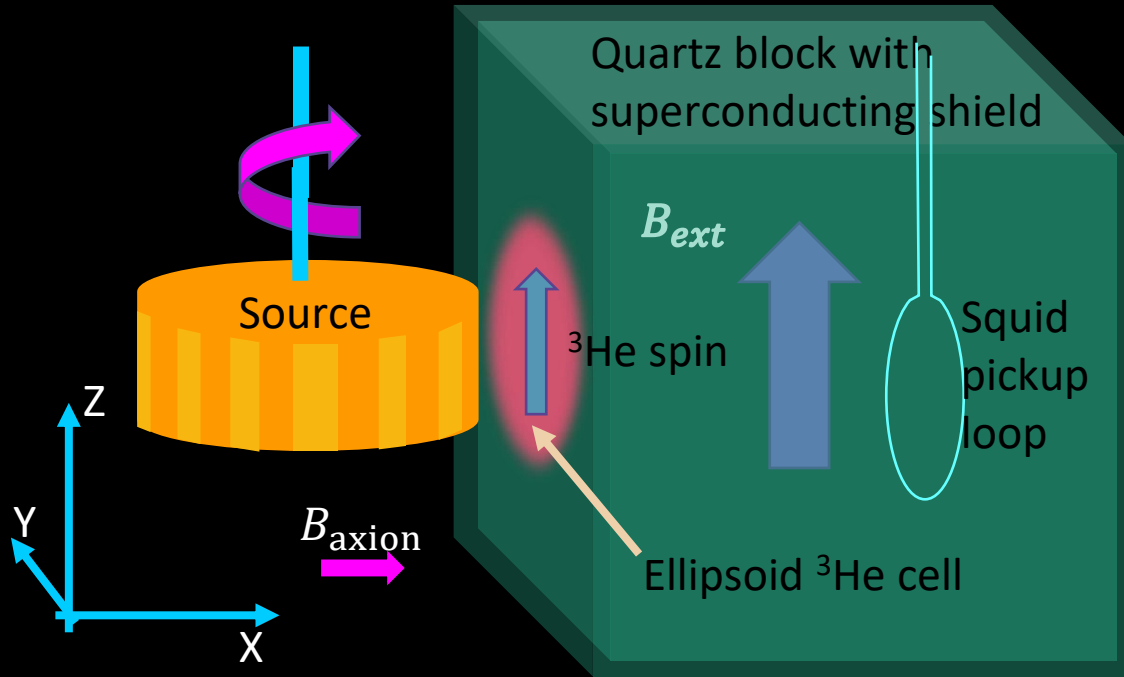


$$U_{sp}(r) = \frac{\hbar^2 g_s^N g_p^N}{8 \pi m_N} \left(\frac{1}{r \lambda_a} + \frac{1}{r^2} \right) e^{-\frac{r}{\lambda_a}} (\hat{\sigma} \cdot \hat{r})$$

$$10^{-29} \left(\frac{10^9 \text{ GeV}}{f_a} \right) < g_s^N < 10^{-21} \left(\frac{10^9 \text{ GeV}}{f_a} \right) \quad g_p^N < \frac{C_f m_N}{f_a} \approx 10^{-9} \left(\frac{m_N}{1 \text{ GeV}} \right) \left(\frac{10^9 \text{ GeV}}{f_a} \right)$$

$g_s^N g_p^N$ range predicted by various theoretical models \sim
 $10^{-38} - 10^{-30}$, (depend on mass/ f_a)

ARIADNE EXPERIMENT CONCEPT

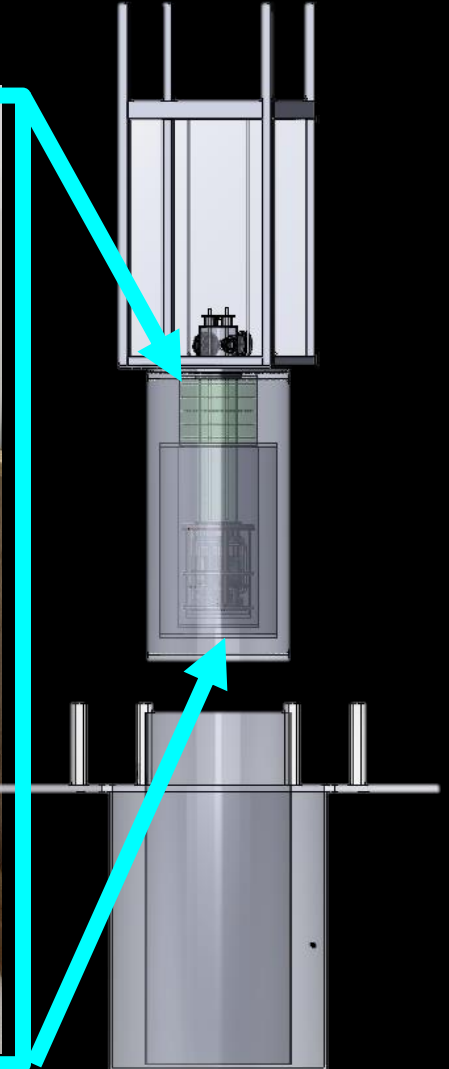
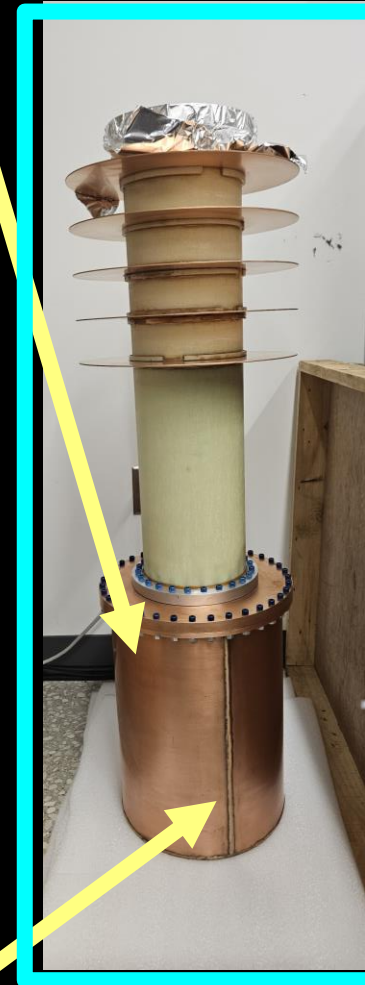
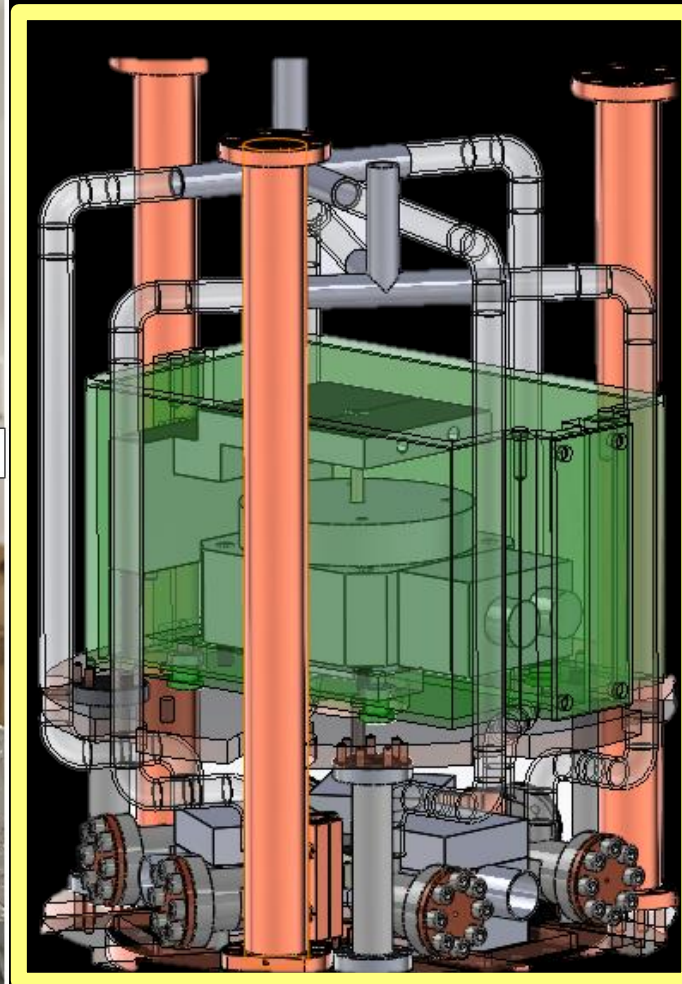
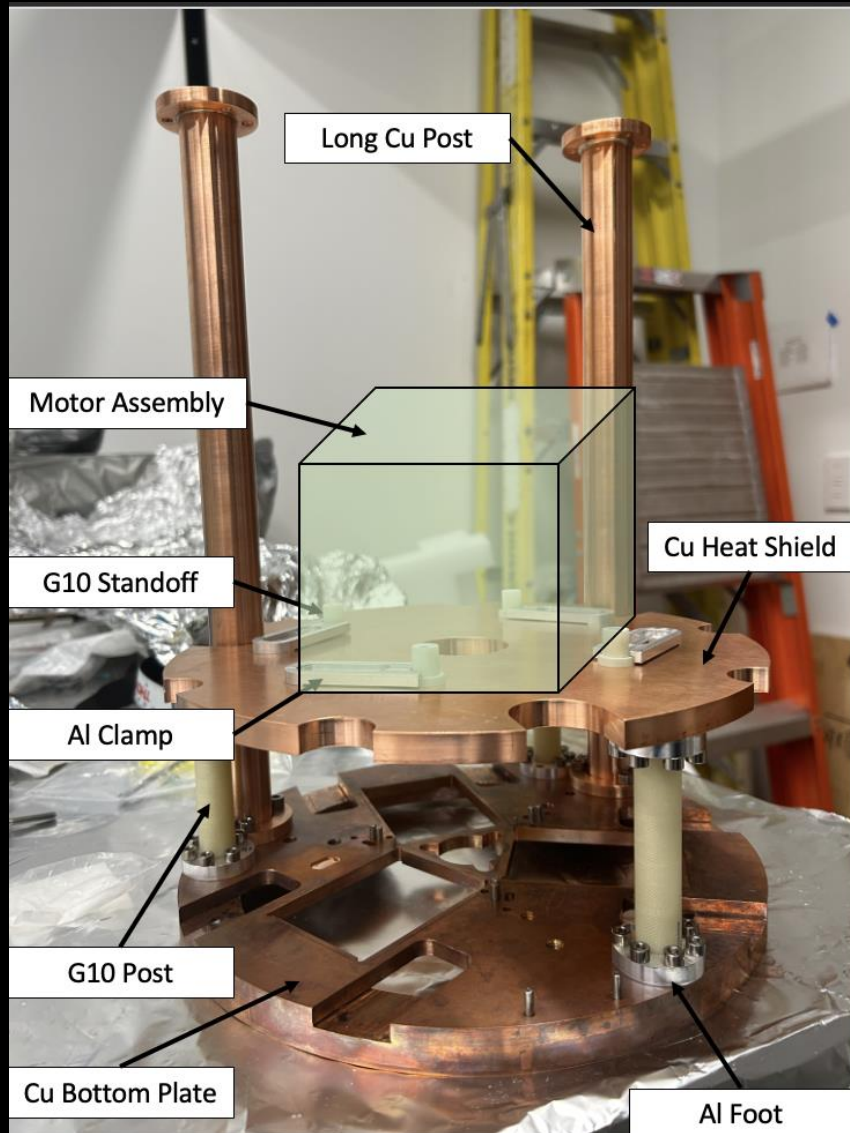


$$U_{sp}(r) = \frac{\hbar^2 g_s^N g_p^N}{8 \pi m_N} \left(\frac{1}{r \lambda_a} + \frac{1}{r^2} \right) e^{-\frac{r}{\lambda_a}} (\hat{\sigma} \cdot \hat{r})$$

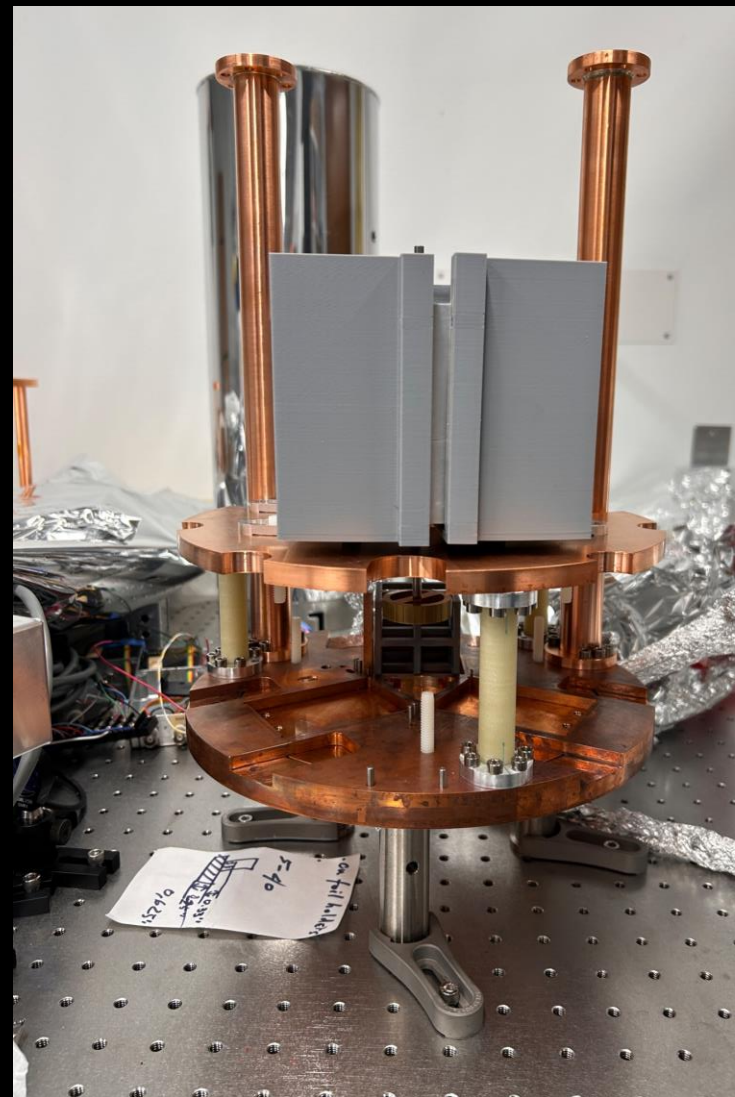
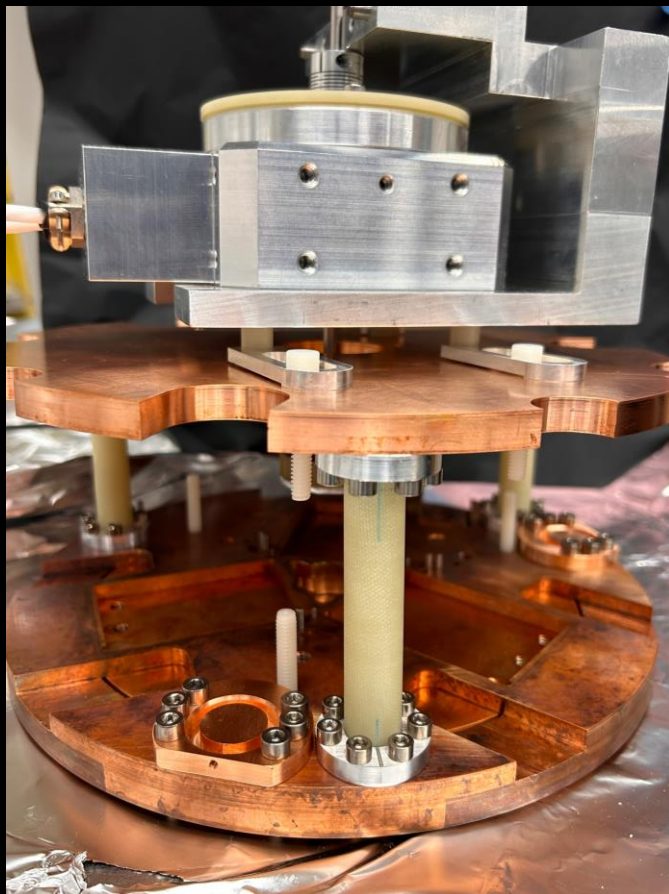
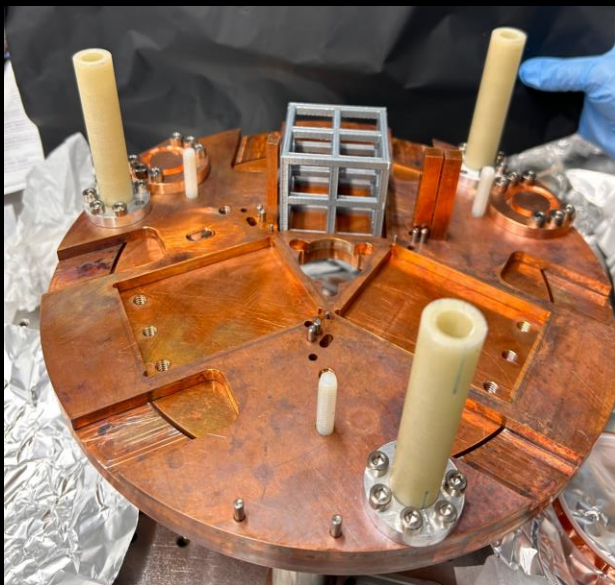
- Spins in hyperpolarized Helium-3 gas
- Transverse modulation by rotating a wheel with gear shaped pattern
- NMR-like transition if modulation matches He Larmor frequency
- Axion field doesn't obey Maxwell's equations, SM fields shielded using a superconductor

$$\omega_L = 11 \omega_{rot}$$

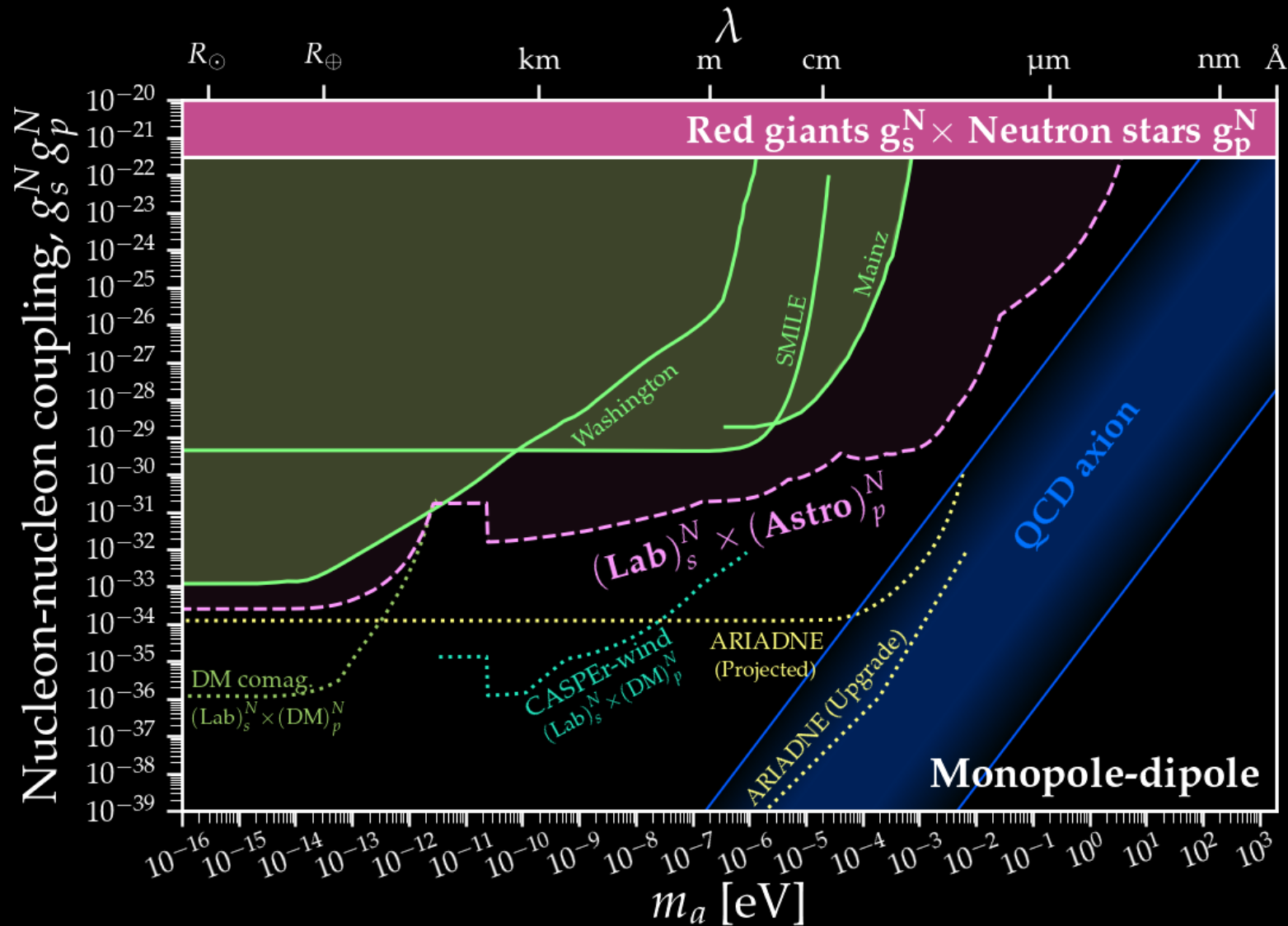
PARTS FINALLY DELIVERED AFTER MANY YEARS DELAY!



CRYOSTAT ASSEMBLY



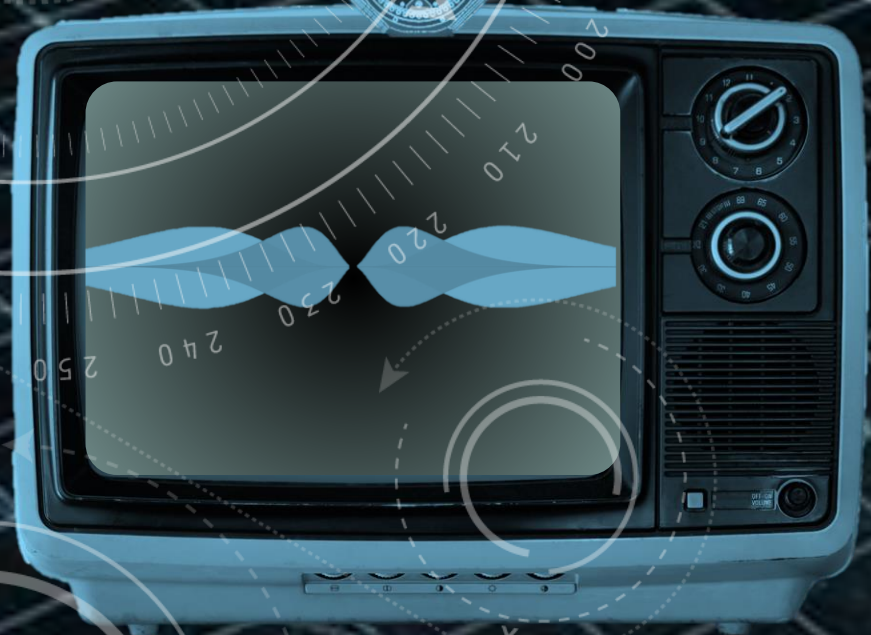
STATE OF THE ART IN $g_s g_p$



- Search for PQ axions $10^{-6} \text{ eV} < m_a < 10^{-3} \text{ eV}$
- probe into the PQ axion parameter space with $\sim 10^8$ improvement over previous techniques

ARIADNE SUMMARY

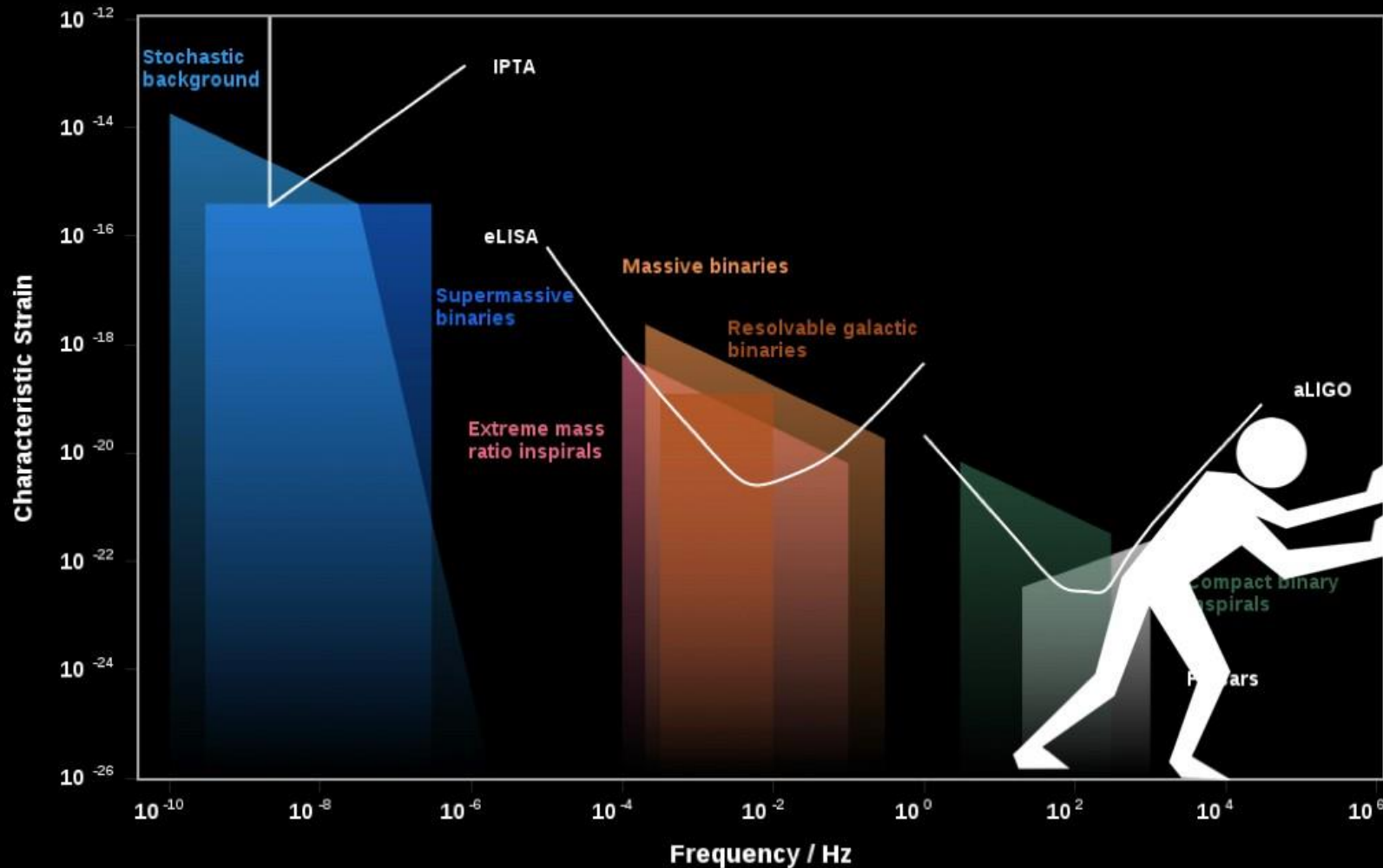
- New spin-dependent forces mediated by QCD axion
- Only experiment looking for axion interaction with nucleons
- μeV to meV mass range
- Searches for axion independent of DM paradigm by looking for axion-mediated interactions between two SM particles instead of axion interacting with one SM particle



DM TELEVISION

Dark Matter Tests using
LEVItated Sensor
Interferometer
Observatory Network

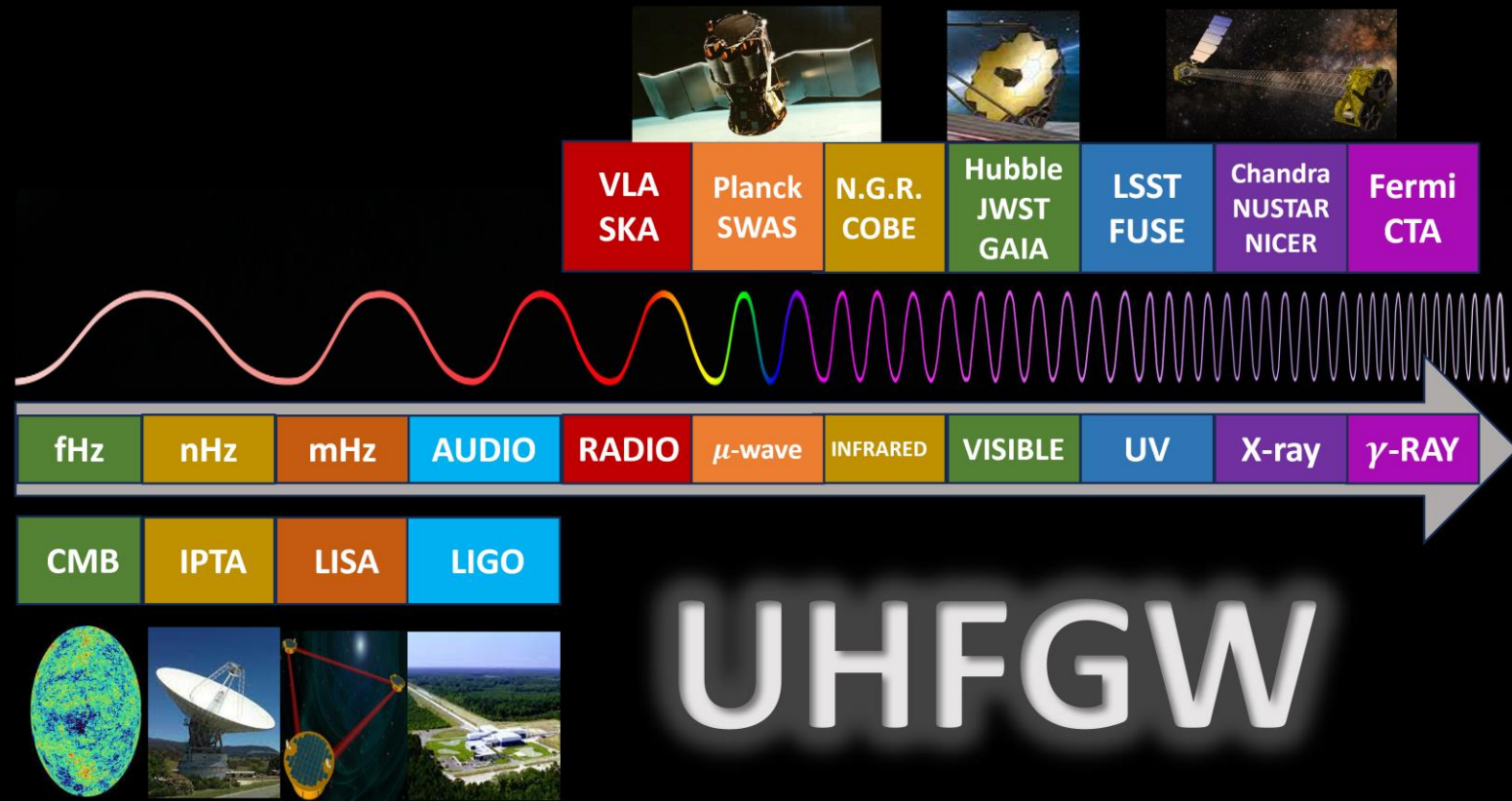
GWS ABOVE THE AUDIO BAND?



<http://www.ctc.cam.ac.uk/activities/UHF-GW.php>

Members: Nancy Aggarwal, Mike Cruise, Valerie Domcke, Francesco Muia, Fernando Quevedo, Andreas Ringwald, Jessica Steinlechner, Sebastien Steinlechner

MISSED OPPORTUNITY FOR MULTI-MESSENGER PROBES



+

1. UHFGWs provide direct window to inflation (ie pre CMB)
2. No vanilla astrophysical sources above 10 kHz (BBHs, BNSs, NSBHs)



No astrophysical foreground

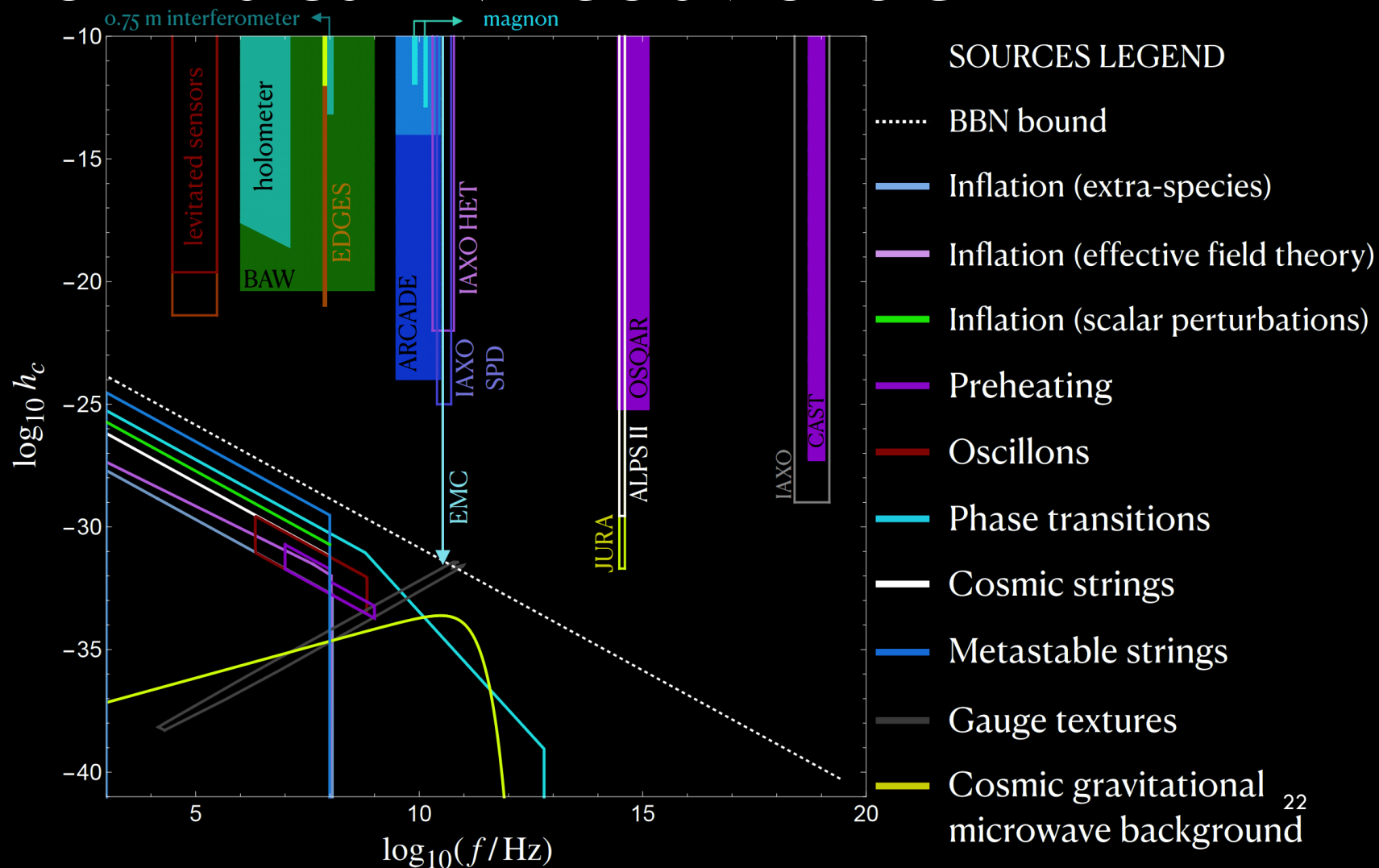


Directly probe cosmology below foreground OR be blocked by exotic sources

FUTURE GW DETECTORS BEYOND THE AUDIO BAND FOR PARTICLE ASTROPHYSICS AND COSMOLOGY

Aggarwal, N., Aguiar, O.D., Bauswein, A. *et al.*
 Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies. *Living Rev Relativ* **24**, 4 (2021).

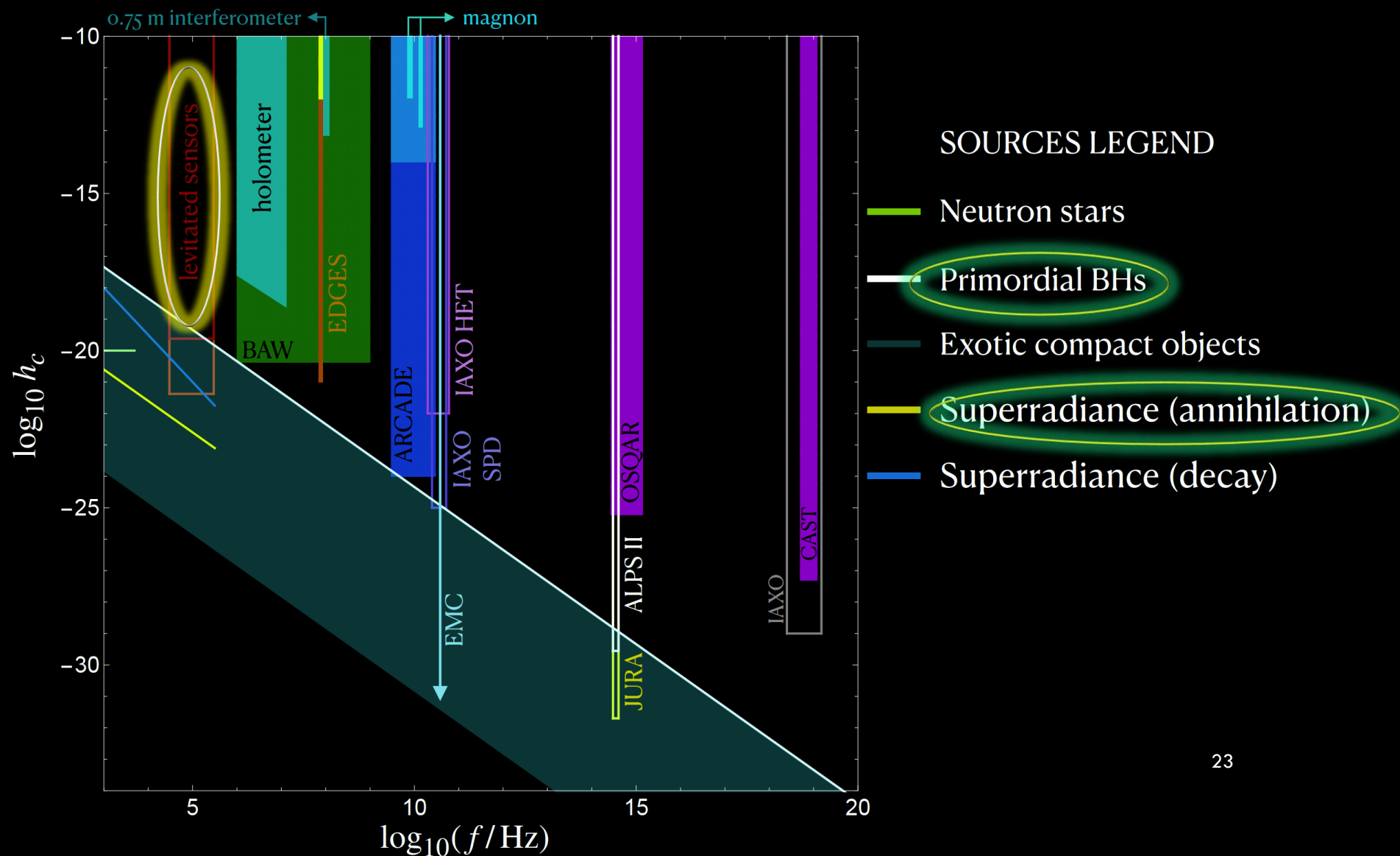
Also see
<https://arxiv.org/pdf/2501.11723>



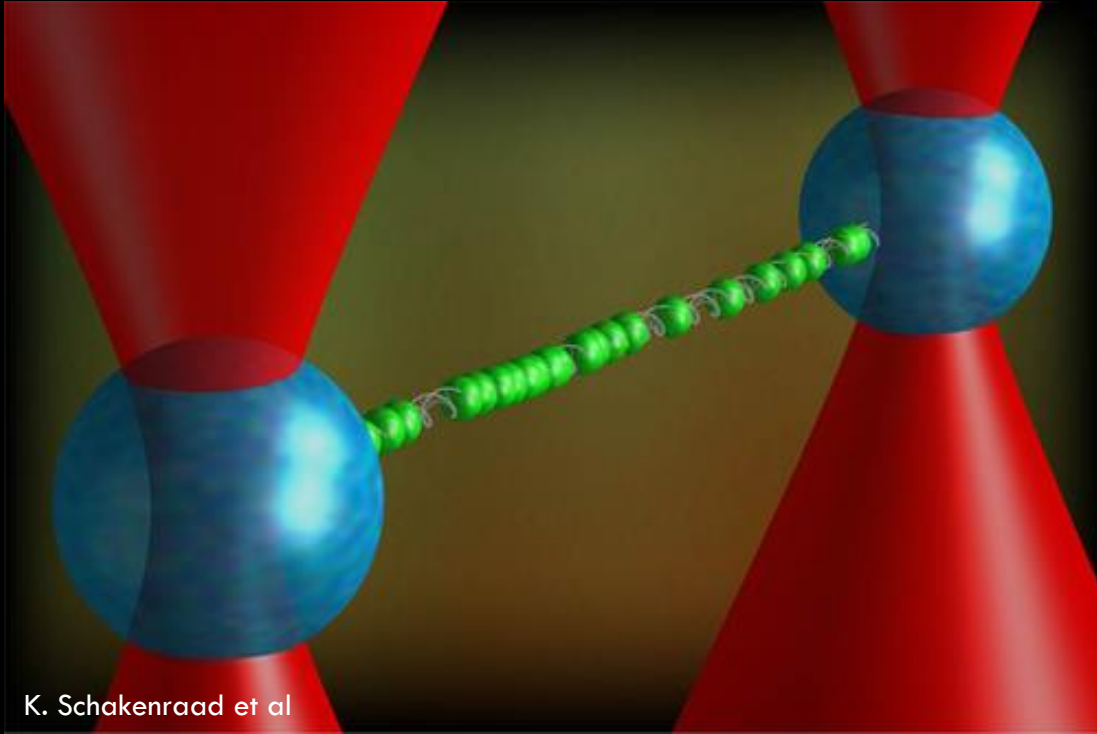
NUMEROUS INTERESTING SOURCES & PROMISING TECHS!!!

Aggarwal, N., Aguiar, O.D., Bauswein, A. *et al.*
 Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies. *Living Rev Relativ* **24**, 4 (2021).

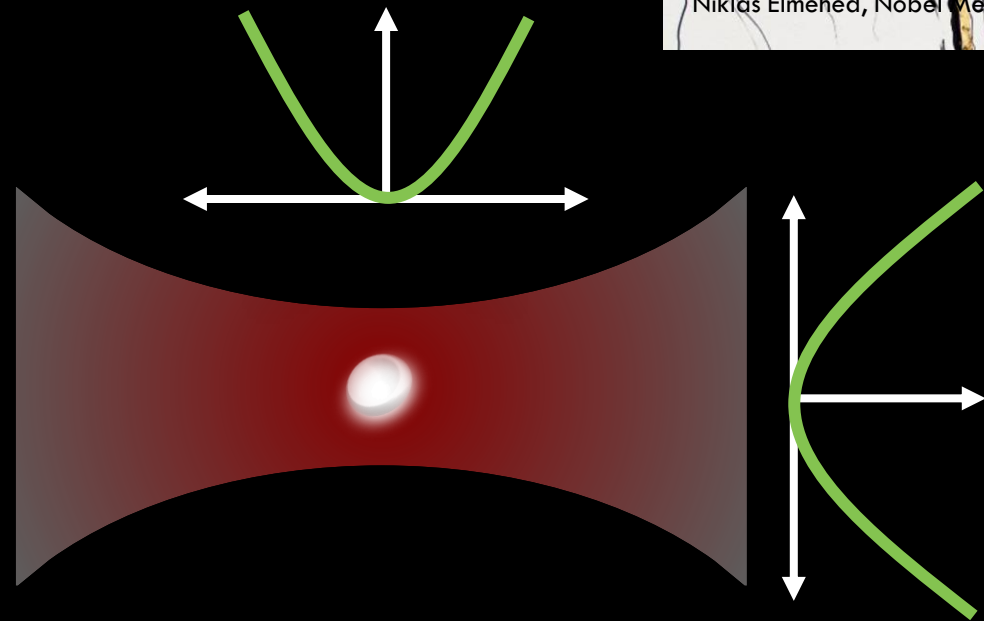
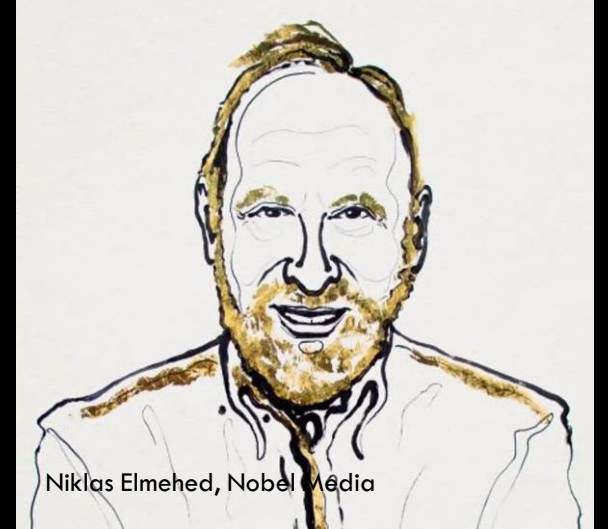
Also see
<https://arxiv.org/pdf/2501.11723>



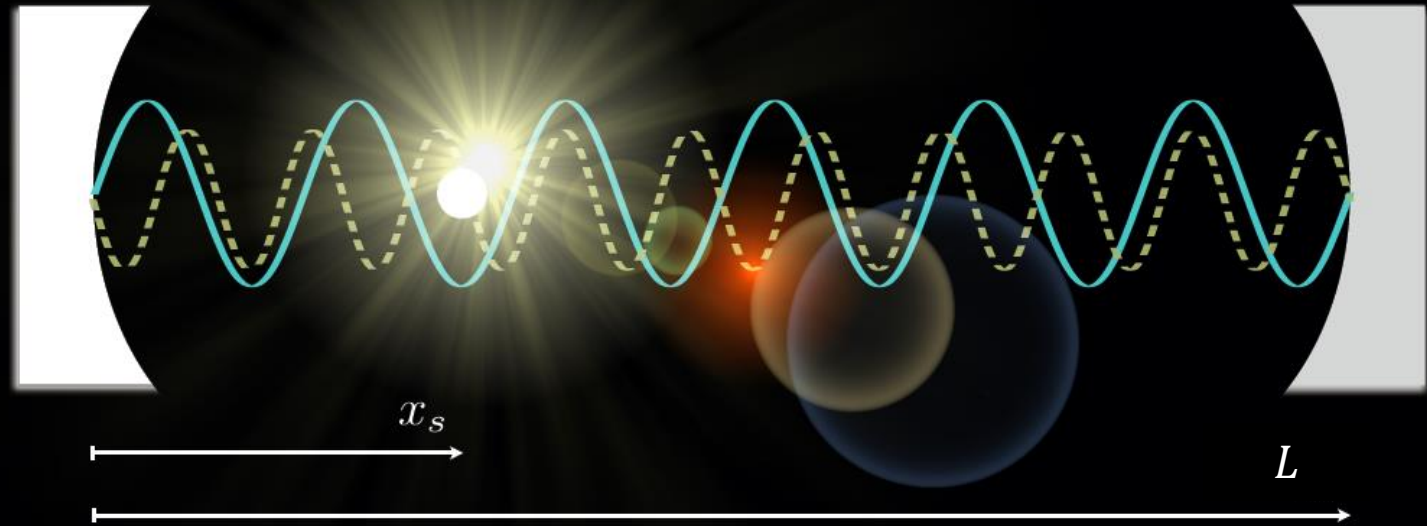
OPTICAL TRAPPING



$$U(\vec{r}) = -\frac{1}{2} \alpha(\vec{r}) E^2(\vec{r})$$



GW DETECTOR USING OPTICAL TRAPS



$$\Delta L = \frac{h}{2} L, \quad \Delta x_a = \Delta L, \quad \Delta x_s = \frac{h}{2} x_s$$

$$\Delta x_{GW} = \Delta x_s - \Delta x_a = \frac{h}{2} (x_s - L), \quad \text{maximized at } x_s \rightarrow 0$$

$$F_{GW} = M \Omega_T^2 \Delta x_{GW} = M \Omega_T^2 \frac{L}{2} h_0 \cos \Omega_{GW} t$$

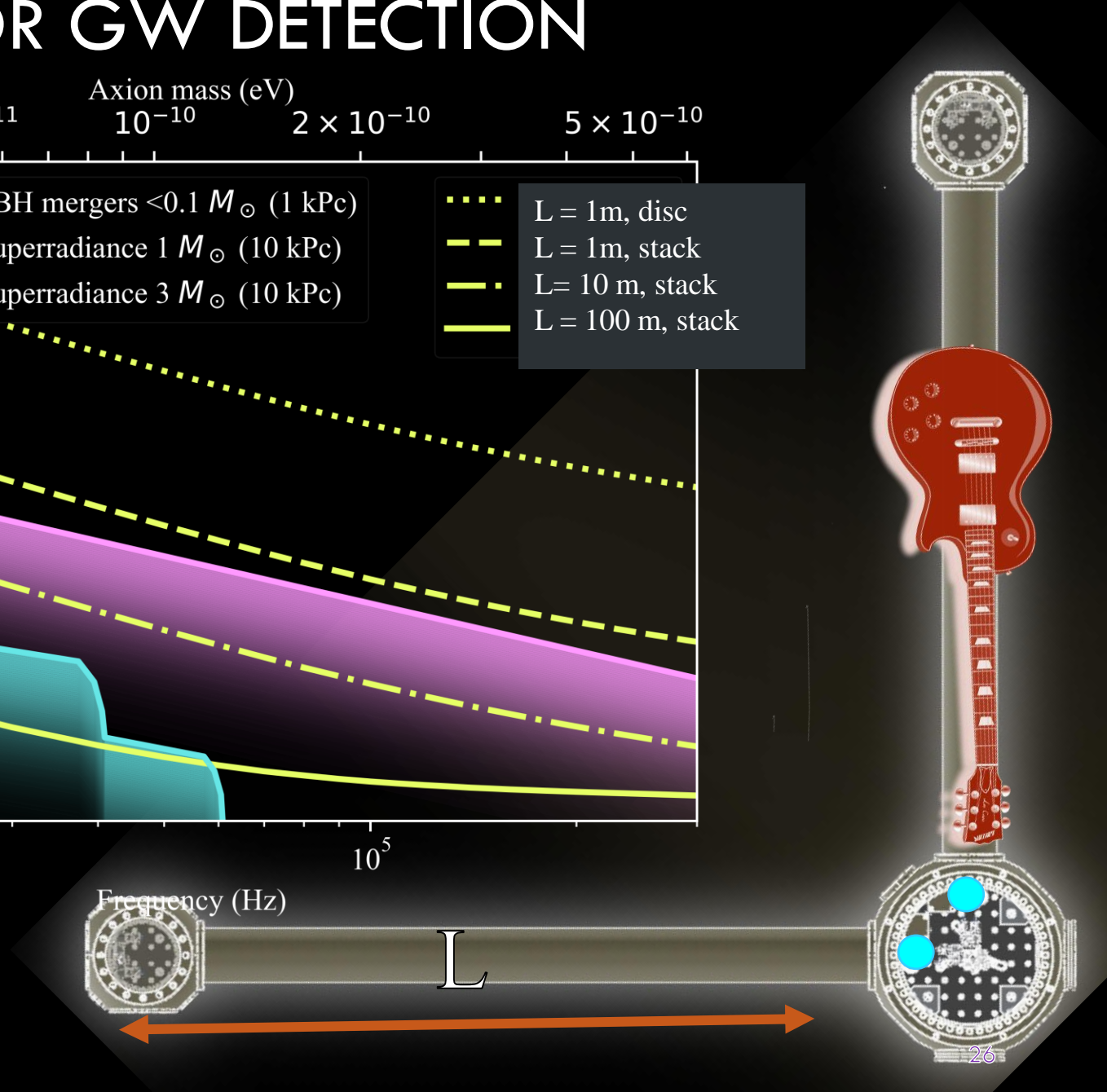
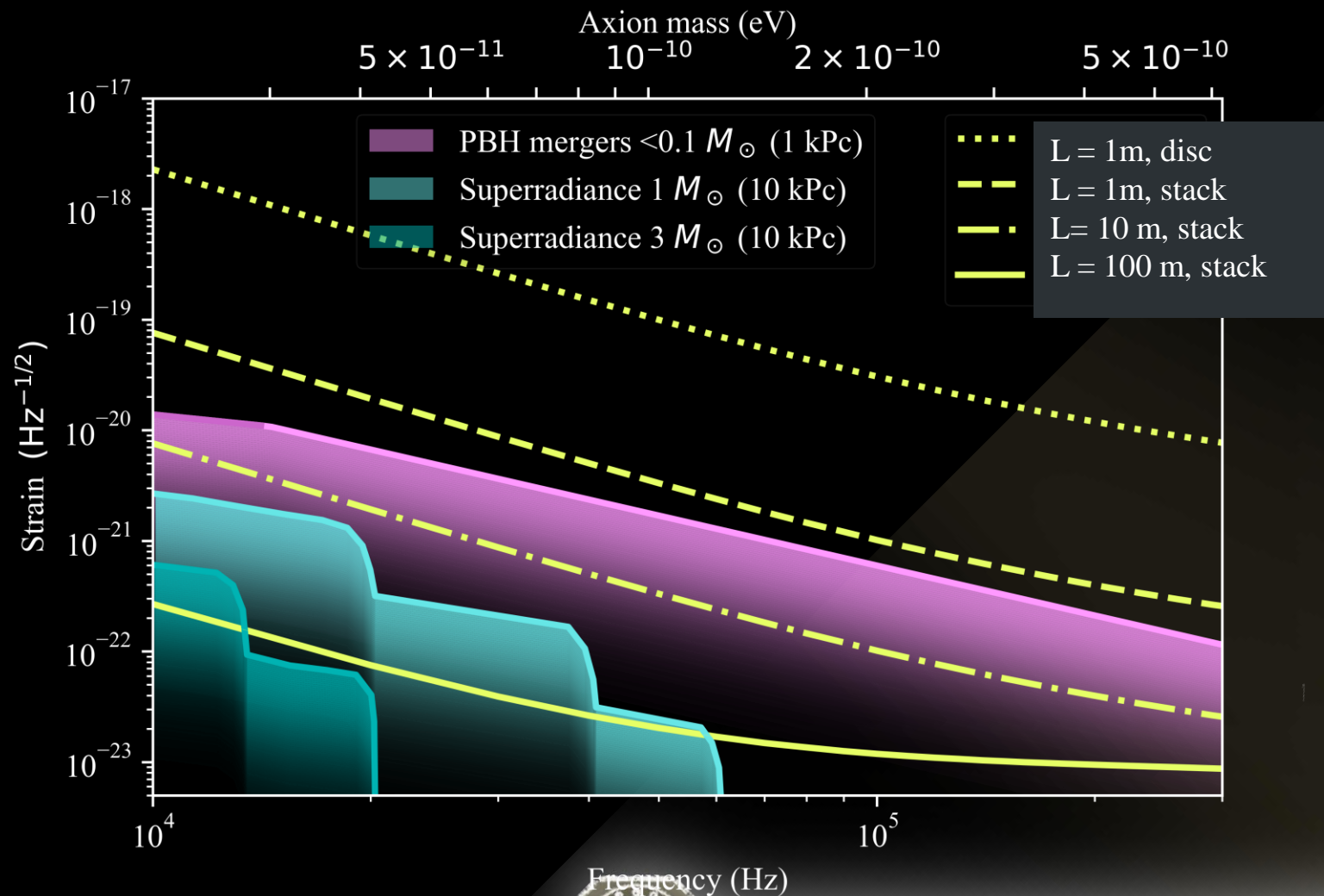
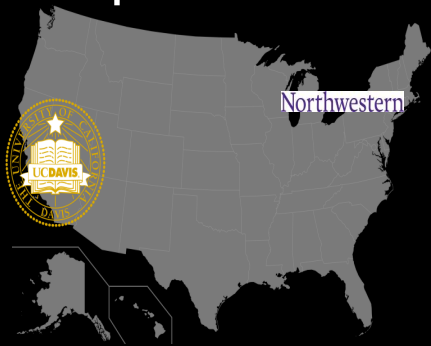
Arvanitaki and Geraci,
PRL 110, 071105 (2013)

Northwestern



OPTICAL TRAPPING FOR GW DETECTION

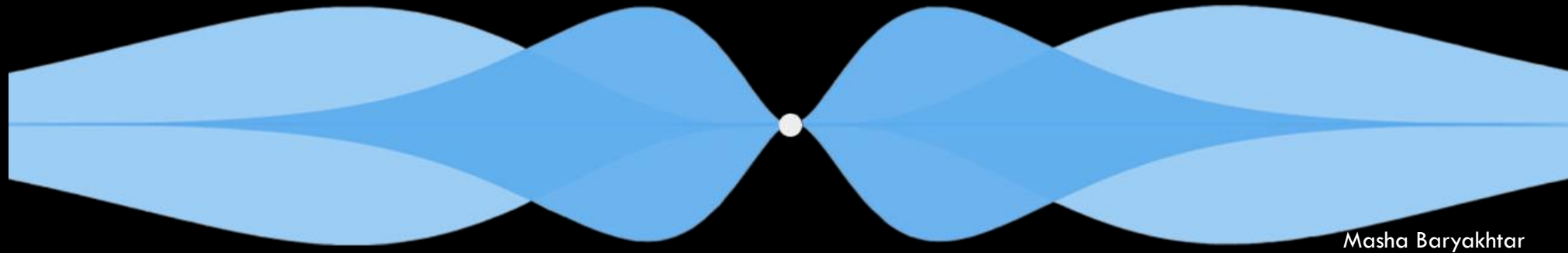
- Network of miniature GW detectors
- Uses optically levitated objects
- Tunable detection frequencies



Searching for new physics with a levitated-sensor-based GW detector
 Aggarwal et al PRL 128, 111101

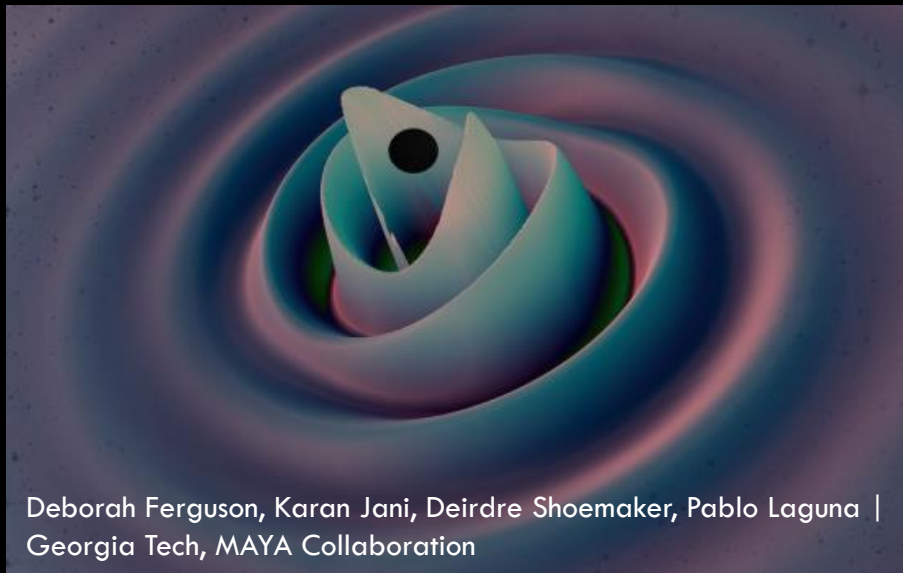
SCIENCE CASE

BH Superradiance



Masha Baryakhtar

Primordial black holes



Deborah Ferguson, Karan Jani, Deirdre Shoemaker, Pablo Laguna | Georgia Tech, MAYA Collaboration



The unknown unknowns???

LIMITING NOISE: GAS DAMPING AND PHOTON RECOIL HEATING

- $S_{FF} = 4 M (k_B T \gamma_g + \hbar \omega \gamma_{sc})$
- Limit on resonance ($\Omega \rightarrow \Omega_T$),

$$S_{hh} \sim 16 \frac{1}{\Omega_T^4} \frac{1}{M} \frac{1}{L^2} (\hbar \omega \gamma_{sc} + k_B T \gamma_g)$$

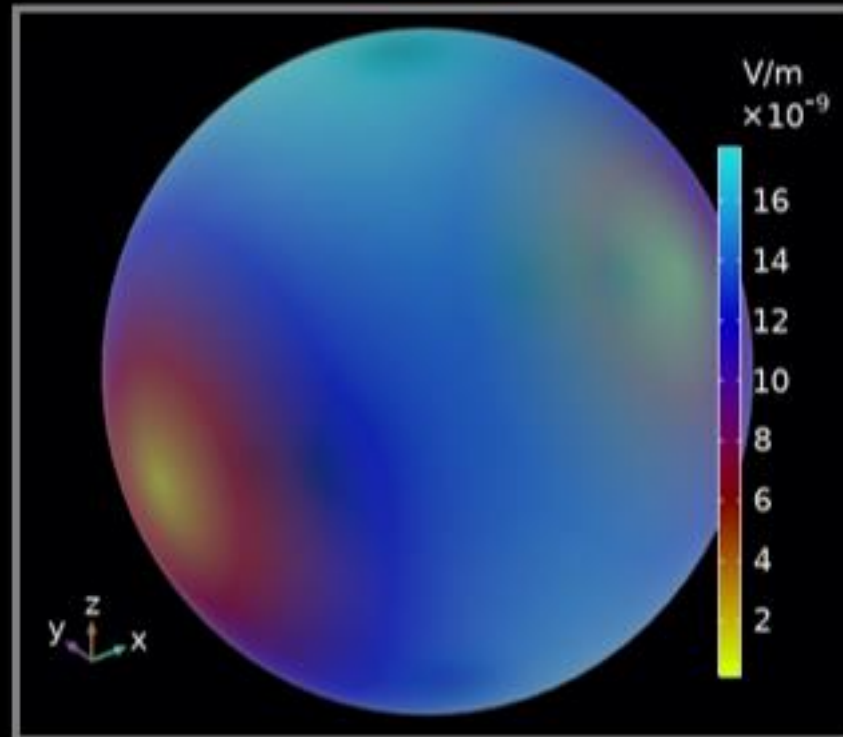
Arvanitaki and Geraci,
PRL 110, 071105 (2013)



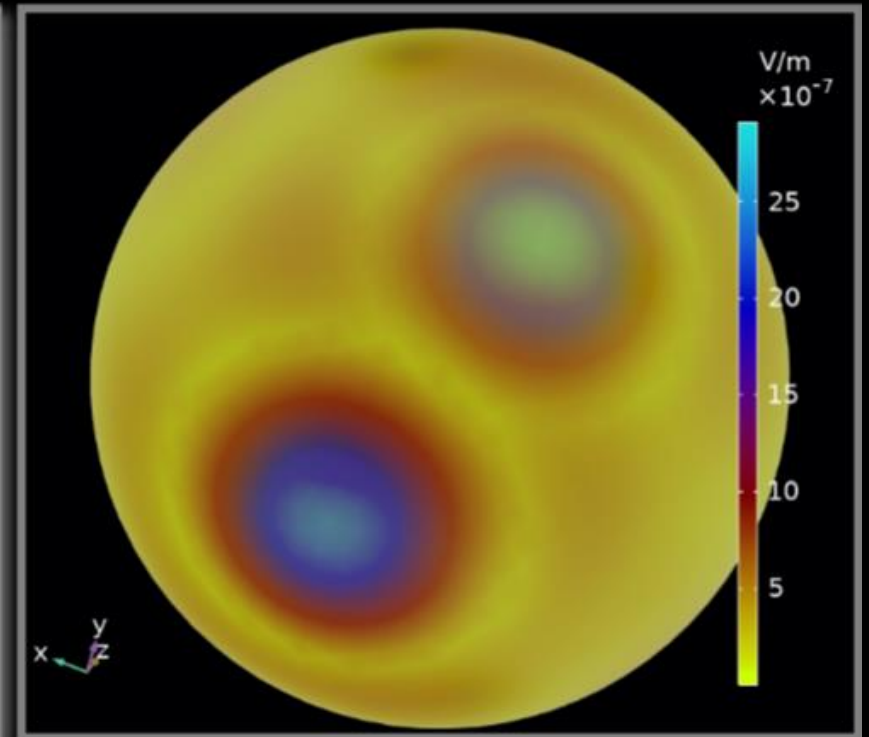
GEOMETRY AFFECTS SCATTER

- Sphere scatters light in all directions
- Disk scatters light in the beam direction (low γ_{sc})
- Numerical simulations of scattering from disks show low scattering loss, hence low recoil heating

plane wave incident: $\vec{E} = 1 \text{ Vm}^{-1} \hat{x} \cos kz$



SiO₂ Sphere (d=300 nm)

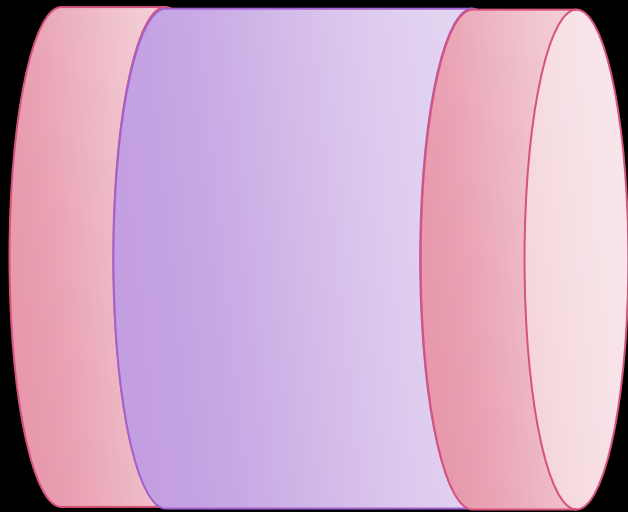


NaYF Hexagon (d=4 μm , $\tau = 200 \text{ nm}$),
300 times more mass

Aggarwal et al arxiv:2010.13157 Phys. Rev. Lett. 128, 111101,
Winstone et al arxiv:2204.10843 Phys. Rev. Lett. 129, 053604

INCREASE MASS WHILE KEEPING SCATTER LOW?

- Stacked disks to increase mass (high M)



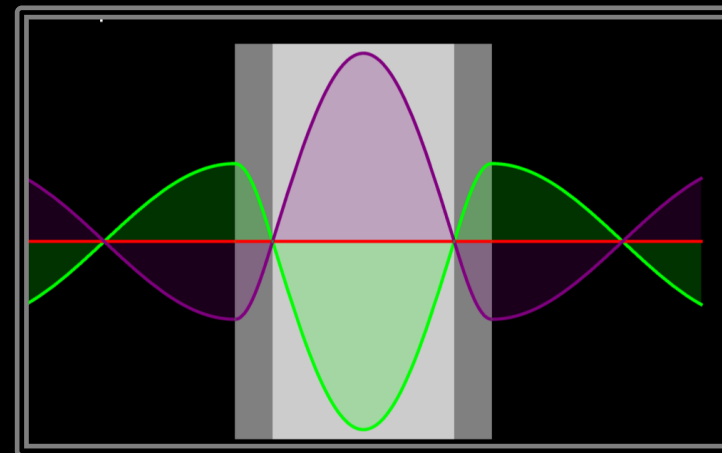
Modified
wavelength

$$\lambda_i = \frac{\lambda_0}{n_i}$$

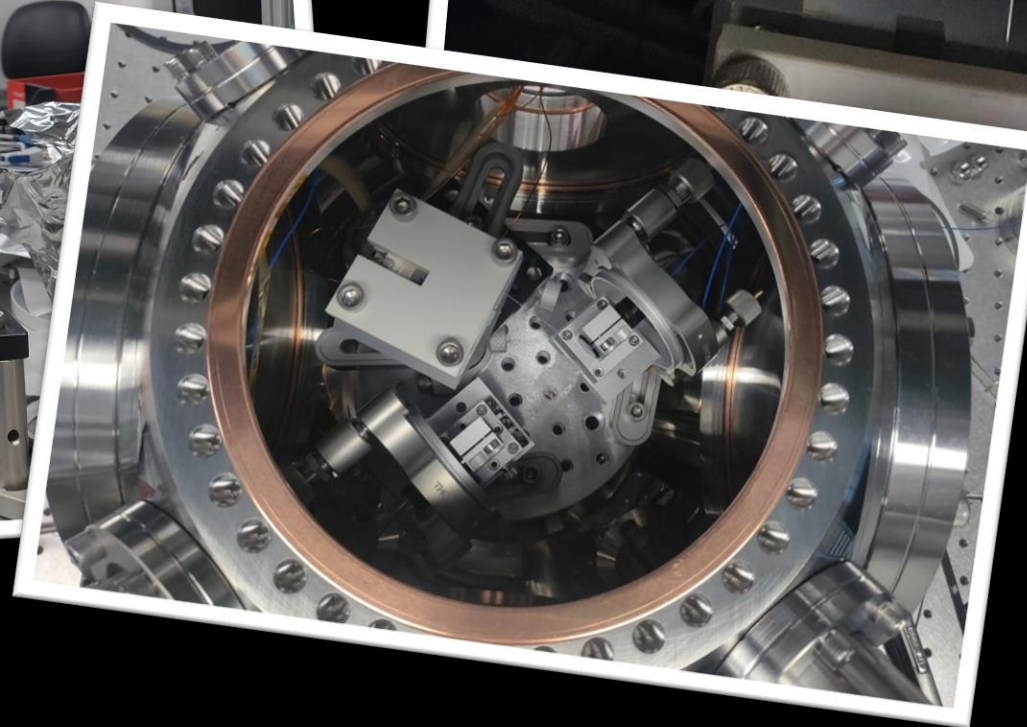
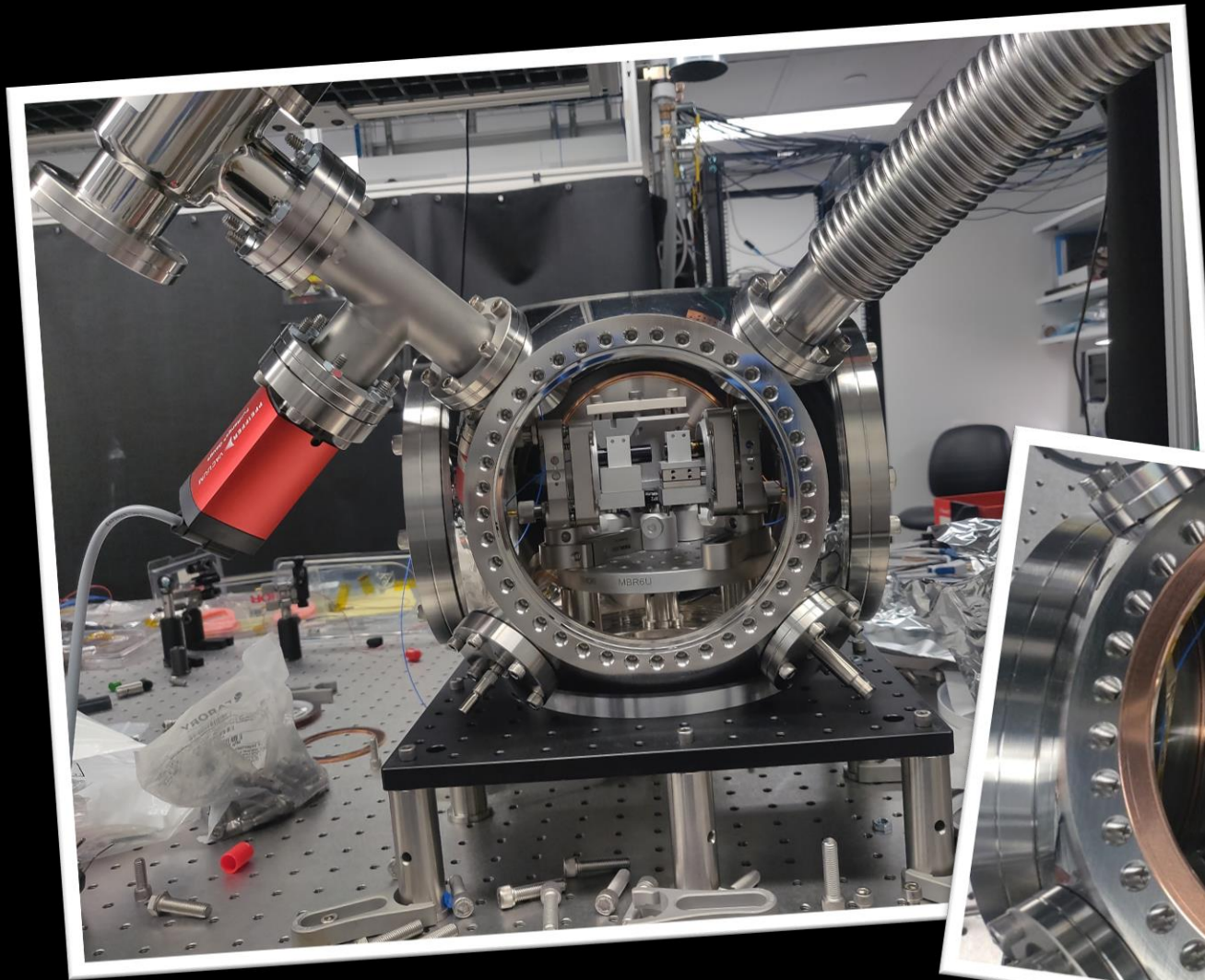
$$t_1 = \frac{\lambda_1}{4} \quad t_2 = \frac{\lambda_2}{2} \quad t_1$$

Is such a stack trappable?

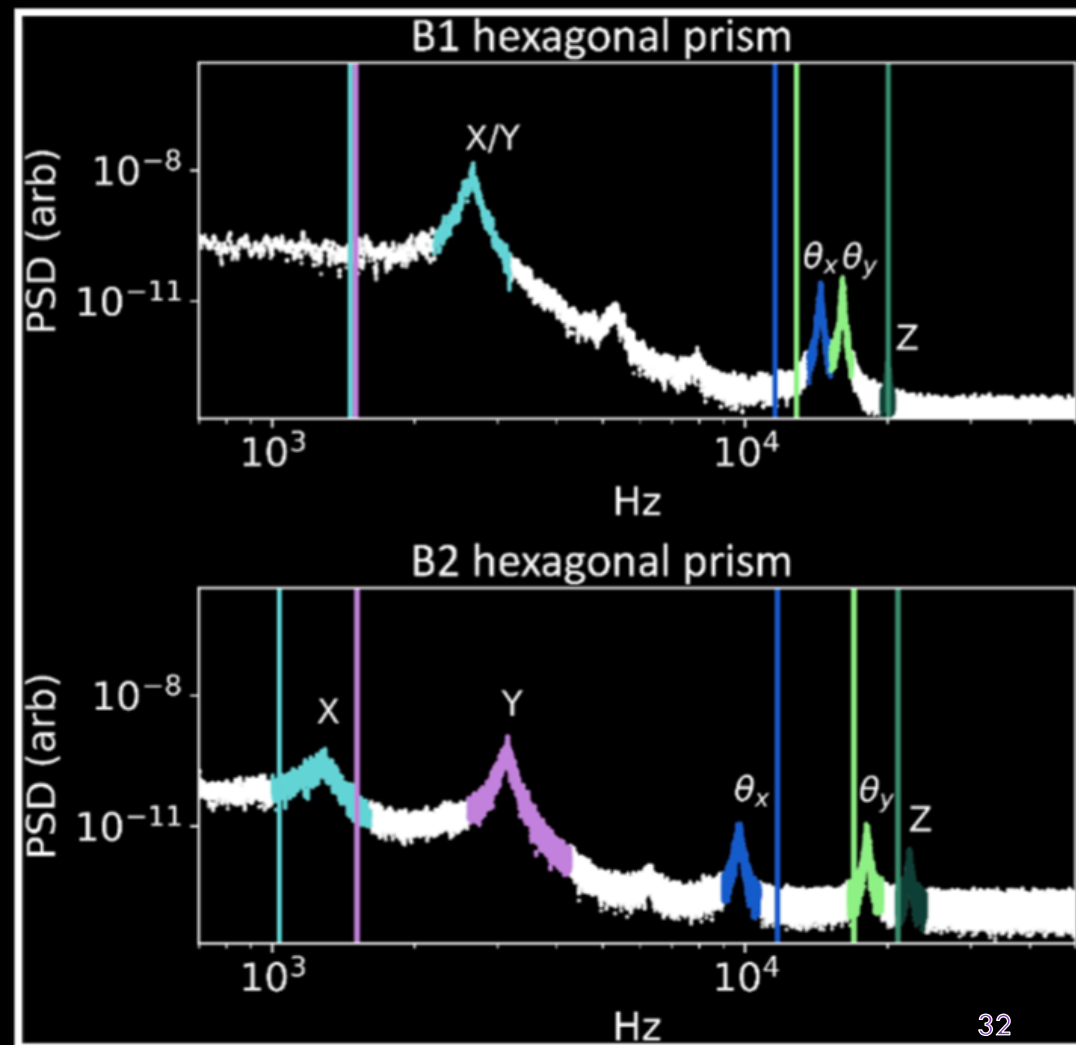
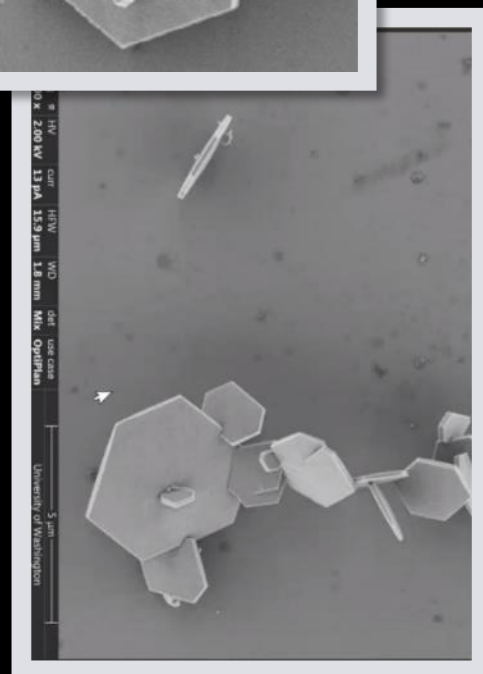
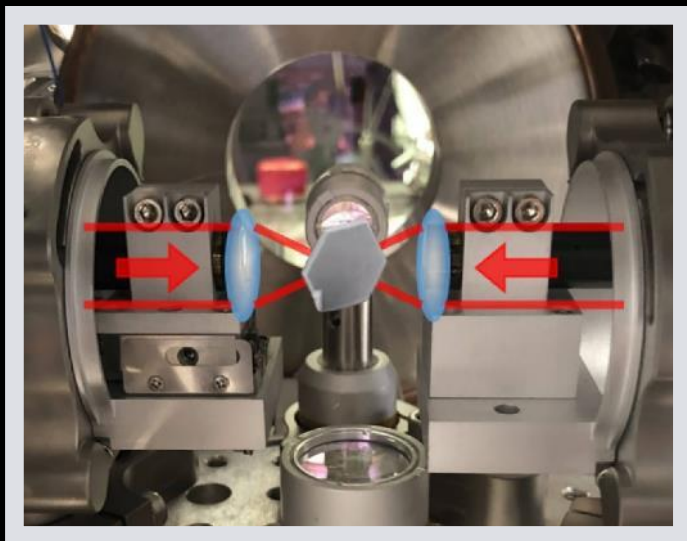
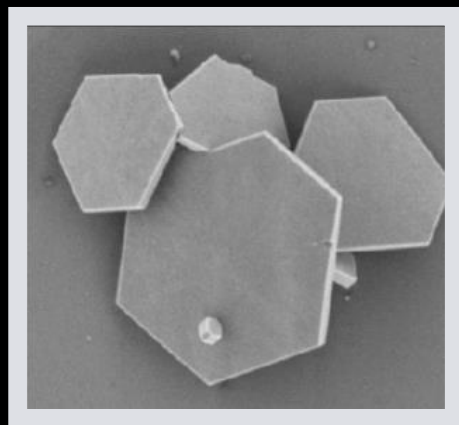
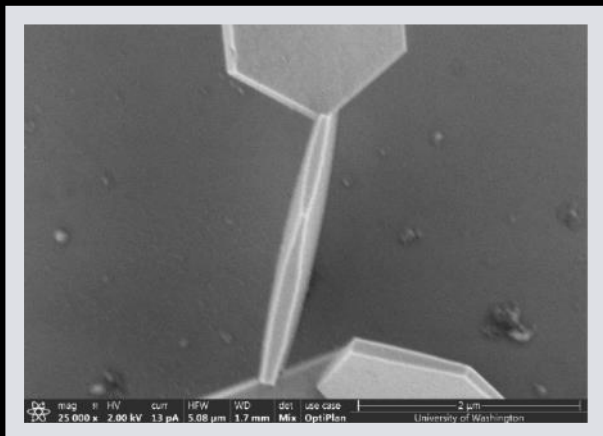
1. What is the transmission through the stack?
2. What is the field inside the stack?
3. What is the trapping frequency/stiffness?
4. Can these things be fabricated in the lab?



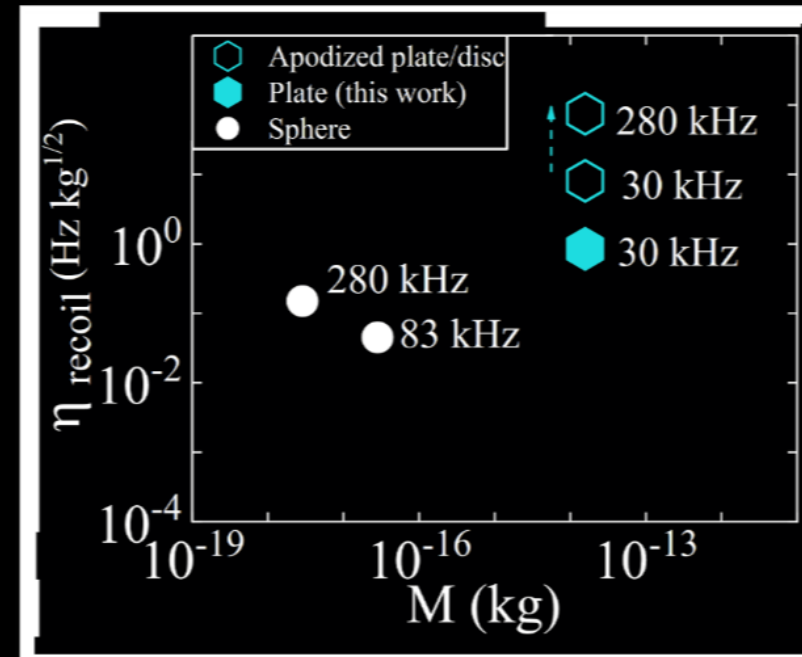
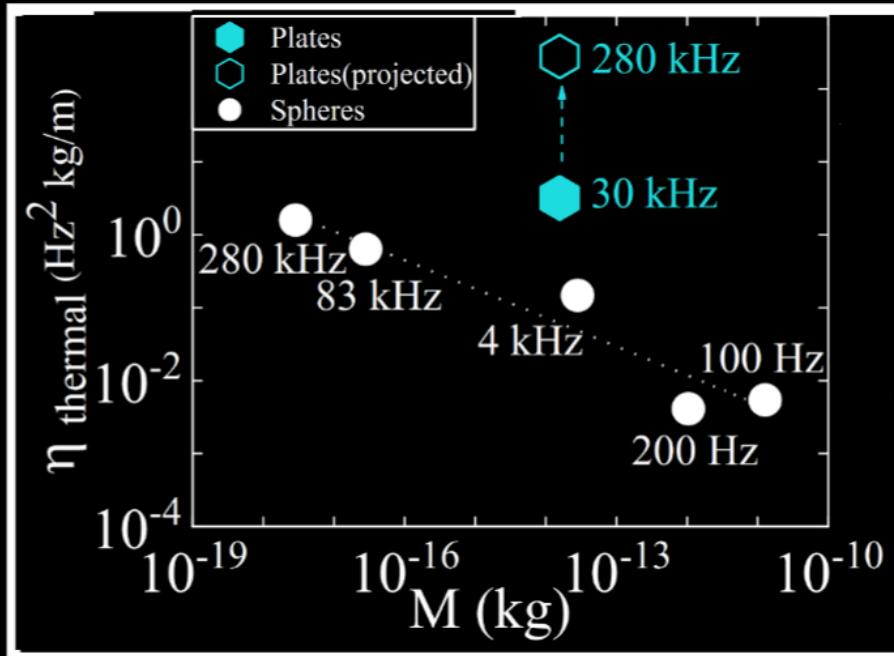
TRAPPING OF FLAT OBJECTS IN THE LAB...



TRAPPING OF NAYF HEXAGON PLATES



STATE OF THE ART IN OPTICAL TRAPPING



$$\eta_{\text{thermal}} = \left(\frac{\Omega_z}{2\pi}\right)^2 \sqrt{M\rho\tau}$$

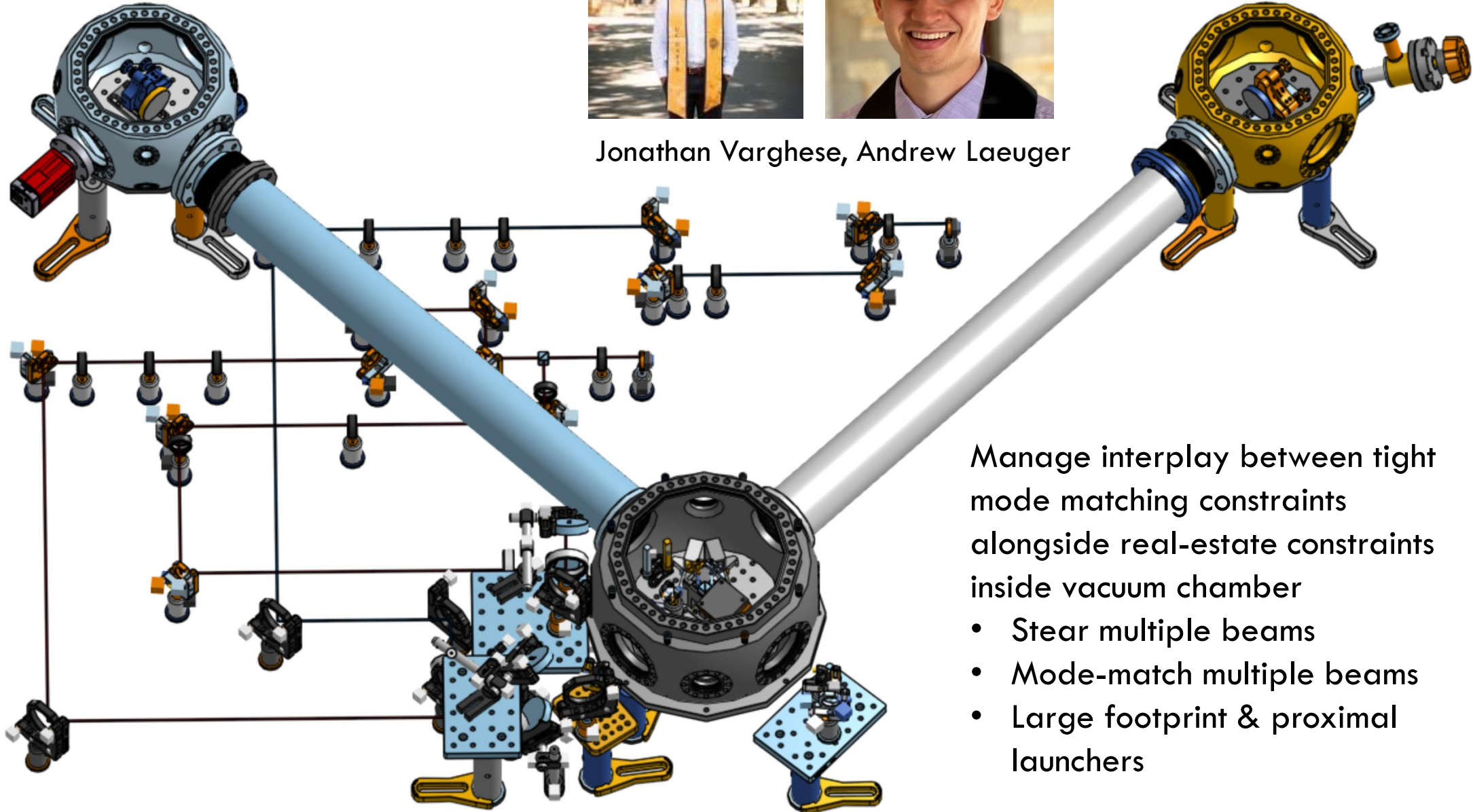
$(\gamma_g \propto 1/\rho\tau)$

$$\eta_{\text{recoil}} = \left(\frac{\Omega_z}{2\pi}\right)^{3/2} \sqrt{\frac{M}{\gamma_{sc}}}$$

DAVIS IFO LAYOUT



Jonathan Varghese, Andrew Laeuger



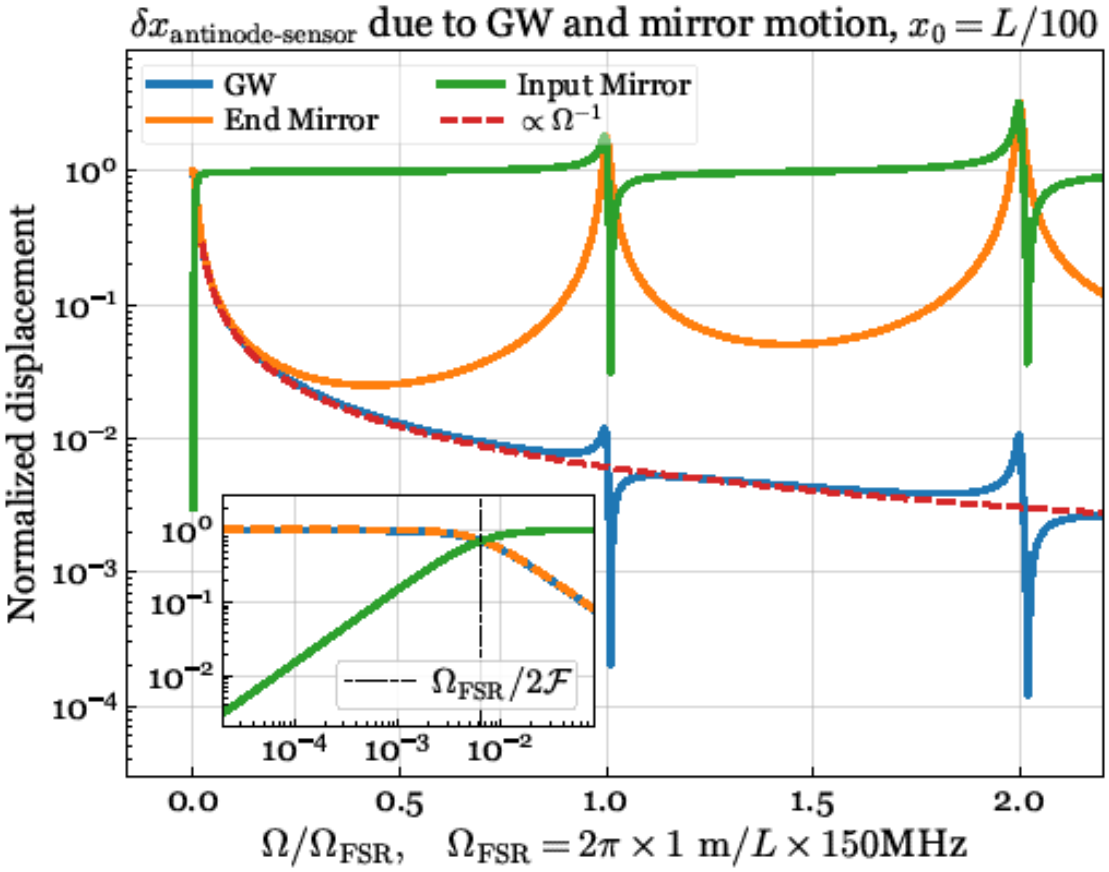
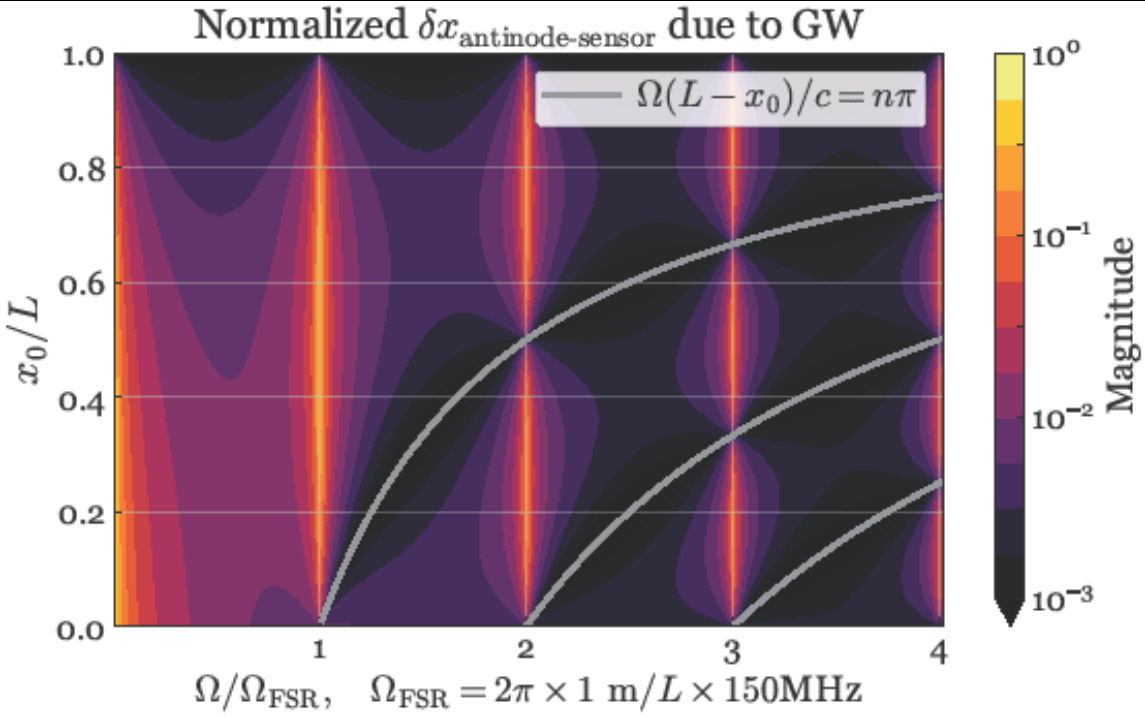
Manage interplay between tight mode matching constraints alongside real-estate constraints inside vacuum chamber

- Steer multiple beams
- Mode-match multiple beams
- Large footprint & proximal launchers

FULLY RELATIVISTIC DETECTOR RESPONSE AND NOISE



Andrew Laeuger

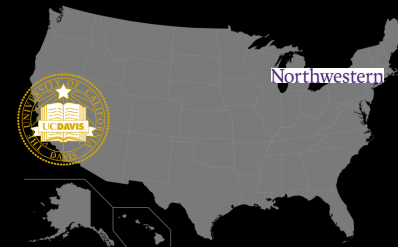
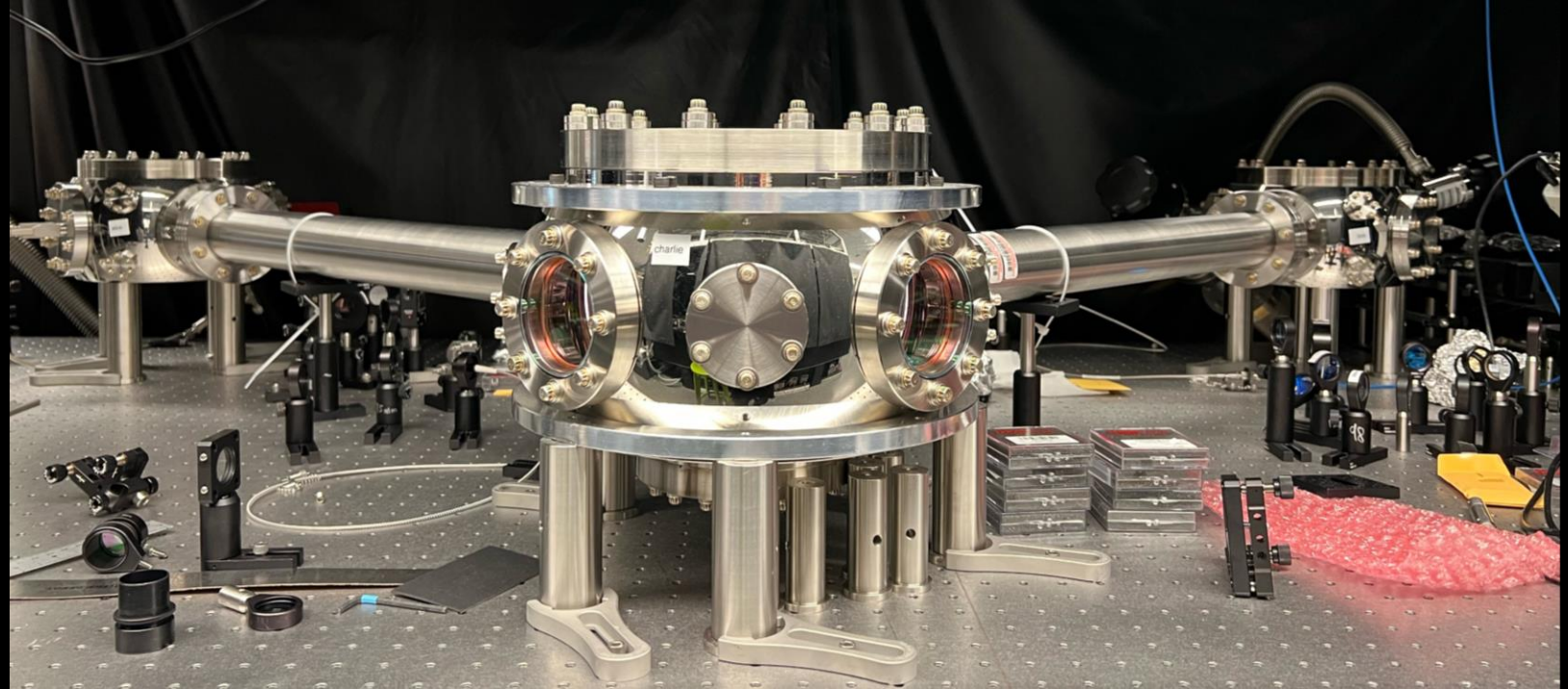


arxiv2604.07302

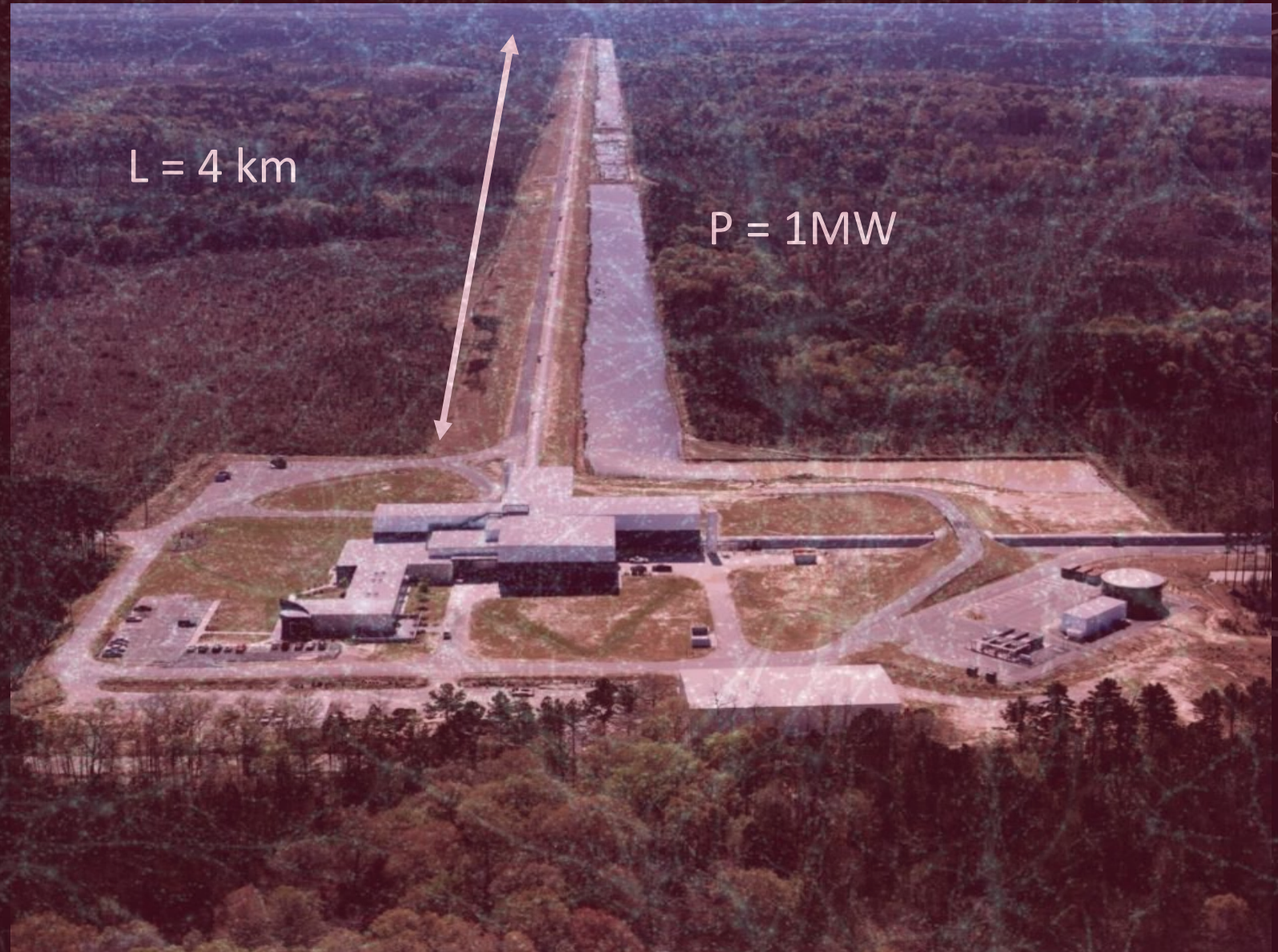
Laeuger et al, Gravitational wave signal and noise response of an optically levitated sensor in a Fabry Perot Cavity

DM TELEVISION SUMMARY

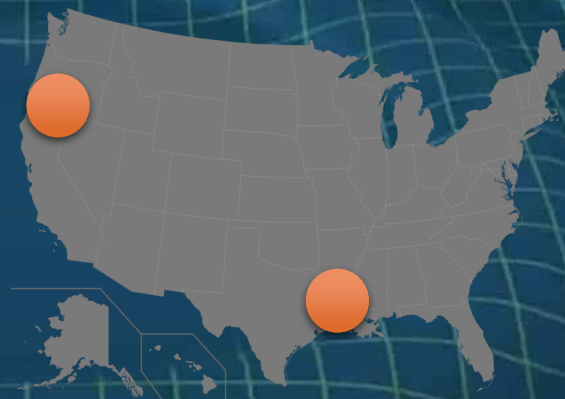
- New initiative for building high-frequency GW detectors
- Network of miniature radio-frequency GW detectors
- Based on optical levitation
- Tunable resonance in the 10-300 kHz range
- Will set independent limits on axions from blackhole superradiance and primordial black holes
- **Surprises!!!**



ULTRALIGHT
DILATONIC
SCALAR
DARK
MATTER
SEARCHES
WITH LIGO



TINY MEASUREMENTS WITH BIG THINGS

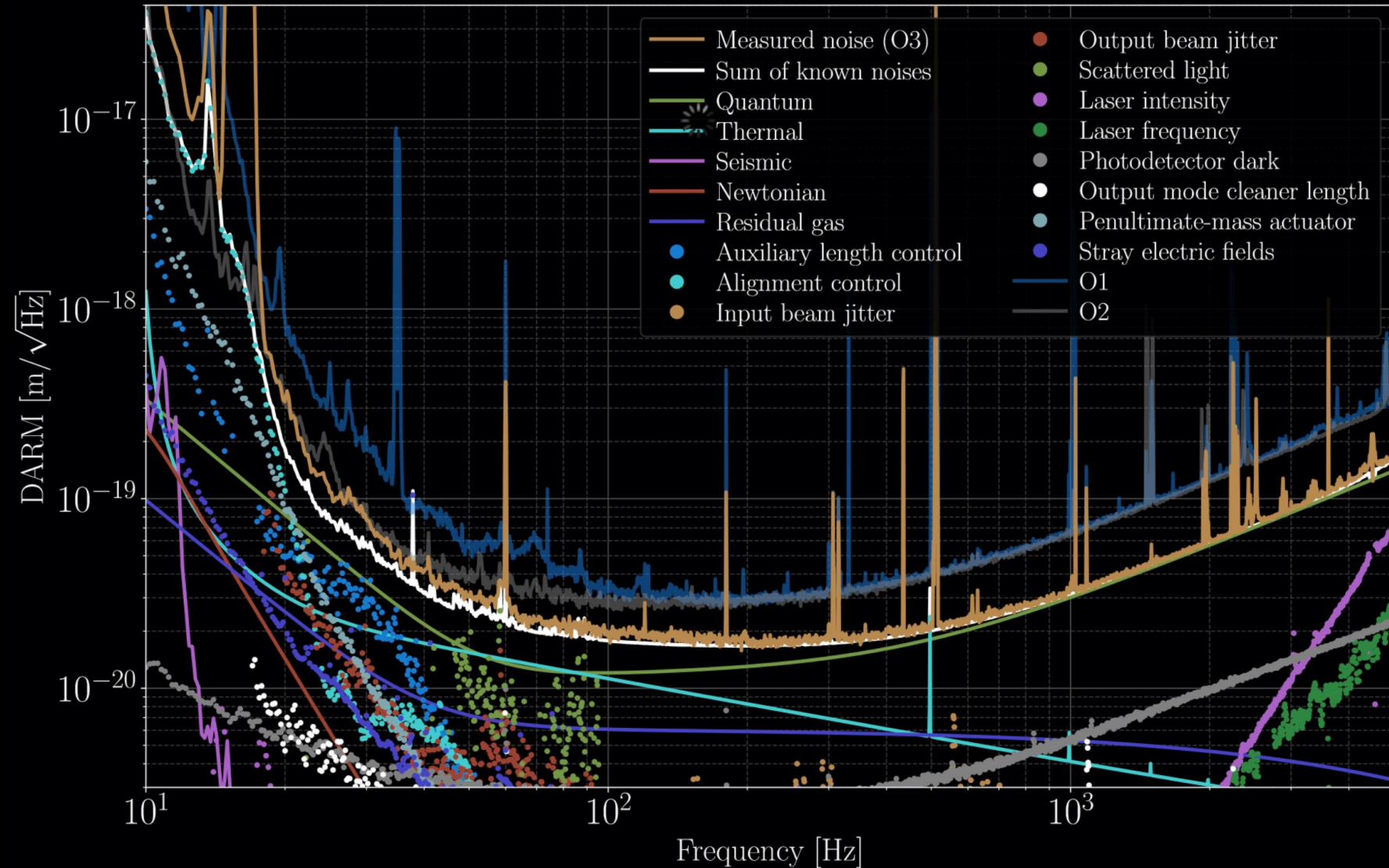


$$h = \frac{\Delta L}{L} = 10^{-21}$$

$$\Delta L = 10^{-18} \text{ m}$$
$$= \frac{R_p}{1000}$$



MOST SENSITIVE DISPLACEMENT MEASUREMENT



GWS INFORM ASTROPHYSICS AND COSMOLOGY

Messages in the Stellar Graveyard

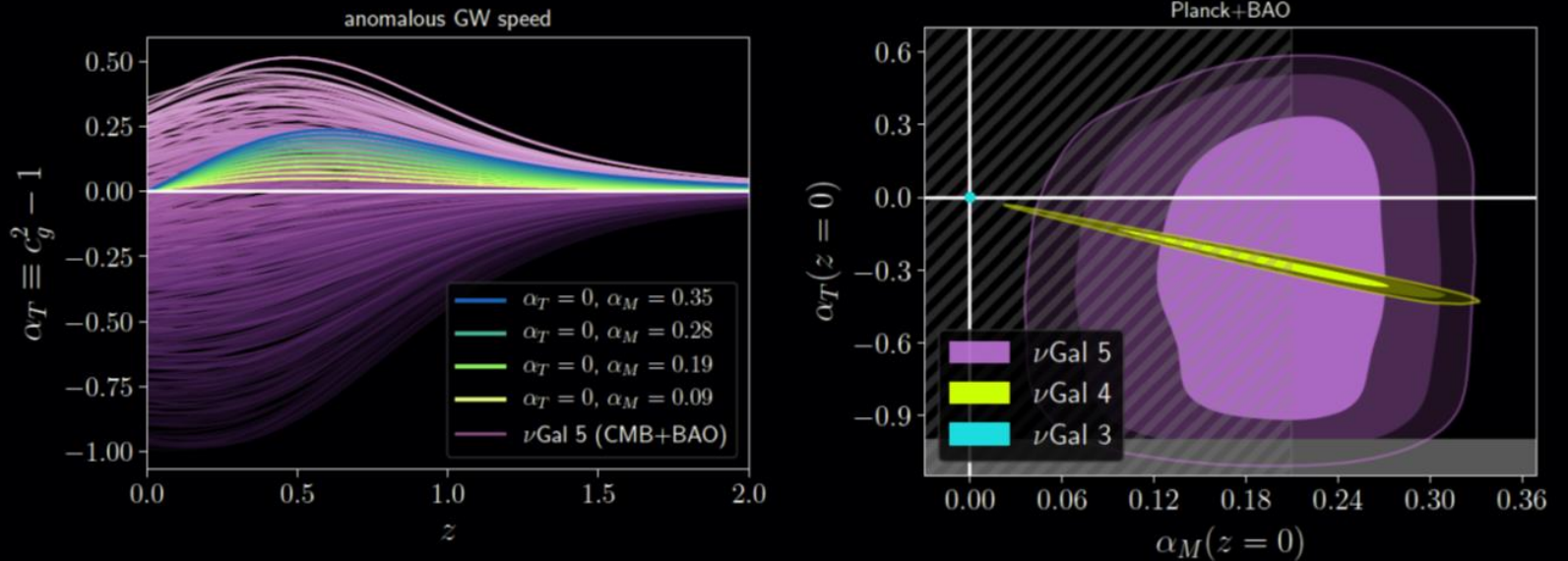
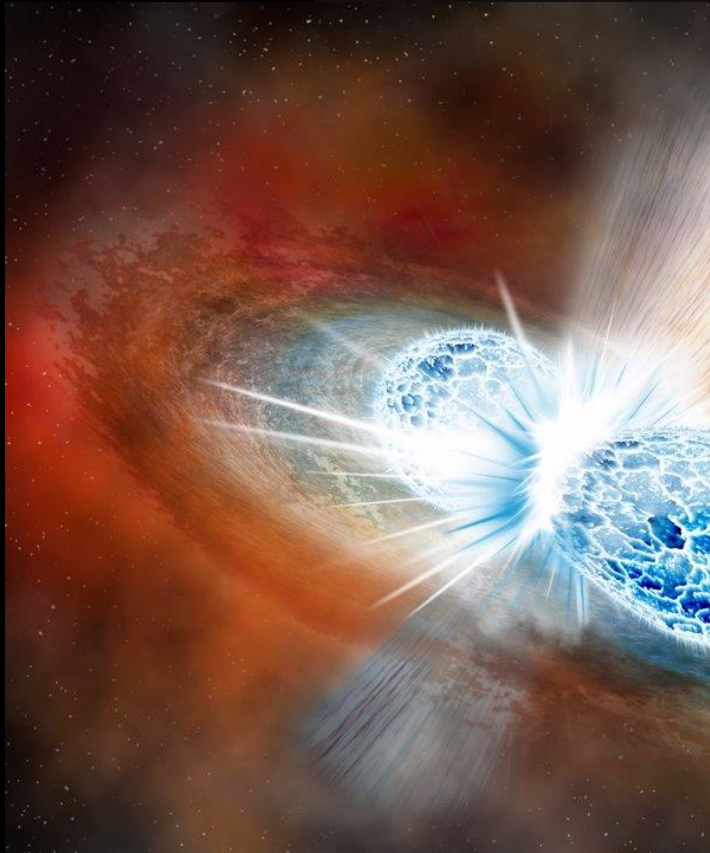


FIG. 1: **Left:** time evolution of the tensor speed excess α_T as a function of redshift for 300 different realizations of viable quintic Galileon cosmologies. Only quintic fine tuned cases (colored) predict $\alpha_T(z=0) \approx 0$. **Right:** 1, 2 and 3 σ confidence regions of the parameter space w.r.t. Planck+BAO for cubic (red), quartic (blue) and quintic (green) Galileons, projected on the $\alpha_T(z=0), \alpha_M(z=0)$ plane. Gray diagonal lines indicate the region disfavored by CMB-LSS cross correlation, measuring the ISW effect (see [33] for details). Models with $\alpha_T < -1$ (gray filled region) have unstable tensor modes.

[Biggish bang: artist's impression of a neutron-star merger \(Courtesy: NASA\)](#)

300 different theories ruled out by a SINGLE measurement!!!

THE CANDIDATE SIGNAL

- Scalar coupling to SM Lagrangian:

$$\mathcal{L}_{\text{int}} \supset -\sqrt{4\pi G_N \phi} \left[d_{m_e} m_e \bar{e}e - \frac{d_e}{4} F_{\mu\nu} F^{\mu\nu} \right],$$

- Modulates fine structure constant and mass of electron:

$$\frac{\Delta\alpha(t)}{\alpha} = A_e \cos(\Omega_{\text{DM}} t)$$
$$\frac{\Delta m_e(t)}{m_e} = A_{m_e} \cos(\Omega_{\text{DM}} t)$$

$$\Omega_{\text{DM}} = m_{\text{DM}} c^2 / \hbar$$

$$A_i \sim d_i \sqrt{8\pi\rho_{\text{DM}} G} \frac{\hbar}{m_{\text{DM}} c^3}$$

IMPACT ON SOLID OBJECTS

$$h_{\text{DM}}(t) = - \left(\frac{\Delta\alpha(t)}{\alpha} + \frac{\Delta m_e(t)}{m_e} \right)$$

(due to change in Bohr radius and bond lengths)

IMPACT ON GW DETECTORS

$$h_{DM}(t) = - \left(\frac{\Delta\alpha(t)}{\alpha} + \frac{\Delta m_e(t)}{m_e} \right)$$

due to change in Bohr radius and bond lengths
(ignore change in refractive index due to small contribution)

- A. Modulation of **thickness of beamsplitter**
 - Can be measured at dark port of Michelson (shown in GEO600)
 - $h_{DM}(t) = \mathcal{G}_{arm} \frac{L_{arm}}{l_{BS}} h_{GW}(t)$
- B. Modulation of **length of solid reference cavity**
 - Can be measured by comparing frequency fluctuations of reference cavities w.r.t. suspended cavities – typically one of the auxiliary channels of a GW detector

WHERE IS THE REFERENCE CAVITY?

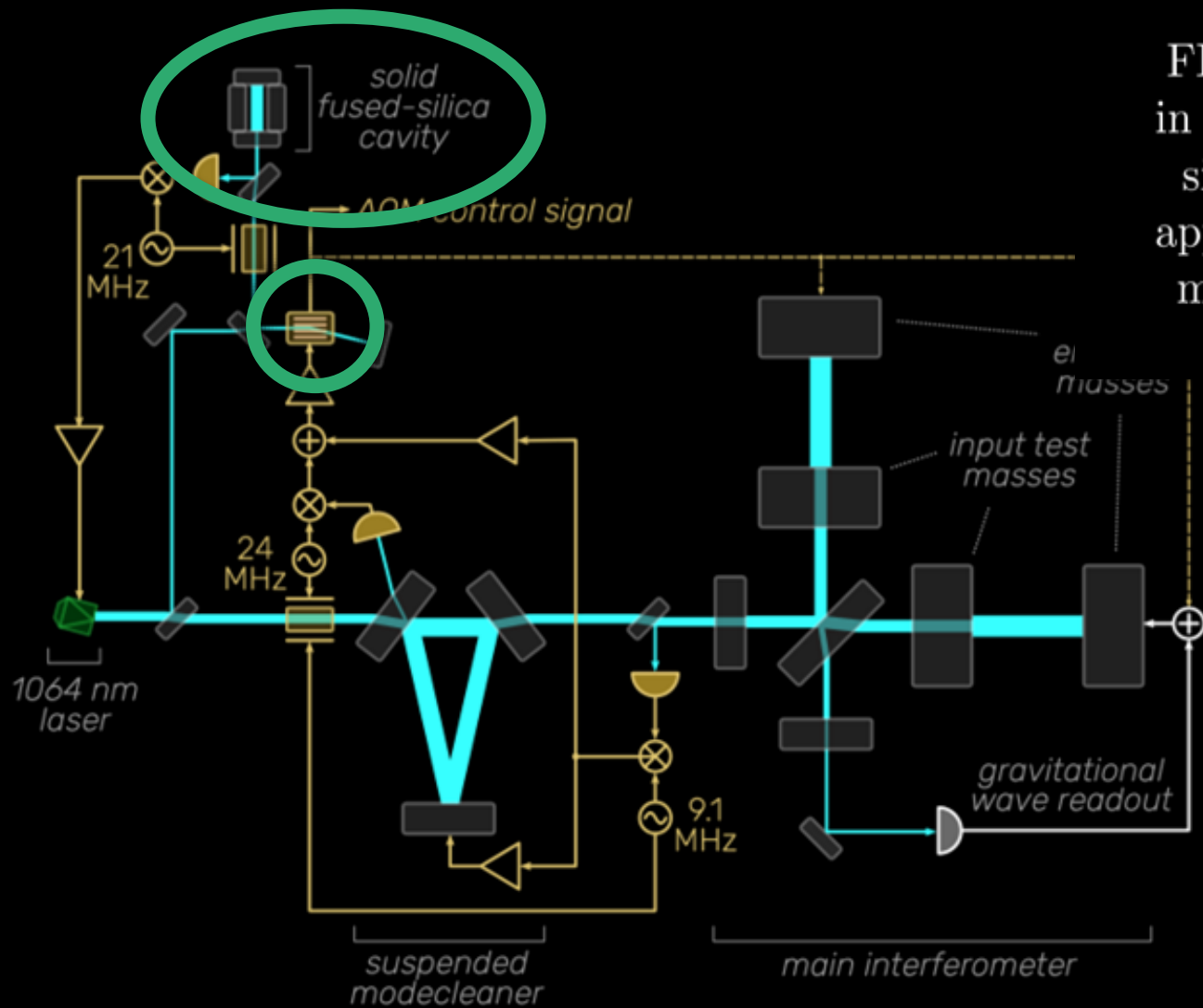
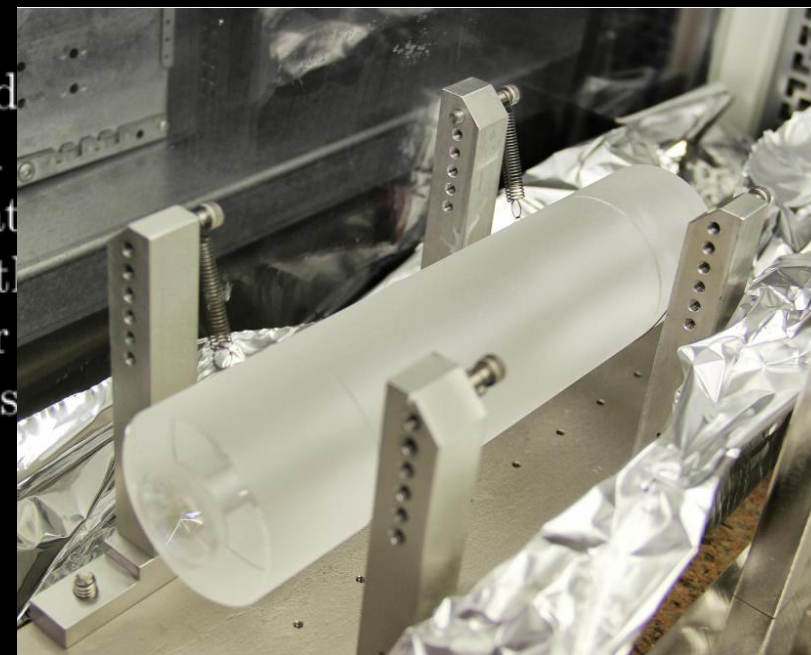


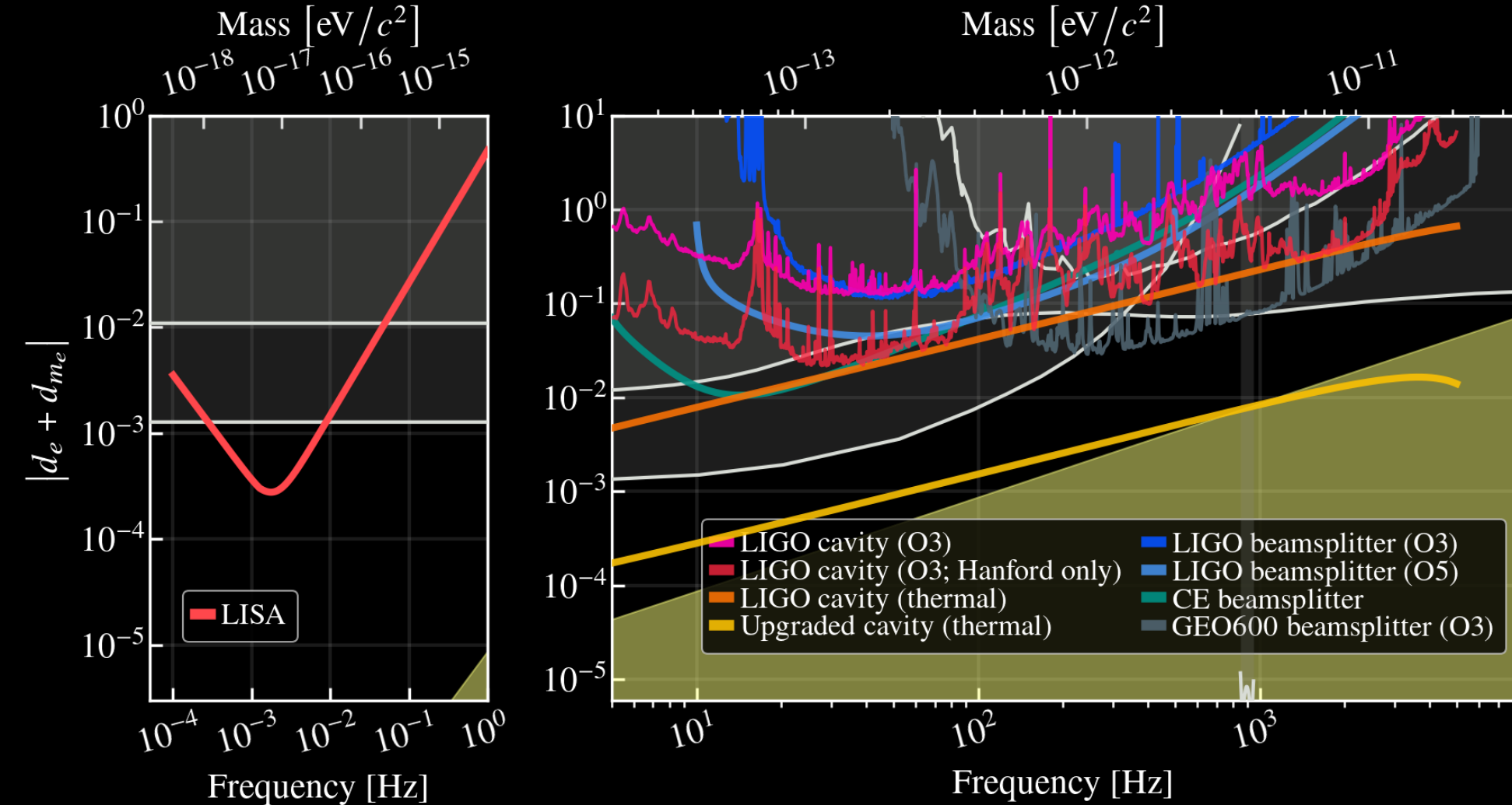
FIG. 1: Addition of the reference cavity in the solid silica channel. The signal that appears on the modulator is this



Noise matter will appear on the optical channels to

Relative frequency shifts will show up in this auxiliary channel

PROJECTED UPPER LIMITS (COUPLING)



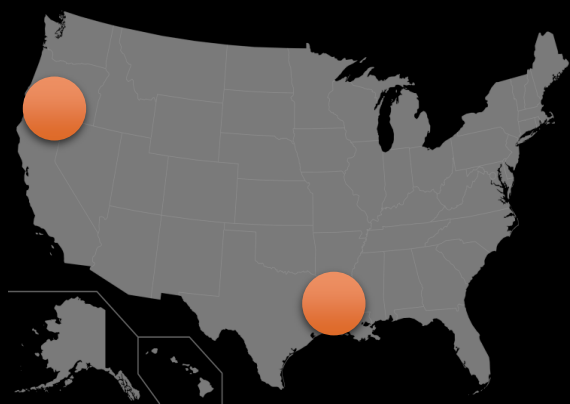
Hall, E and Aggarwal, N
Advanced LIGO, LISA,
and Cosmic Explorer as
dark matter transducers,
2022, arxiv 2210.17487

CROSS-CORRELATE BETWEEN TWO LIGOS

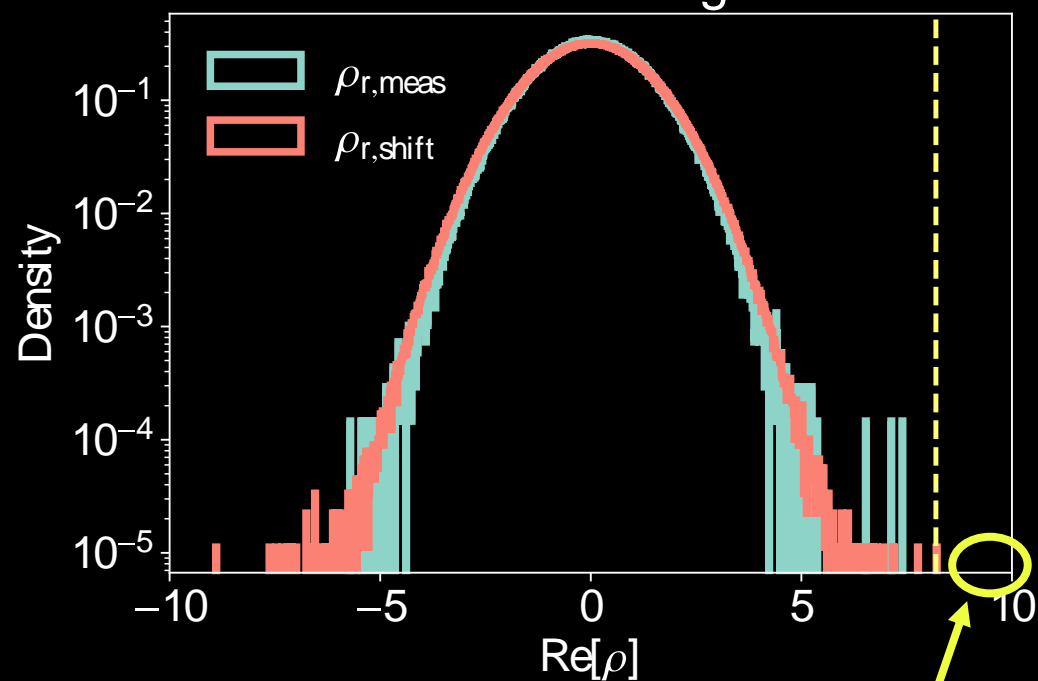
Swadha Pandey
Evan Hall



- Cross spectral density $S_{HL}(\Omega) = S_{DM}(\Omega)$
- $S_{DM}(\Omega) \propto$ coupling constant $|d_e + d_{me}|^2$



Estimator histogram



Outliers?

Optimal estimator for correlated search between detectors: $\rho = \frac{S_{HL}(\Omega)}{\sqrt{S_{HH}(\Omega)S_{LL}(\Omega)}}$

SUMMARY LIGO ULDM

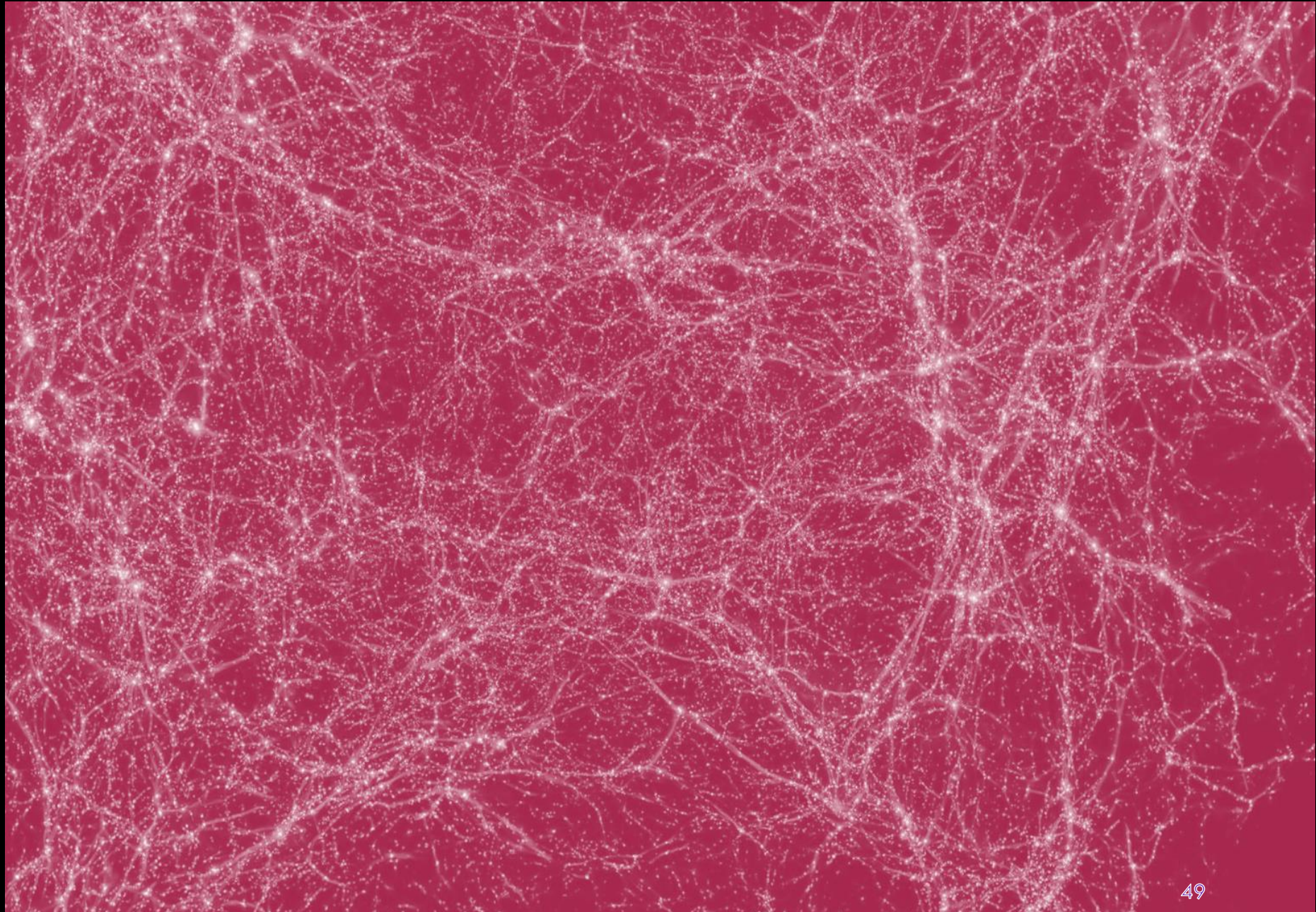
- Repurposing GW detectors as DM detectors
- Many other DM searches use LIGO
- Reference cavity is the only method that is
 - sensitive below 10 Hz.
 - Extracting science out of auxiliary channels
- Compares frequency fluctuations in a solid cavity with those in a free-space cavity to obtain differential noise suppression

SUMMARY

- Dark matter spans a huge mass range
- Scalar bosons span an even larger mass range (may or maynot be DM)
- Experimental strategies at different masses look different.
- Our group is working on three of them combining tabletop and kilometer-scale experiments across quantum optics for precision displacement/frequency measurements and cryogenics for precision magnetic field measurements.

- Thank you!

ULTRALIGHT
DILATONIC
SCALAR
DARK
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SEARCHES
WITH LIGO



- **Opening / Big Picture (3 slides)**
- **Title / hook slide** – “Probing the Invisible: Ultralight Bosons in the Lab and Beyond”
Figure: Conceptual schematic of “particle → weak signal → experiment”
- **Motivation: why ultralight bosons matter**
Takeaway: Physics beyond the Standard Model; dark matter candidate
Figure: mass vs coupling cartoon
- **Problem statement / challenge**
Takeaway: Signals extremely weak; need tailored detectors
Figure: simple cartoon: “signal invisible without precision tools”
-

- **2. Conceptual Map / Regimes (3 slides)**
- **Observable-based classification** – static force vs oscillating field vs radiated signal
Figure: table or schematic
- **Parameter space illustration** – axion mass (log scale), highlight ARIADNE, LIGO, LSD coverage
Figure: single mass-axis diagram
- **Field types & couplings** – pseudoscalar vs scalar, connection to detectors
Figure: simple legend or cartoon
-

- **3. ARIADNE: static-force example (3–4 slides)**
- **Physics motivation / mass range (μeV – meV)**
Figure: cartoon showing short-range force
- **Observable & experimental principle** – spin-dependent force detection
Figure: simplified schematic
- **Key technical challenge / noise limitation**
Figure: magnetic noise plot or illustration
- **Optional recent result slide** – magnetic noise characterization
Figure: data / example result
- **Tip:** Keep ARIADNE short; purpose = framing and credibility.
-

- **7. Unified view / summary (3–4 slides)**
- **Parameter space recap** – all three regimes together
Figure: final “mass → observable → detector” diagram
- **Take-home message** – “Precision experiments can access previously unreachable physics”
- **Optional team photo / group overview** – humanizes talk
- **Optional future directions / open questions** – small bullets
-

- **4. Transition to low-mass / direct detection (2 slides)**
- **Why lighter mass requires different observables** – signals become coherent oscillating fields

Figure: cartoon: static \rightarrow oscillating field

- **Introduce LIGO / ULDM / dilaton**

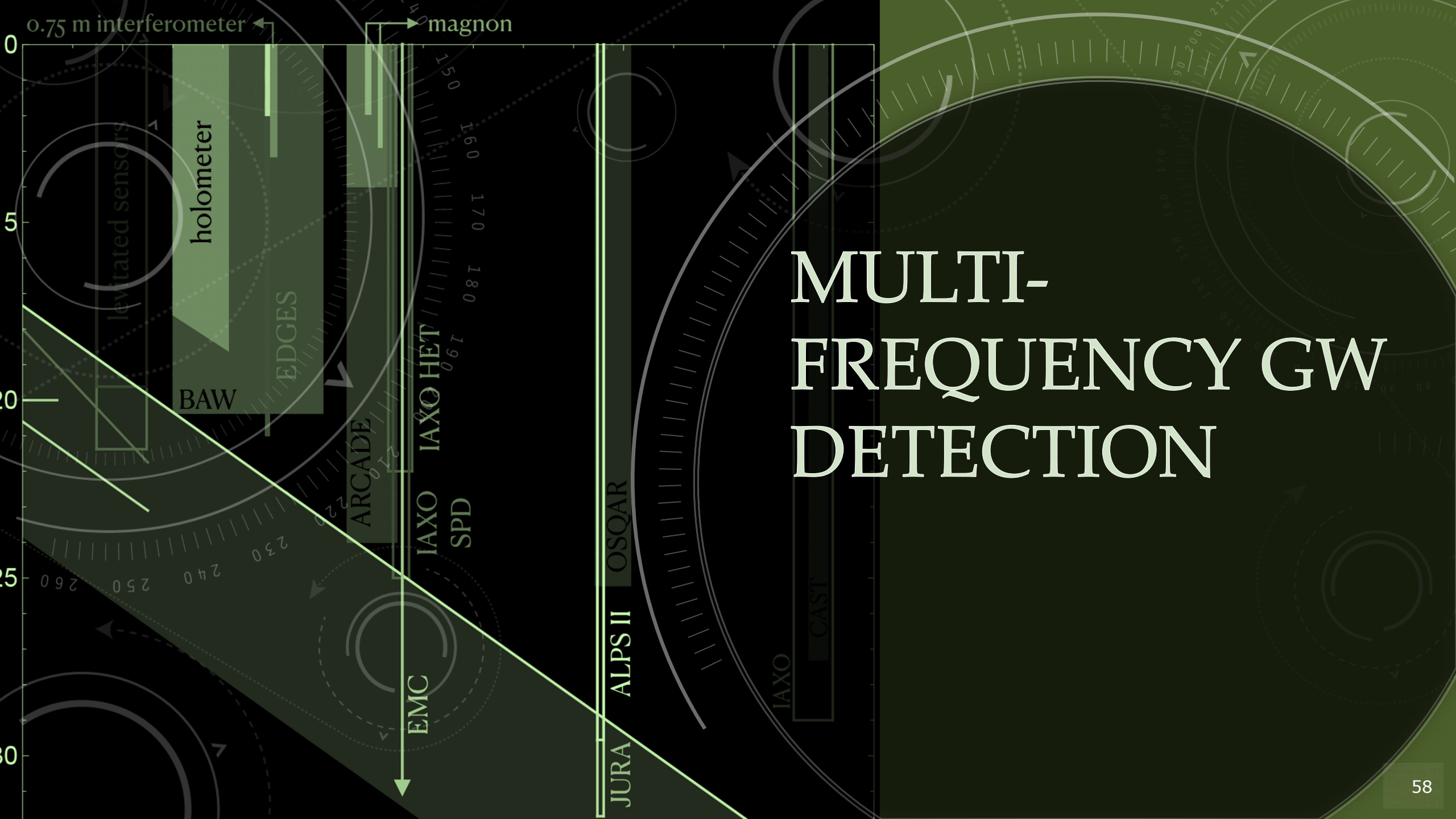
Takeaway: Low-mass scalar DM detectable via strain / frequency shifts

Figure: schematic LIGO arms with oscillating signal overlay

-

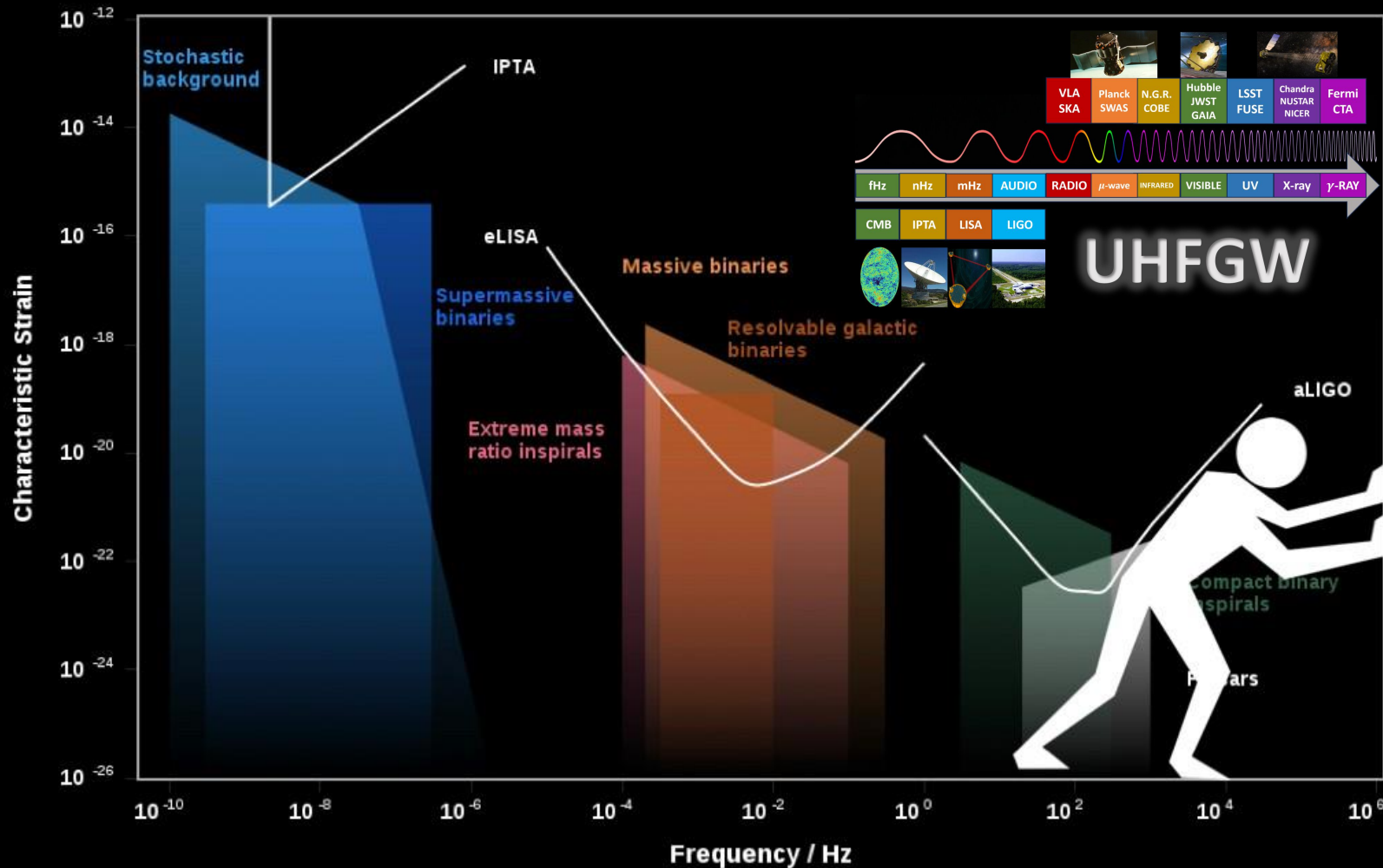
- **5. LIGO / ULDM / scalar DM (4–5 slides)**
- **Phenomenology of scalar DM** – frequency, coherence time
Figure: frequency spectrum cartoon
- **Signal in detector** – strain / effective measurement
Figure: simplified strain vs time diagram
- **Noise & sensitivity argument** – what limits detection
Figure: plot of sensitivity curve
- **Optional recent result 1** – LIGO projection or analysis
- **Optional recent result 2** – alternative mode / ancillary calculation
- **Tip: One core takeaway:** “Field is directly detectable, not astrophysical.”
-

- **6. LSD / BH superradiance (6–7 slides)**
- **Motivation / mass range ($\sim 10^{-11}$ eV)**
Figure: mass-axis zoom-in
- **Black hole superradiance signal – simplified explanation**
Figure: cartoon BH + boson cloud
- **Detection principle: levitated sensor – observable in lab**
Figure: schematic levitated system
- **Main noise source & mitigation strategy**
Figure: noise budget schematic
- **Projection / sensitivity figure – LSD reach for axion/BH mass**
Figure: sensitivity vs mass plot
- **Optional recent result 1 – latest measurement / calculation**
- **Optional recent result 2 – ancillary optomechanics or system characterization**
- **Tip:** This is the deep technical core; keep the audience oriented via repeated “observable → detector” reminders.
-



MULTI-FREQUENCY GW DETECTION

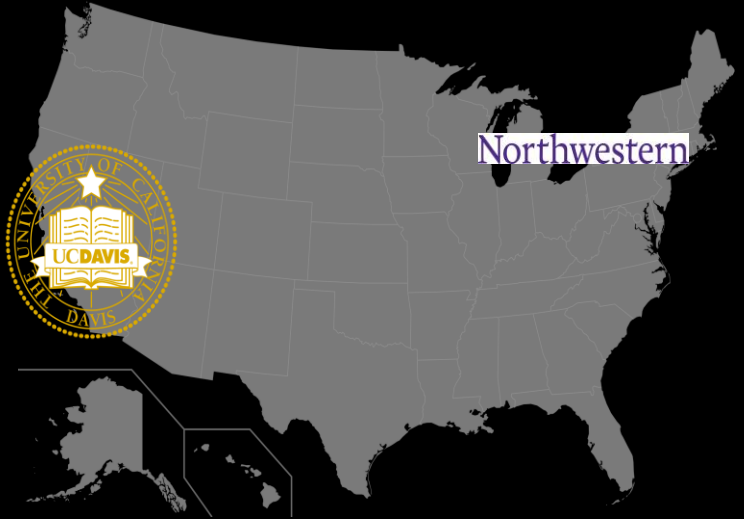
GWS ABOVE THE AUDIO BAND?



1. UHFGWs provide direct window to inflation (ie pre CMB)
2. No vanilla astrophysical sources above 10 kHz (BBHs, BNSs, NSBHs)
 1. No astrophysical foreground
 2. Directly probe cosmology below foreground OR be blocked by exotic sources

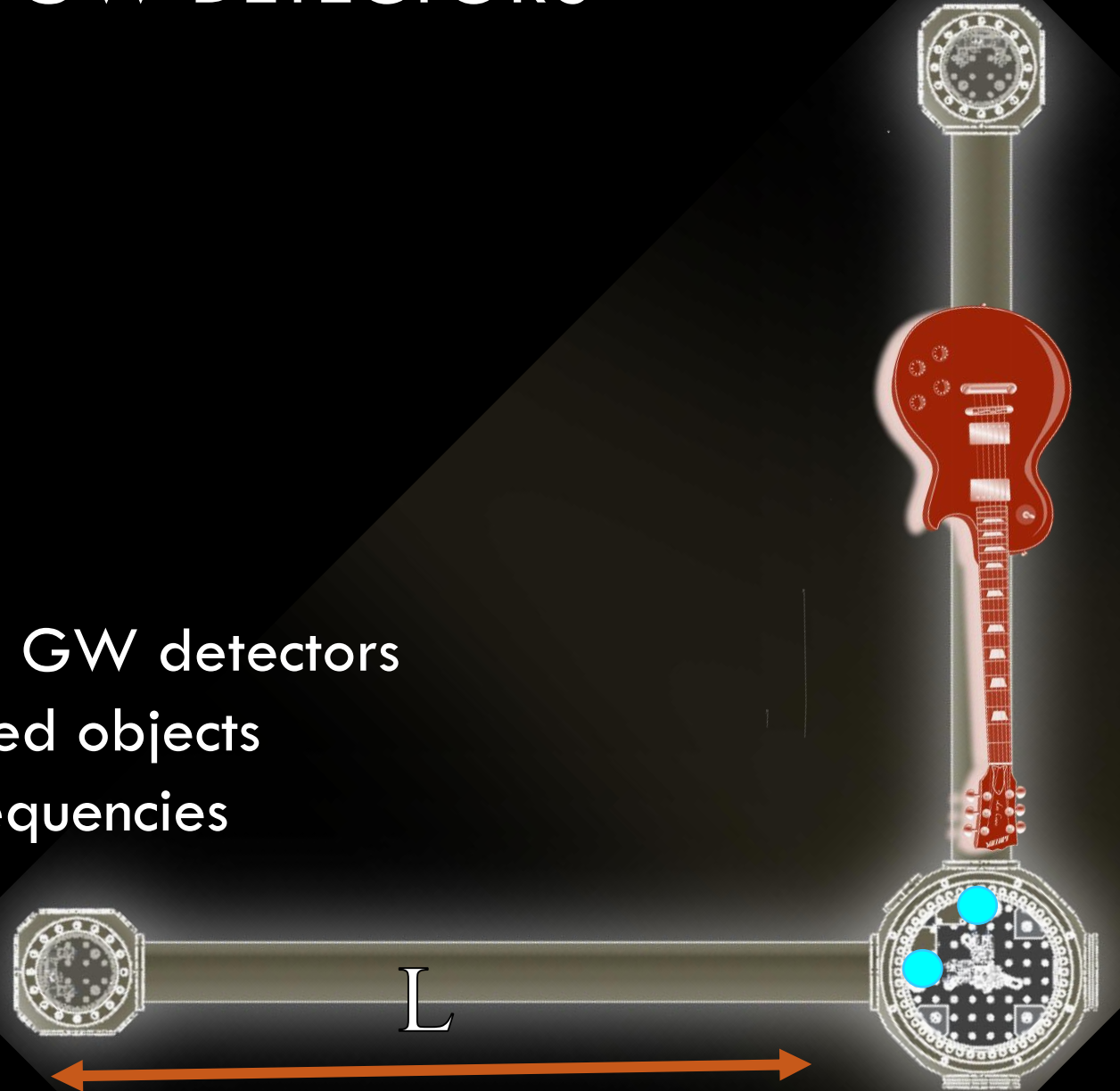
Aggarwal, N., Aguiar, O.D., Bauswein, A. *et al.* Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies. *Living Rev Relativ* **24**, 4 (2021). Also see <https://arxiv.org/pdf/2501.11723>

TWO LEVITATED SENSOR GW DETECTORS



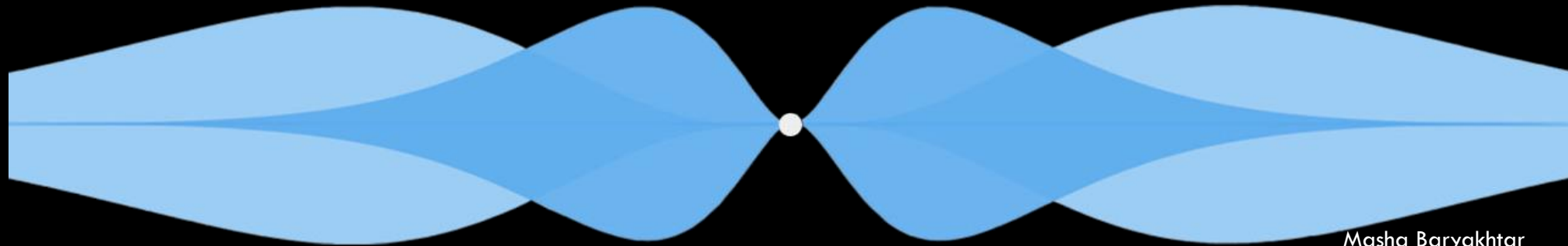
- Network of miniature GW detectors
- Uses optically levitated objects
- Tunable detection frequencies

Searching for new physics with a levitated-sensor-based GW detector
Aggarwal et al PRL 128, 111101



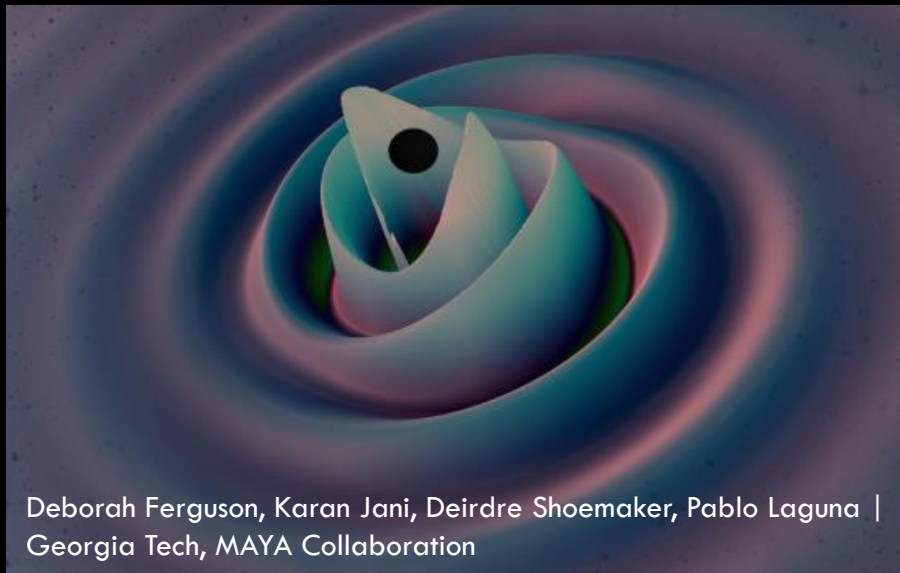
SCIENCE TARGETS

Blackhole Superradiance



Masha Baryakhtar

Primordial black holes



Deborah Ferguson, Karan Jani, Deirdre Shoemaker, Pablo Laguna | Georgia Tech, MAYA Collaboration



The unknown unknowns???

EFFECT OF GRAVITATIONAL WAVES ON LEVITATED SENSORS

Antinode-Particle Displacement (Relativistic Treatment)

Transverse-Traceless Gauge

- Free masses stay at fixed coordinates, distance between coordinates changes through the metric $g_{xx}(t) = 1 + h_+(t)$ and light coordinate velocity is $v = c(1 - h(t)/2)$
- Coordinate velocity dictates internal field phase accumulation

$$\delta\phi(a, b)(t) = \frac{\omega_0}{c} (b - a) + \frac{1}{2} \int_a^b h(t - (b - x')/c) dx'$$

Locally-Lorentz Gauge

- Free mass at L_t displaced by $L_t h(t)/2$, distance between coordinates unaffected
- Internal field phase accumulation affected by mirror displacement, modified light coordinate velocity, and localized gravitational redshift [Rakhmanov 2005]

Solve steady-state system of equations to find $E(x, t)$, then find maxima in $|E(x, t)|^2$ to calculate displacement of cavity antinodes, and with $h_+(t) = h \cos\omega t$:

$$\delta x_{\text{particle-antinode}} = \frac{h(L - L_t)}{2} \left(\cos\omega t + \frac{1}{2} \frac{\omega L}{c} \sin\omega t \right)$$

Laeuger, Aggarwal et al, in prep

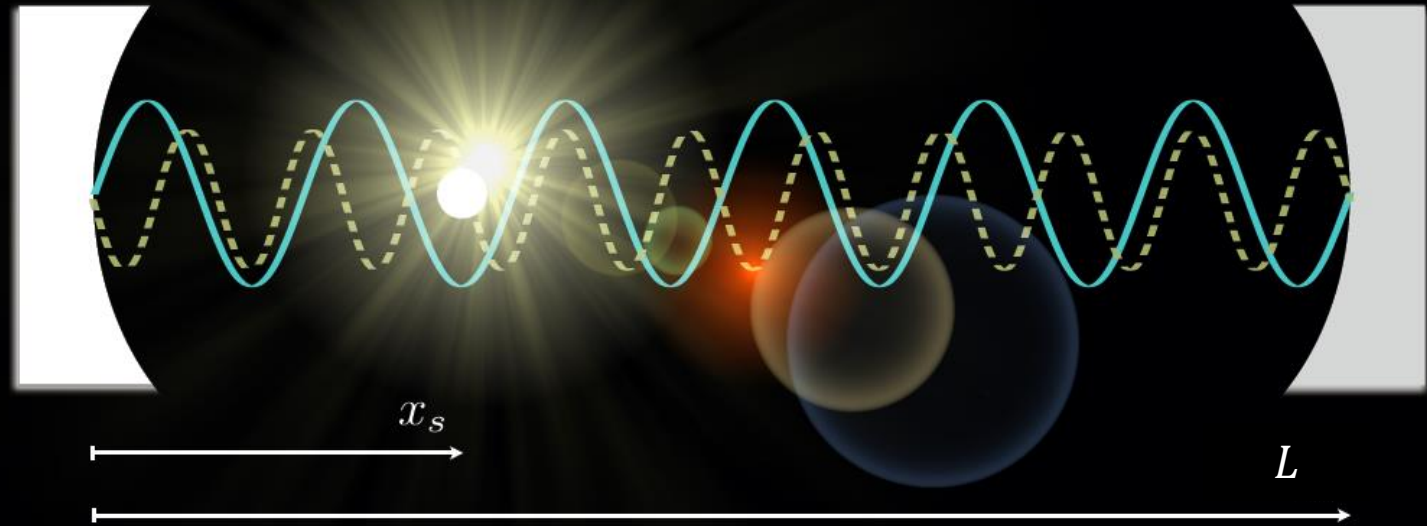


Andrew Laeuger

Poster #9

Breaking the
Cavity: Non-
perturbative
Levitated
Sensor
Systems for
Gravitational
Wave Detection

OPTICAL COUNTERPART OF A WEBER BAR



$$\Delta L = \frac{h}{2} L, \quad \Delta x_a = \Delta L, \quad \Delta x_s = \frac{h}{2} x_s$$

$$\Delta x_{GW} = \Delta x_s - \Delta x_a = \frac{h}{2} (x_s - L), \quad \text{maximized at } x_s \rightarrow 0$$

$$F_{GW} = M \Omega_T^2 \Delta x_{GW} = M \Omega_T^2 \frac{L}{2} h_0 \cos \Omega_{GW} t$$

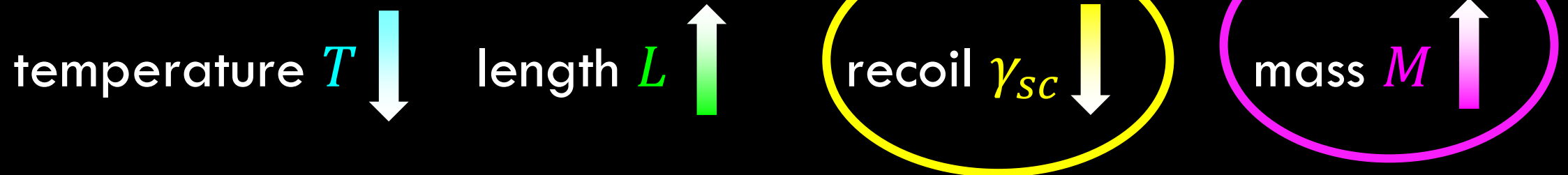
Arvanitaki and Geraci,
PRL 110, 071105 (2013)

LIMITING NOISE: GAS DAMPING AND PHOTON RECOIL HEATING

- $S_{FF} = 4 M (k_B T \gamma_g + \hbar \omega \gamma_{sc})$
- Limit on resonance ($\Omega \rightarrow \Omega_T$),

$$S_{hh} \sim 16 \frac{1}{\Omega_T^4} \frac{1}{M} \frac{1}{L^2} (\hbar \omega \gamma_{sc} + k_B T \gamma_g)$$

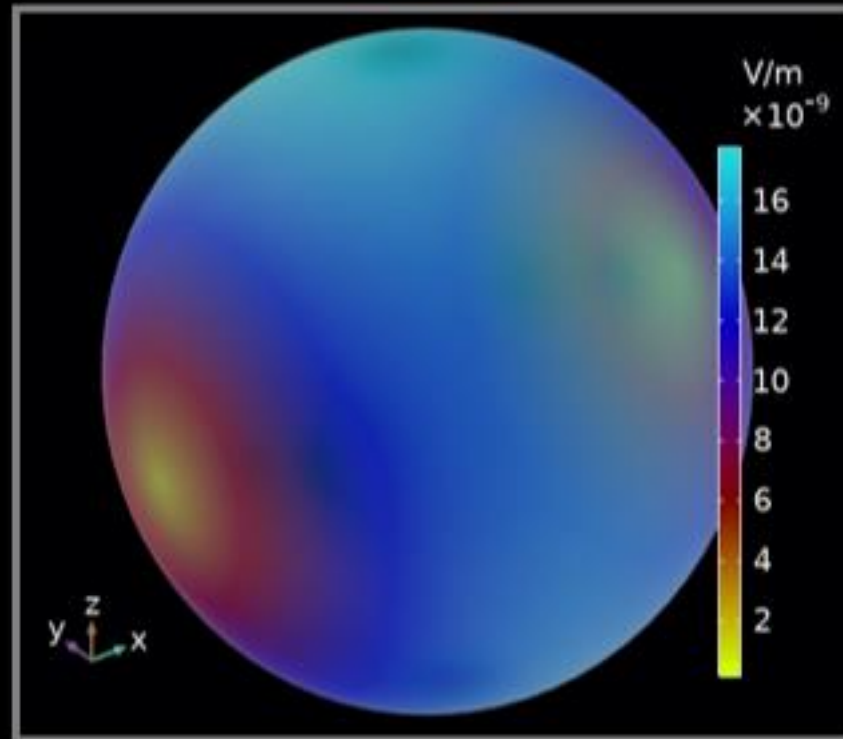
Arvanitaki and Geraci,
PRL 110, 071105 (2013)



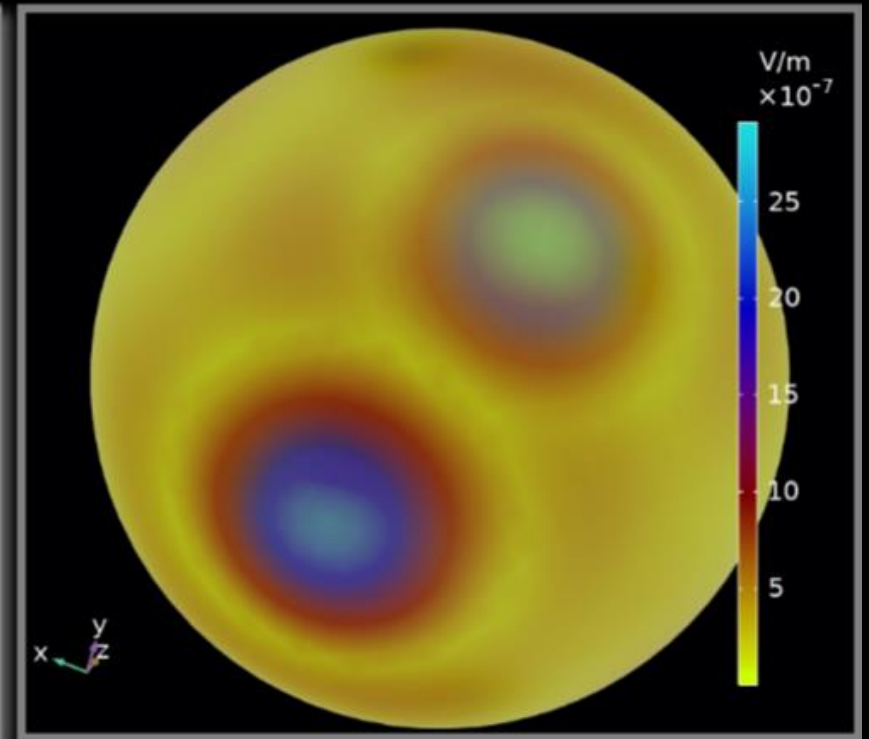
GEOMETRY AFFECTS SCATTER

- Sphere scatters light in all directions
- Disk scatters light in the beam direction (low γ_{sc})
- Numerical simulations of scattering from disks show low scattering loss, hence low recoil heating

plane wave incident: $\vec{E} = 1 \text{ Vm}^{-1} \hat{x} \cos kz$



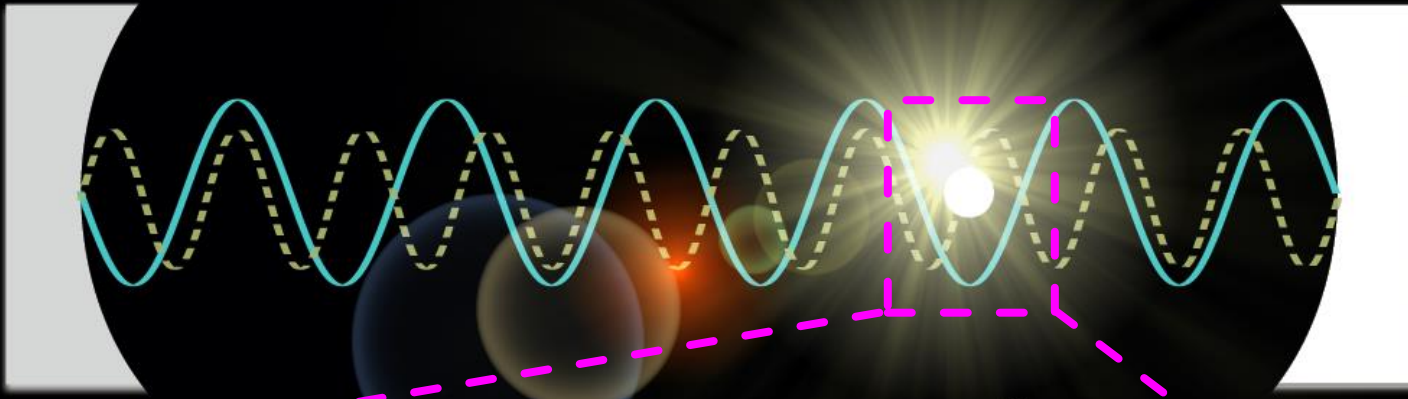
SiO₂ Sphere (d=300 nm)



NaYF Hexagon (d=4 μm , $\tau = 200 \text{ nm}$),
300 times more mass

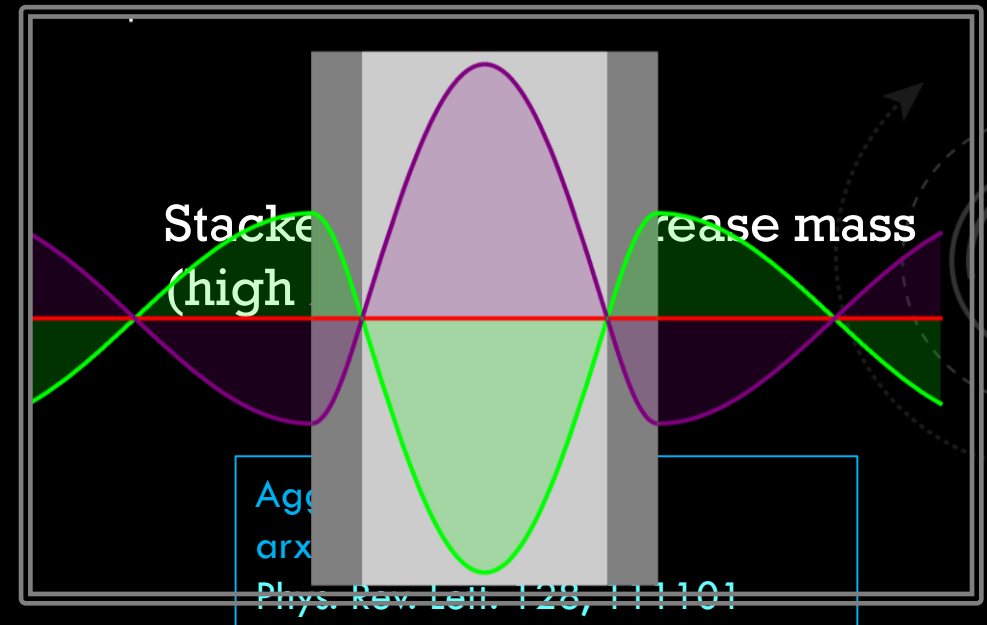
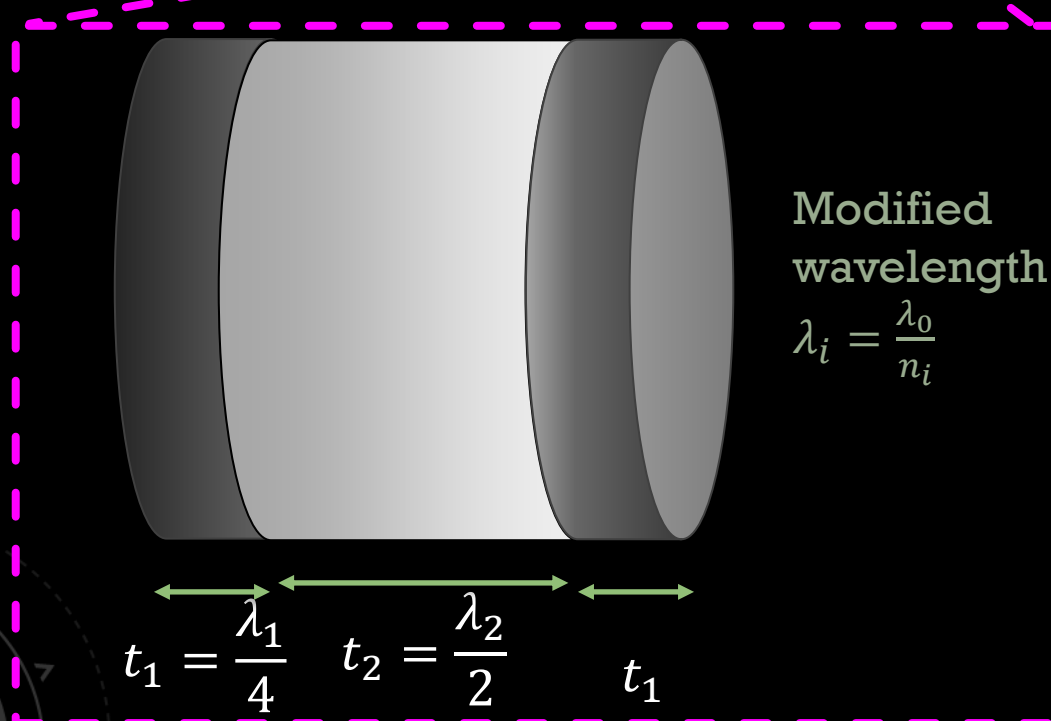
Aggarwal et al arxiv:2010.13157 Phys. Rev. Lett. 128, 111101,
Winstone et al arxiv:2204.10843 Phys. Rev. Lett. 129, 053604

ALTERING SHAPE: CAN WE TRAP A BILLY LOW?

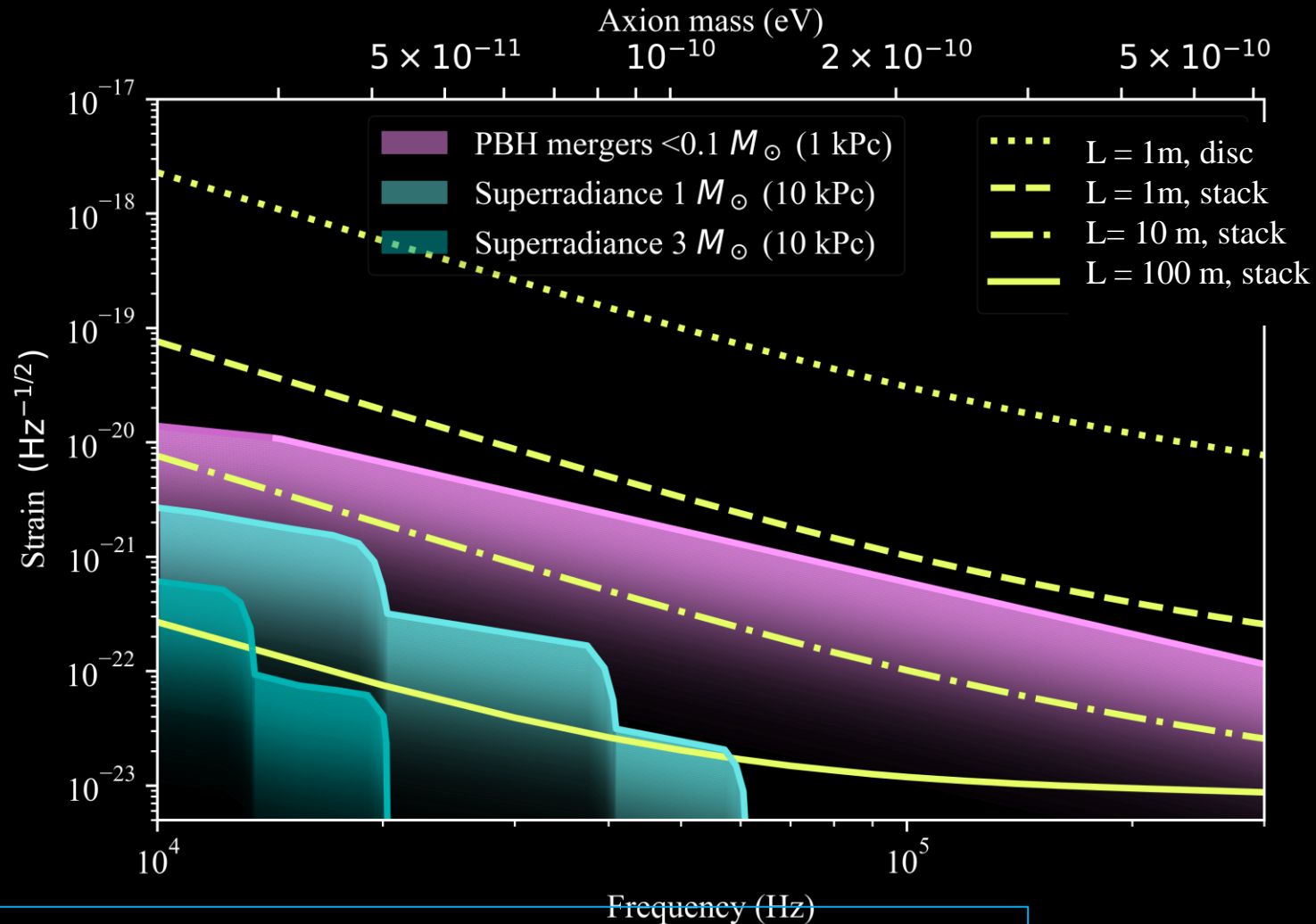


Is a stack trappable?

1. What is the transmission through the stack?
2. What is the field inside the stack?
3. What is the trapping frequency/stiffness?
4. Can these things be fabricated in the lab?

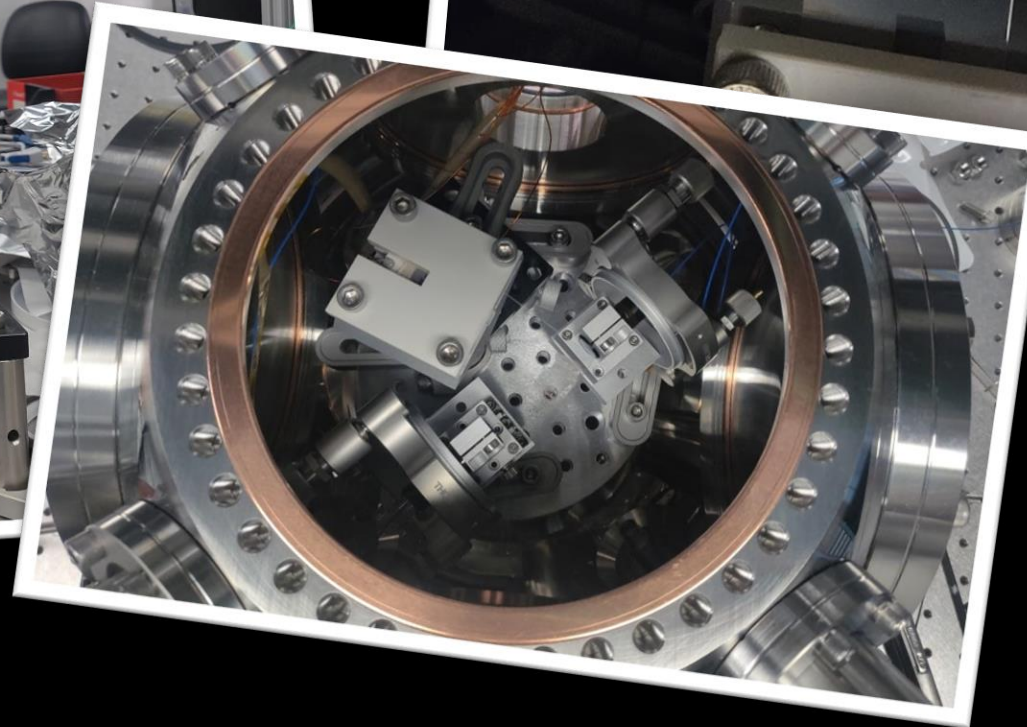
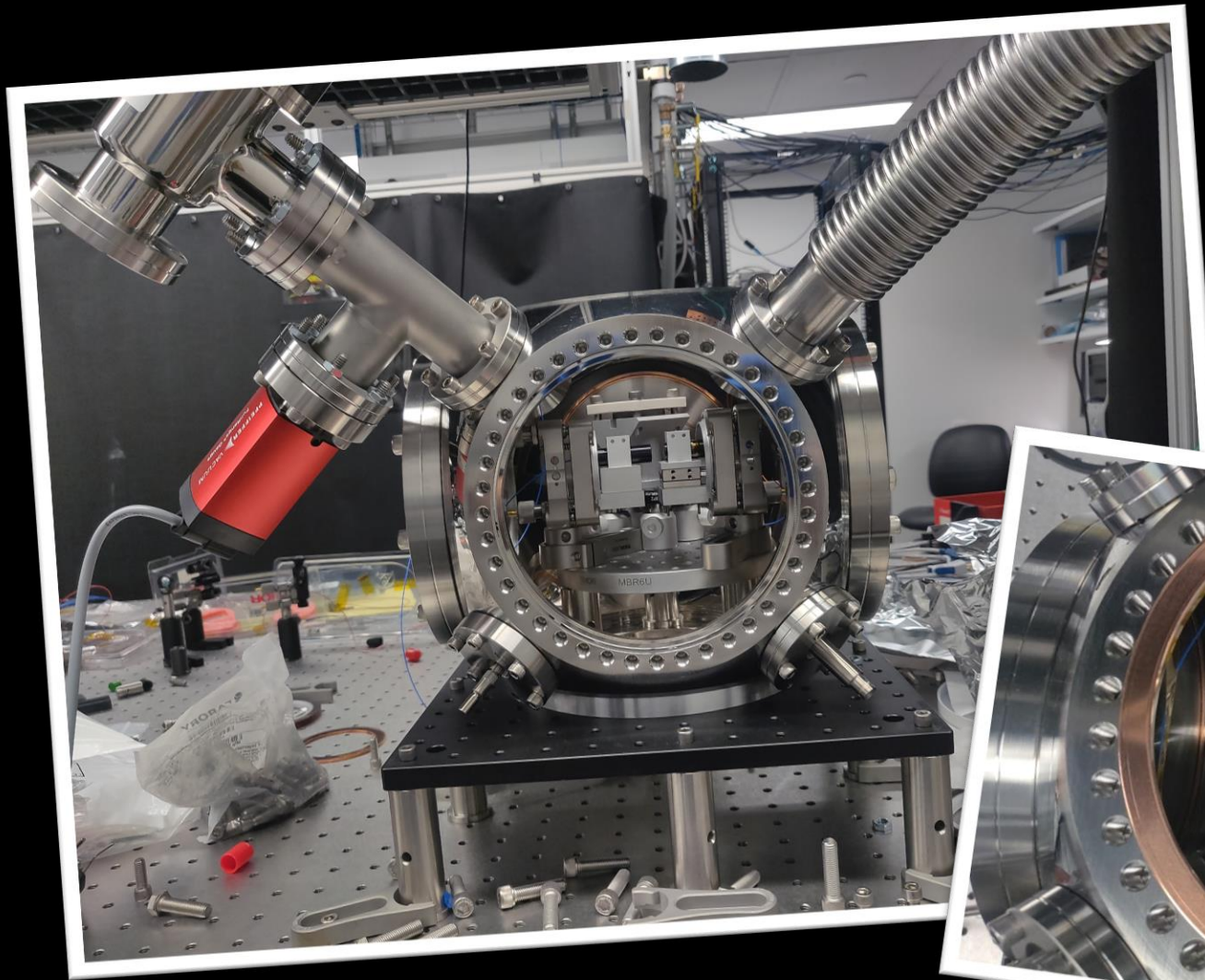


IMPROVED SENSITIVITY

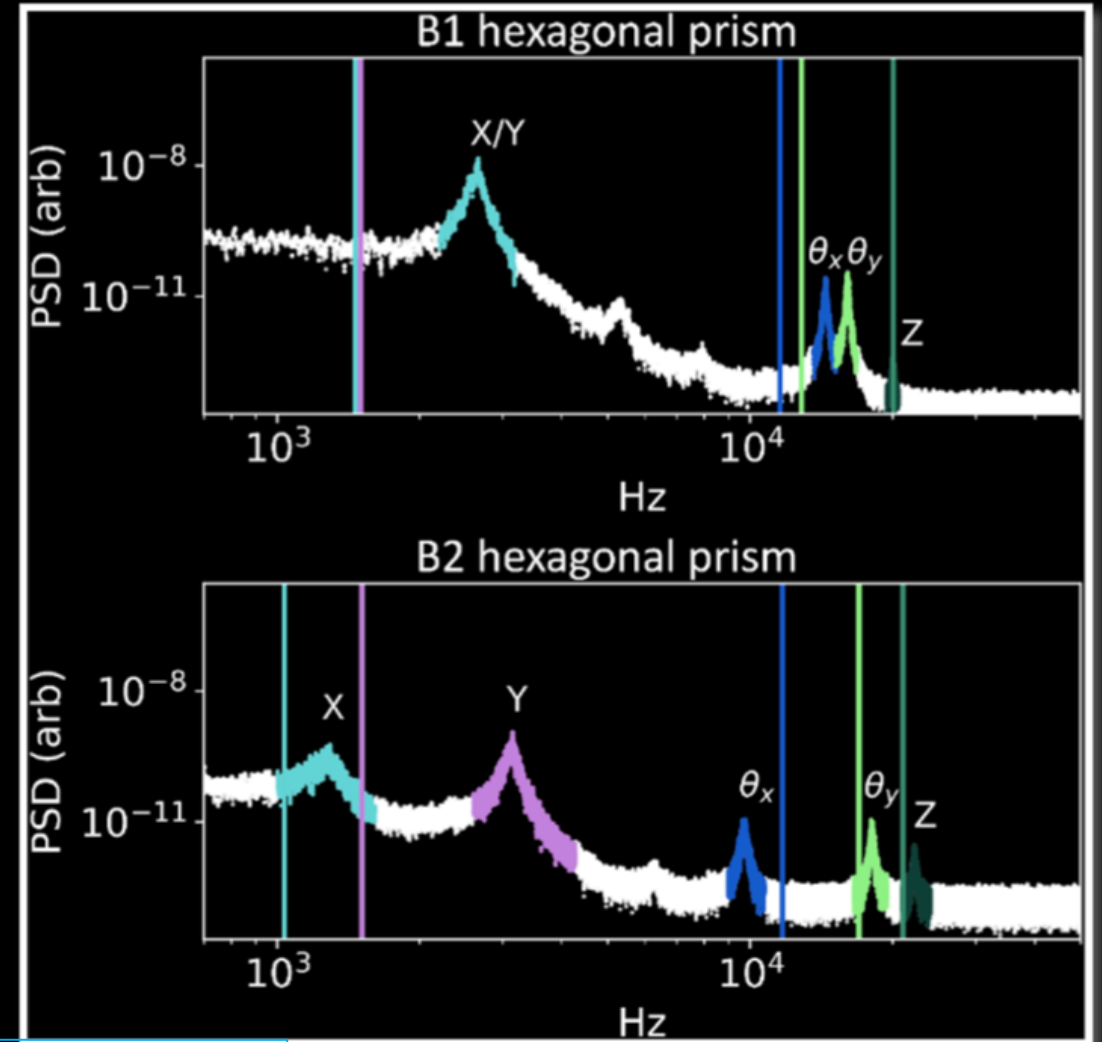
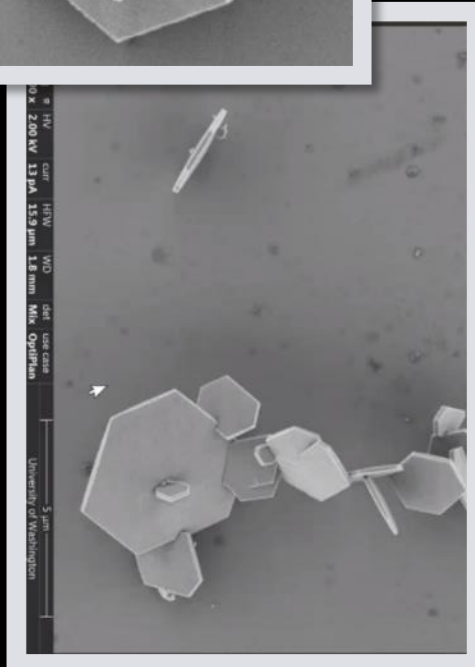
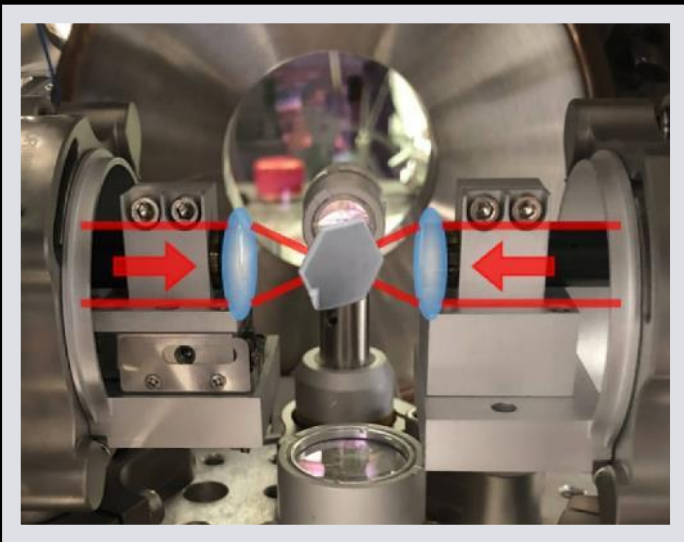
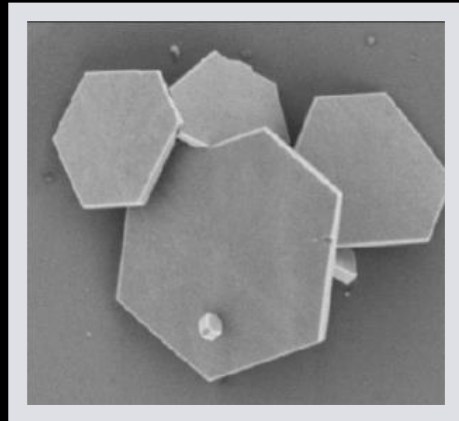
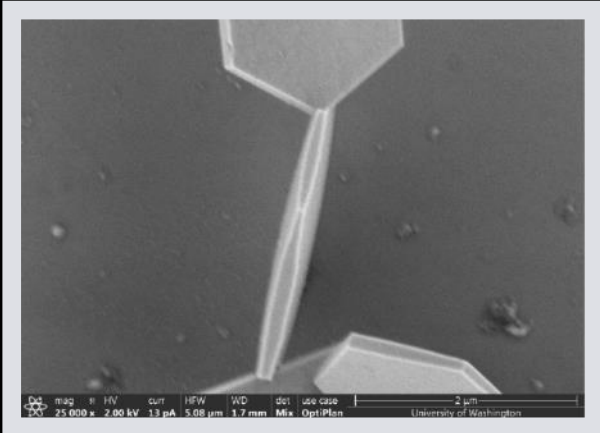


Aggarwal et al arxiv:2010.13157 Phys. Rev. Lett. 128, 111101

TRAPPING OF FLAT OBJECTS IN THE LAB...

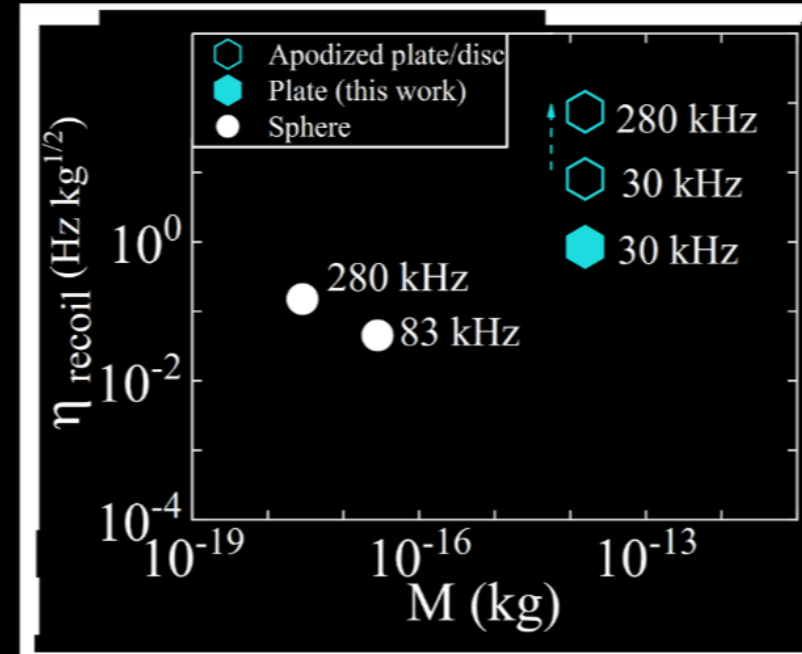
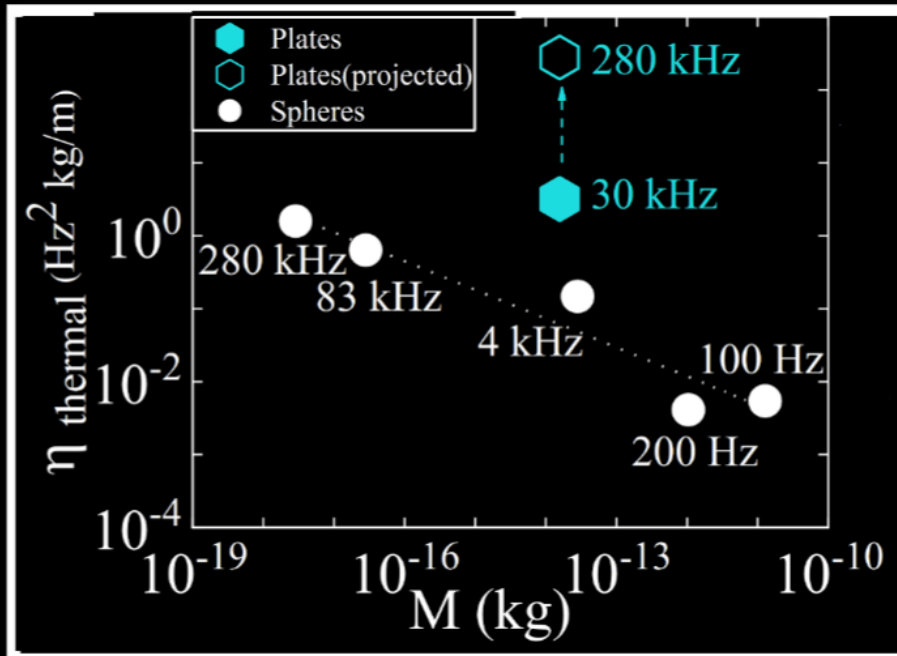


TRAPPING OF NAYF HEXAGON PLATES



Winstone et al arxiv:2204.10843 Phys. Rev. Lett. 129, 053604

STATE OF THE ART IN OPTICAL TRAPPING



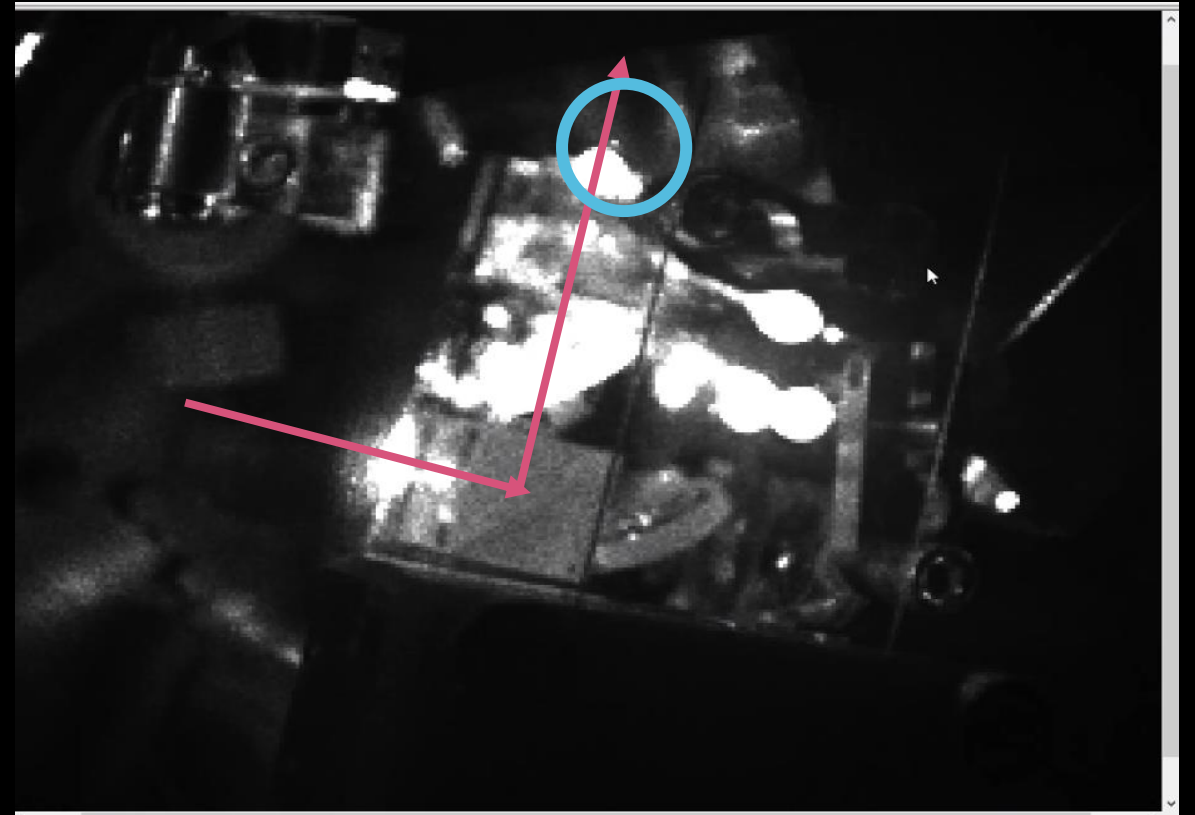
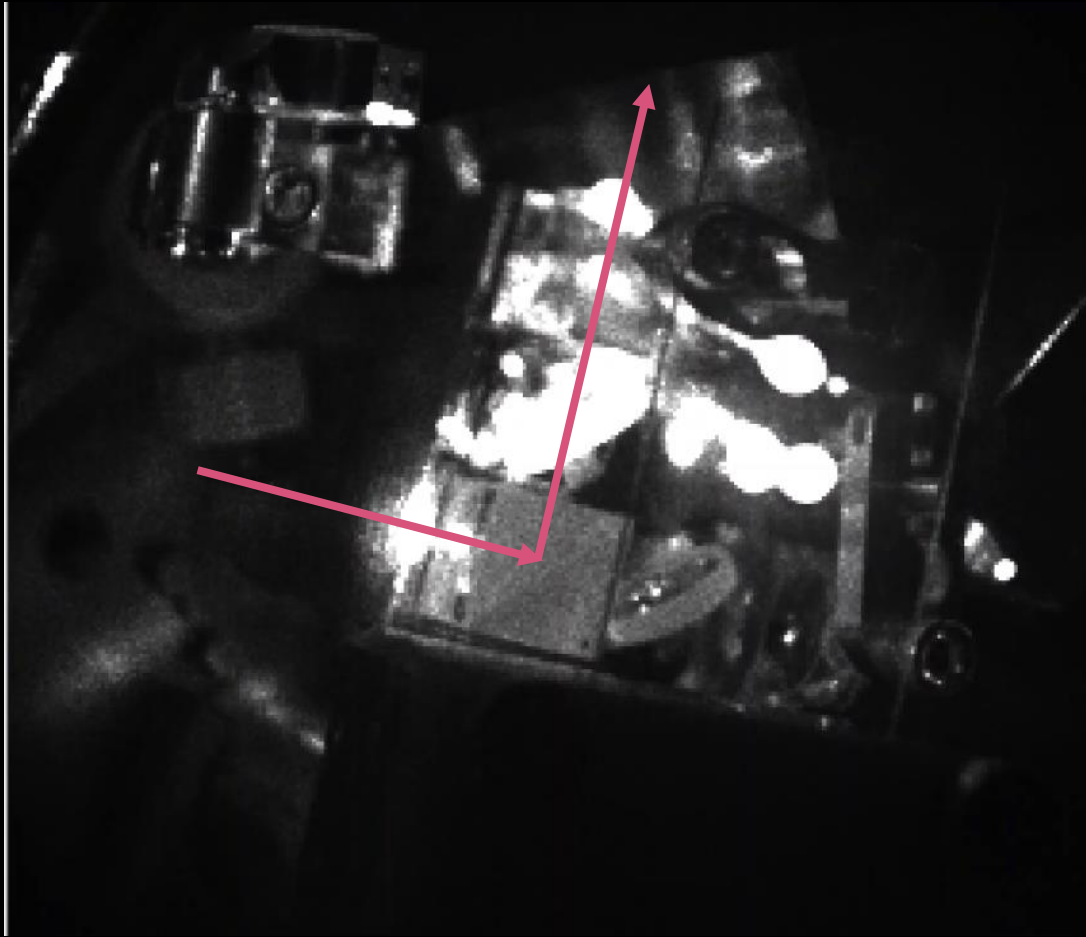
$$\eta_{\text{thermal}} = \left(\frac{\Omega_z}{2\pi}\right)^2 \sqrt{M\rho\tau}$$

$(\gamma_g \propto 1/\rho\tau)$

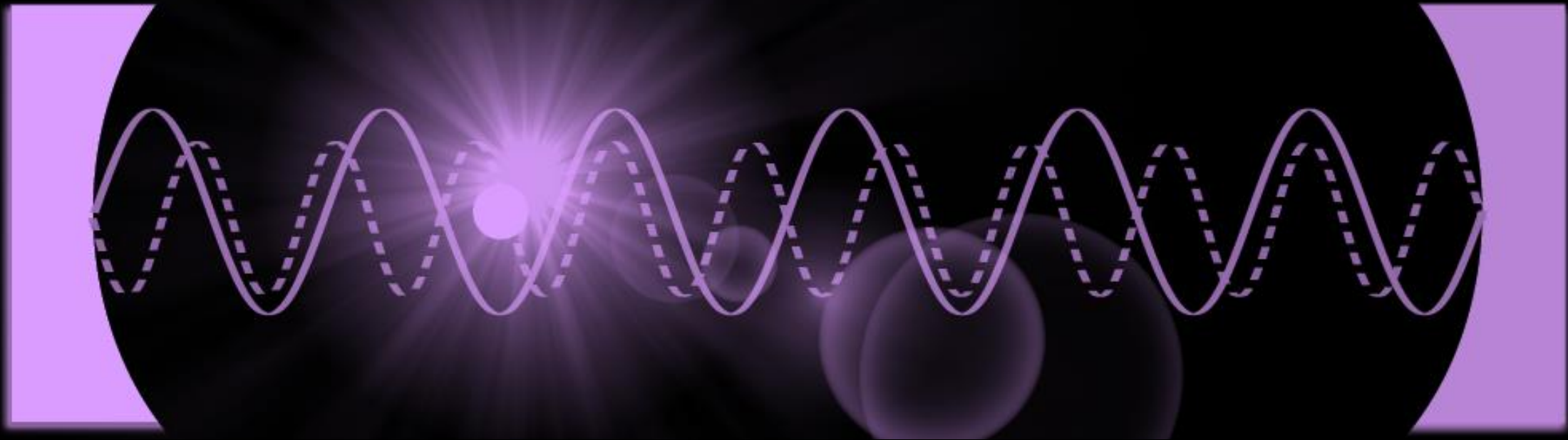
$$\eta_{\text{recoil}} = \left(\frac{\Omega_z}{2\pi}\right)^{3/2} \sqrt{\frac{M}{\gamma_{sc}}}$$

Winstone et al arxiv:2204.10843 Phys. Rev. Lett. 129, 053604

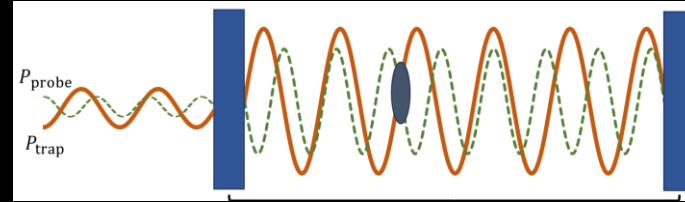
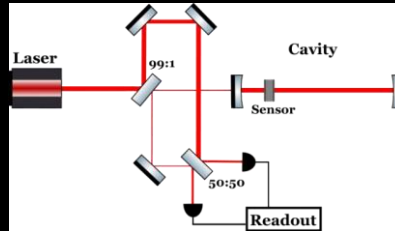
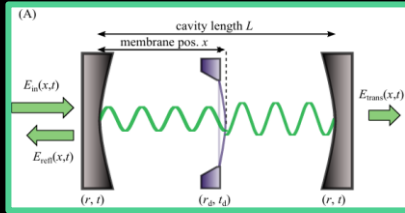
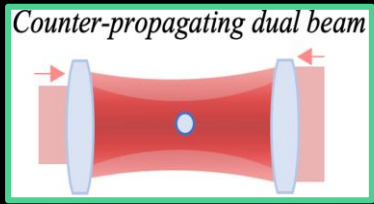
HEXAGONS TRAPPED IN CAVITY



OPTOMECHANICS SIMULATIONS



NEED A NEW CUSTOM SIMULATION PACKAGE



Andrew Laeuger

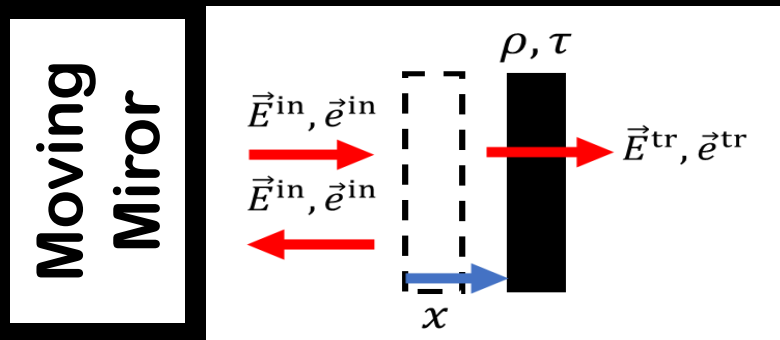
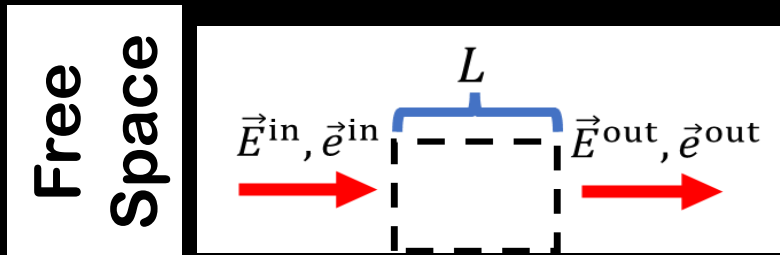
Poster #9

Breaking the Cavity: Non-perturbative Levitated Sensor Systems for Gravitational Wave Detection

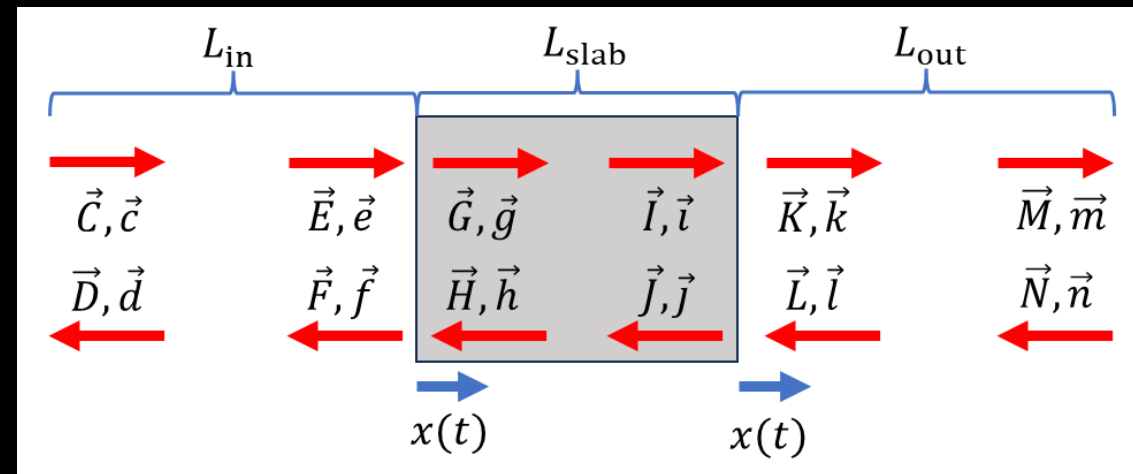
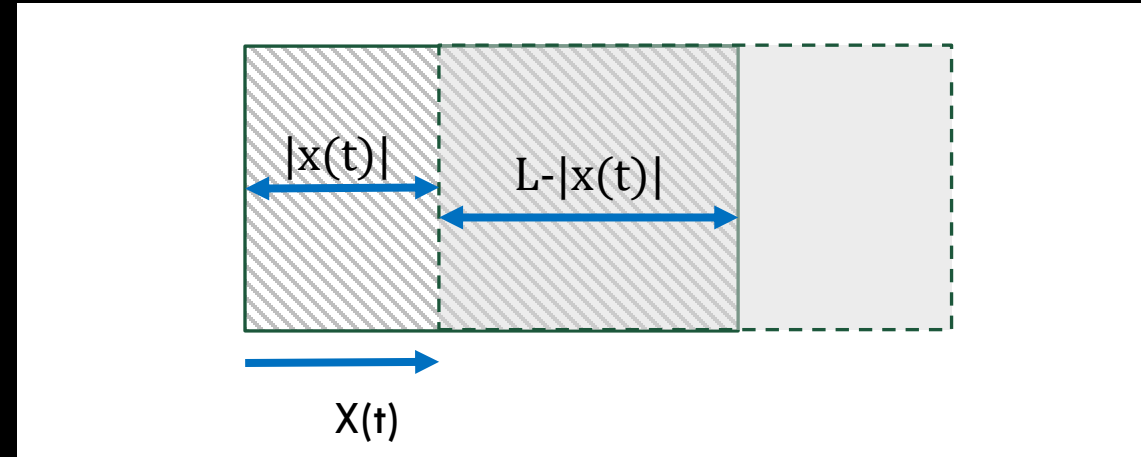
Laeuger, Aggarwal et al, in prep

Levitated Optomechanics	Membrane in the middle	LIGO-like systems/Finesse	DM TELEVISION
$d \ll \lambda$			$d > \sim \lambda$
Phase accumulation only important when $d \sim \lambda$			Phase accumulation important for $d \ll \lambda$ due to cavity and due to $R \gg w$ from gradient force
	High-reflectivity		~ 1 transmission \rightarrow strong subcavity coupling
Perturbative Cavity Mode			Split cavity, non-perturbative
		Finesse only has one laser	Trapping laser noises need to be added ad-hoc in finesse
		Only scattering force is important	Both gradient and scattering force are important

TREAT MEMBRANE AS A PAIR OF MOVING MIRRORS?

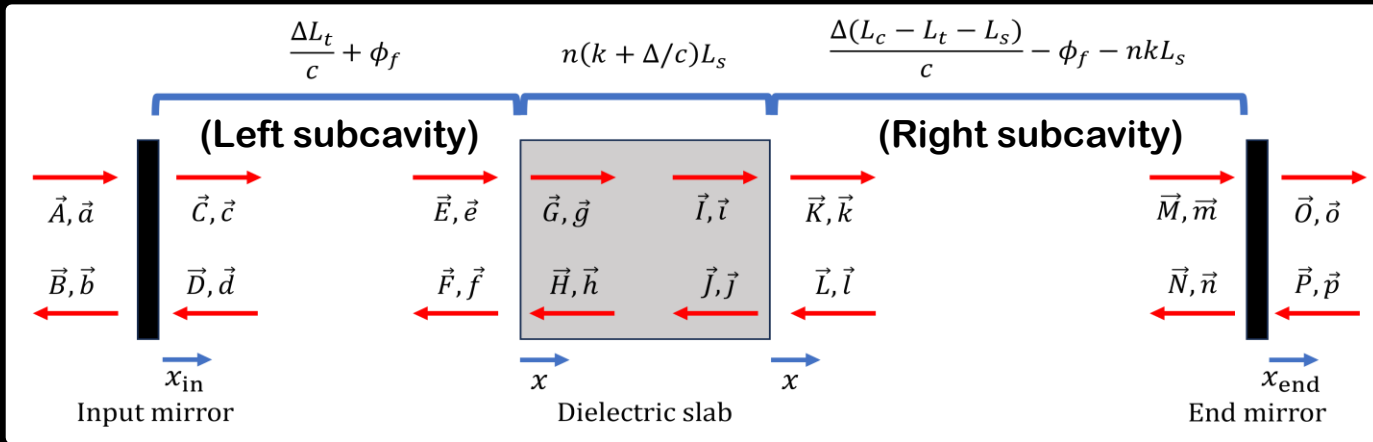


Corbitt et al, PRA 2005

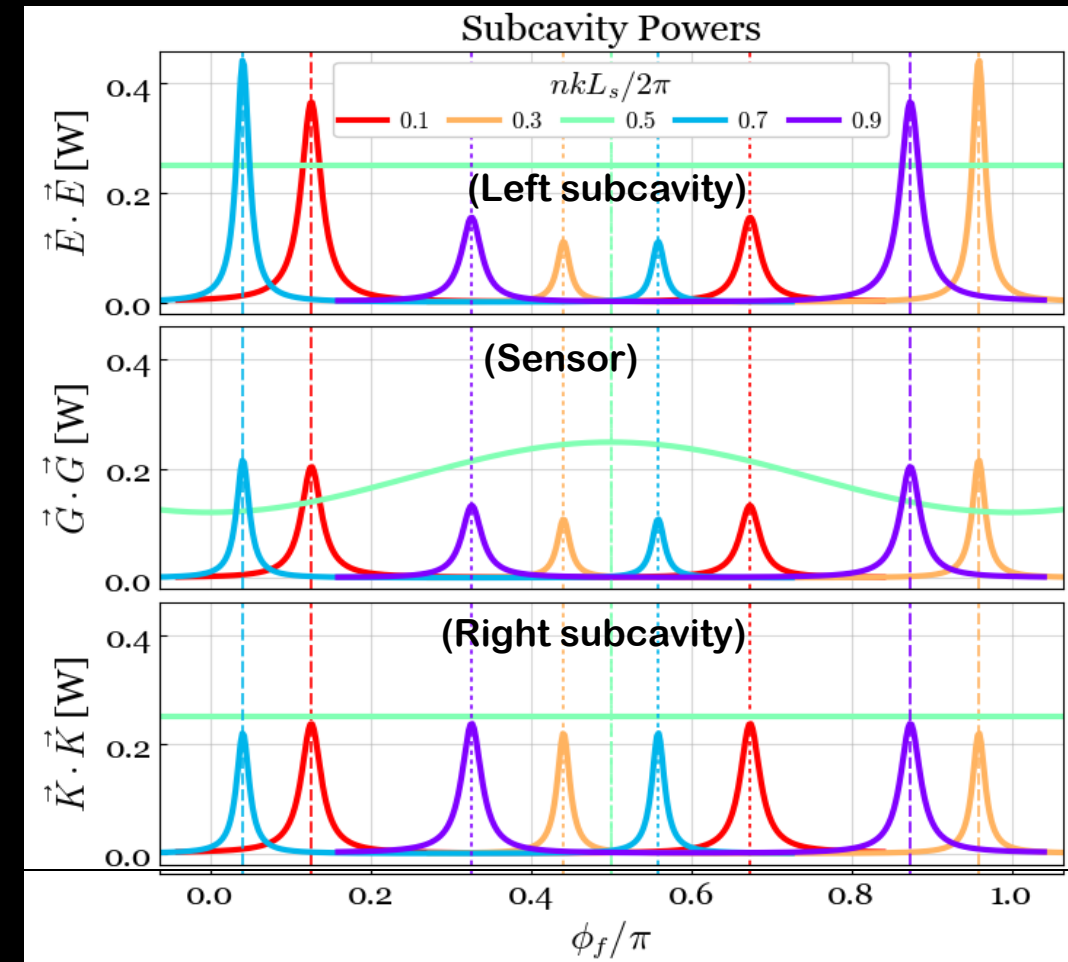


Laeuger, Aggarwal et al, in prep

SENSOR LOCATION AFFECTS CAVITY RESONANCE



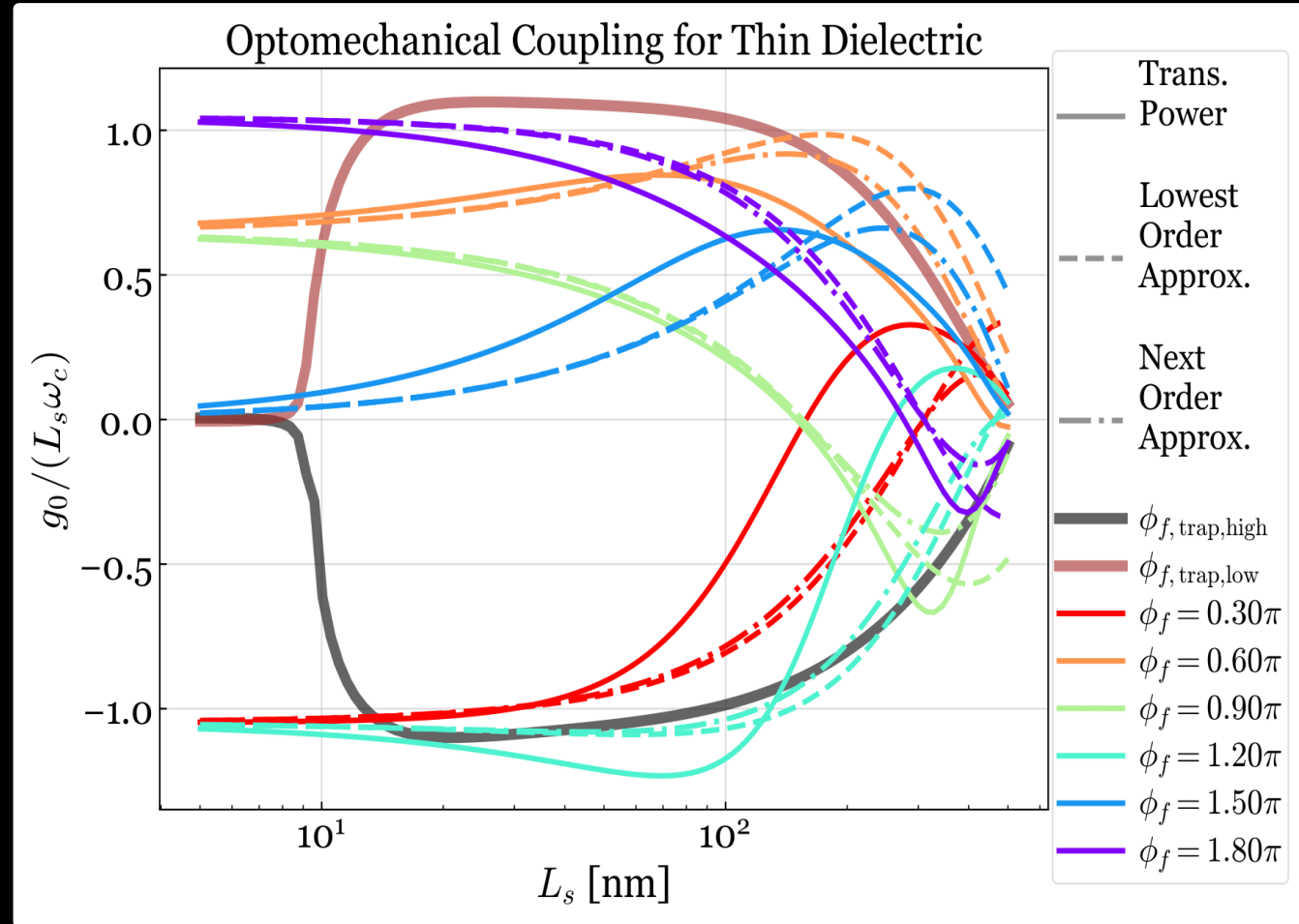
- the sensor produces a non-negligible effect on the cavity fields!



WHAT IS THE OM COUPLING?

- **Detector response to sensor motion often characterized by the coupling $g_0 \equiv \partial\omega_c/\partial\phi_f$.**
- **Perturbation theory: inserting dielectric \rightarrow resonant frequency \rightarrow**

$$\frac{\delta\omega_c}{\omega_c} \approx -\frac{1}{2} \frac{\int d^3\vec{r}' \delta\epsilon(\vec{r}') \vec{E}_0(\vec{r}')^2}{\int d^3\vec{r}' \vec{E}_0(\vec{r}')^2}.$$
- **Deviations occur at just ~ 100 nm – further evidence of nonperturbative physics.**



LIGHT-MATTER INTERACTION: FORCES

Stability of radiation-pressure particle traps: an optical Earnshaw theorem

A. Ashkin and J. P. Gordon

Bell Laboratories, Holmdel, New Jersey 07733

Received June 6, 1983

but that is not necessary to our argument. On inserting this development for μ into the expression for \mathbf{F}_l , we obtain $\mathbf{F}_l = \mathbf{F}_g + \mathbf{F}_s$, where

$$\mathbf{F}_g = (1/4)\text{grad}(\mathbf{E}^* \cdot \chi' \cdot \mathbf{E}), \quad (3)$$

$$\mathbf{F}_s = (1/2)\text{Im}\{\hat{x}_j \mathbf{E}^* \cdot \chi'' \cdot \partial \mathbf{E} / \partial x_j\}. \quad (4)$$

These are the general expressions for the gradient force and the scattering force, respectively. One can see that

Also see:

- A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and Steven Chu, 1986
- P. C. Chaumet and M. Nieto-Vesperinas, 2003
- Giuseppe Pesce I, Philip H. Jones, Onofrio M. Maragò, Giovanni Volpe, 2020
- Winstone, Grinin, Bhattacharya, Geraci, Li, Pauzauskie, Vamivakas, 2024

Mathematical framework for simulation of quantum fields in complex interferometers using the two-photon formalism

Thomas Corbitt,¹ Yanbei Chen,^{2,3} and Nergis Mavalvala¹

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³Max-Planck-Institut für Gravitationsphysik, Am Mühlenberg 1, 14476 Golm, Germany

$$\dot{P}_j(\Omega) = \sqrt{\frac{\hbar\omega}{c^2}} \mathbf{D}_j^T \mathbf{j}(\Omega), \quad (30)$$

where we have defined

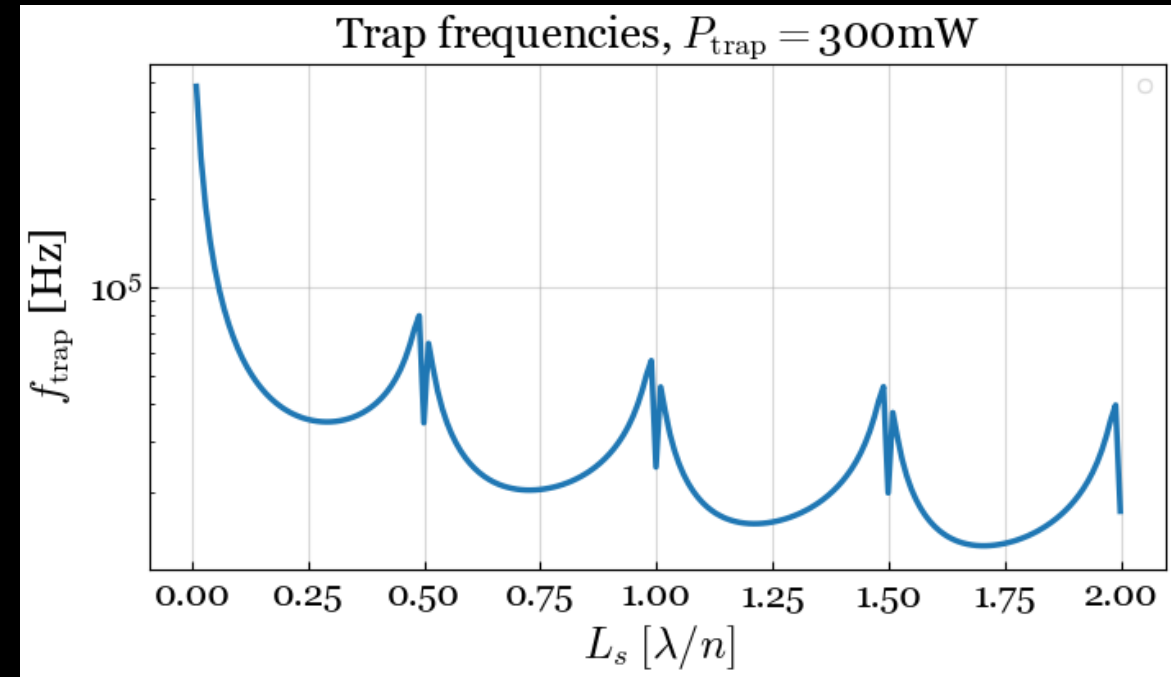
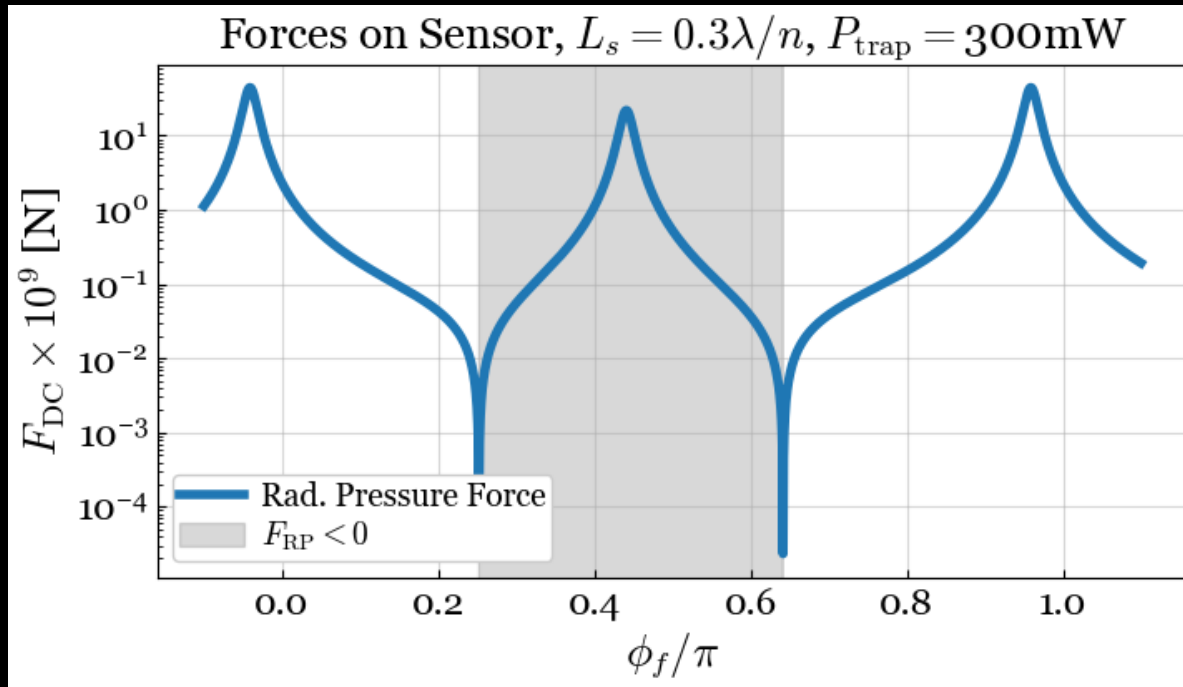
$$\mathbf{D}_j \equiv \sqrt{\frac{\mathcal{A}c}{4\pi}} \mathbf{E}_j^{\text{carrier}} = \sqrt{2I_j} \begin{pmatrix} \cos \theta_j \\ \sin \theta_j \end{pmatrix} \quad (31)$$

as the carrier quadrature field, and $\mathbf{j}(\Omega)$ is the sideband component at angular frequency Ω .

Also see:

- Jackson, E&M
- A. Xuereb, 2009

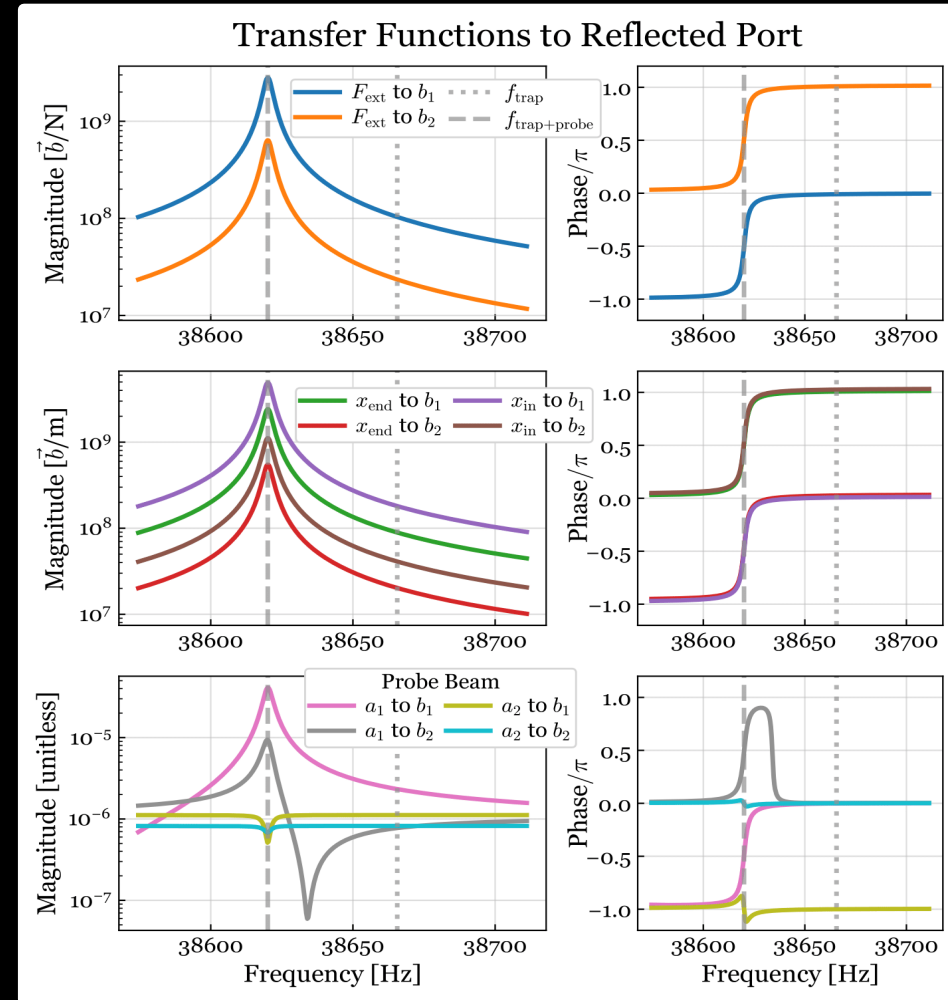
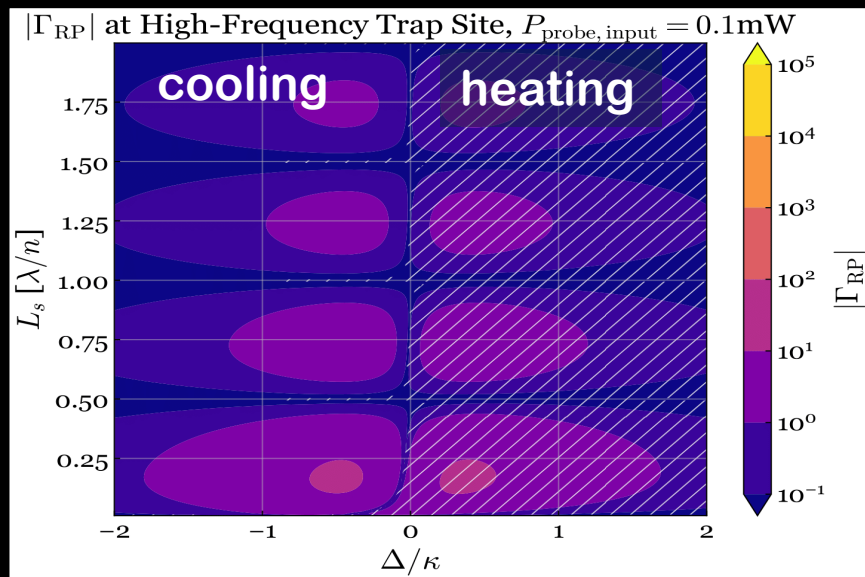
PUTTING IT ALL TOGETHER: LEVITATION FREQUENCY



PUTTING IT ALL TOGETHER: SYSTEM RESPONSE

Full system response includes

- Trap laser
- Sensor
- Cooling/sensing laser



Next: detector noise budgets and optimal operational parameters

AXION POPULATION SIMULATIONS

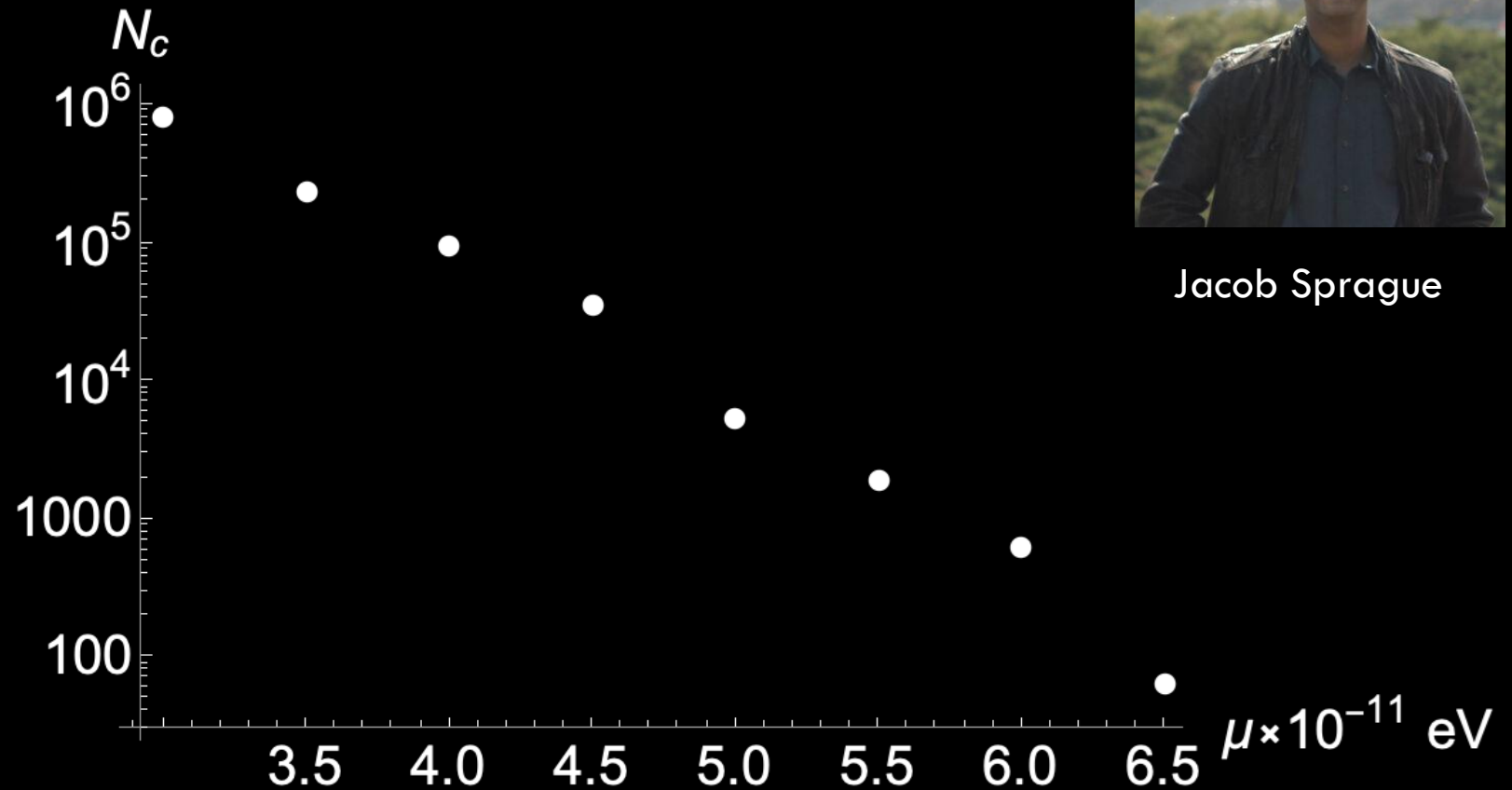
GALACTIC AXION CLOUD POPULATION

1. Fix the axion mass; assume 10^8 BHs in the Milky Way
2. Of these, how many will have an axion cloud?

$$\alpha \equiv GM_{BH}\mu/\hbar c^3$$

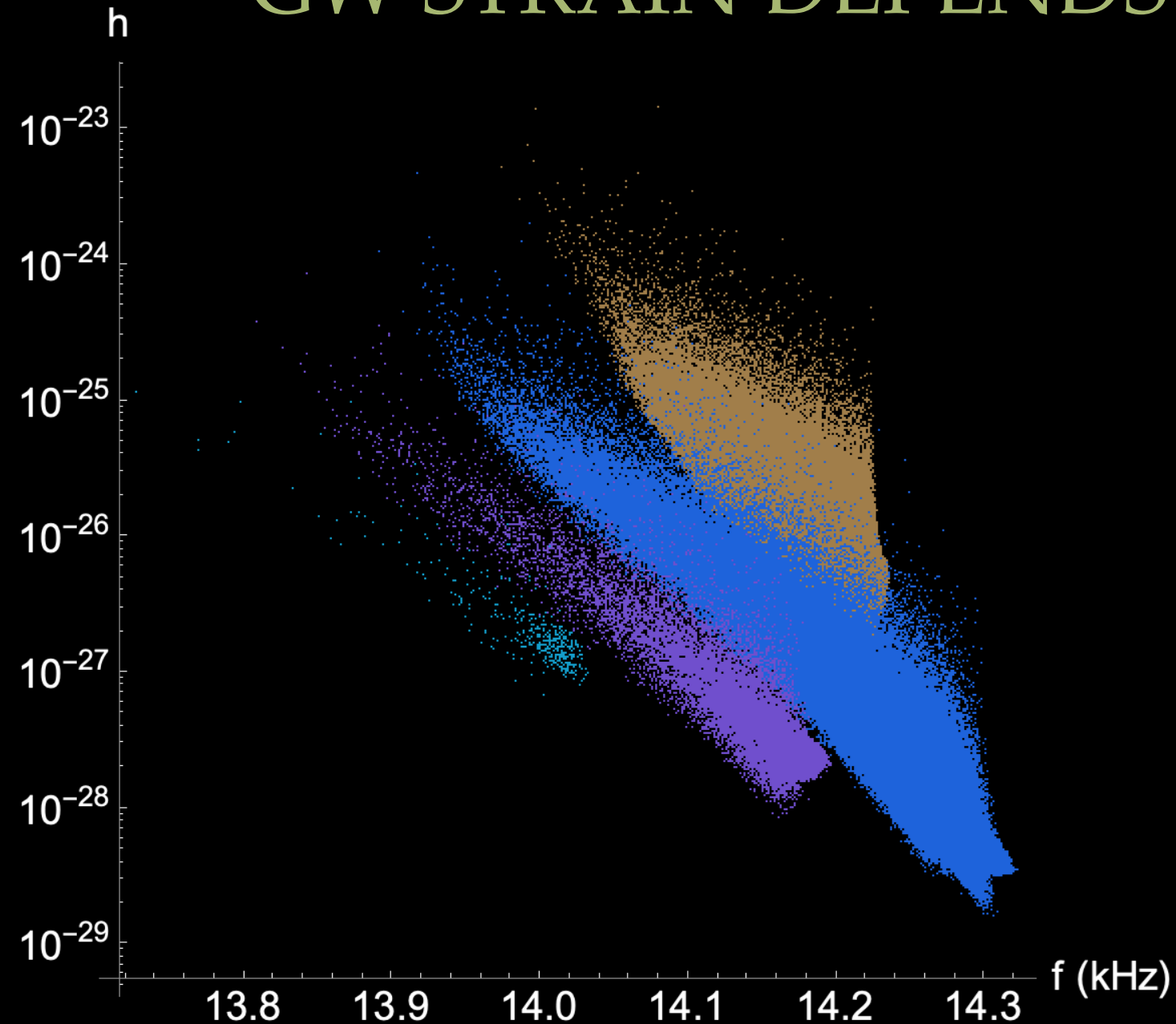
Superradiance when:

$$\alpha \leq \frac{m}{2} \frac{\chi}{1 + \sqrt{1 - \chi^2}}$$



Jacob Sprague

GW STRAIN DEPENDS ON MANY PARAMS



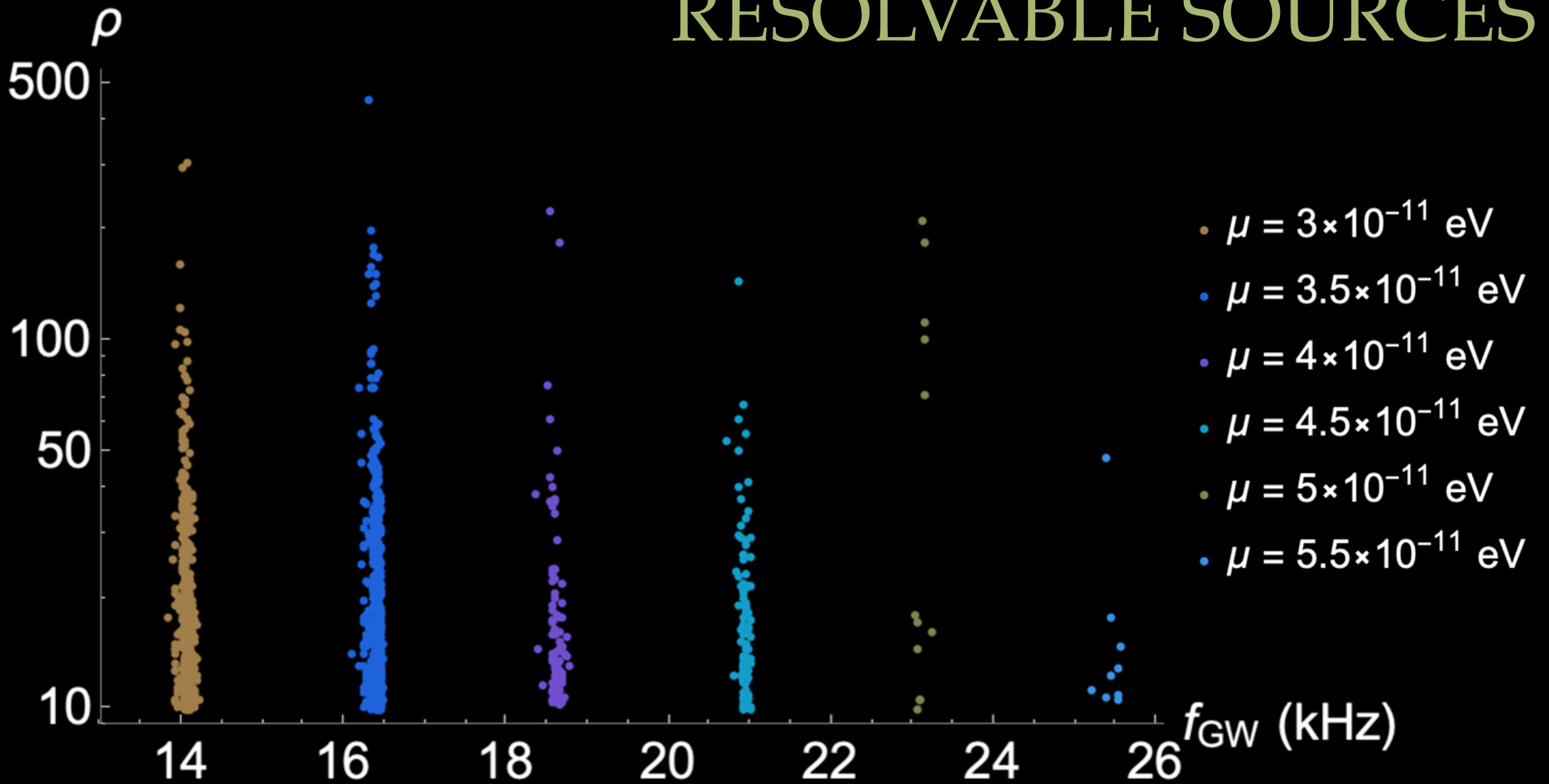
Calculate strain
for each cloud.

- $n = 6$
- $n = 7$
- $n = 8$
- $n = 9$

Example for $\mu =$
 $3 \times 10^{-11} \text{ eV}$

Sprague et al. Phys. Rev. D **110**, 123025
(2024)

RESOLVABLE SOURCES



UNRESOLVEABLE SOURCES

$h_q \sqrt{T_{\text{coh}}} \text{ (Hz}^{-1/2}\text{)}$

