GRAVITATIONAL WAVES AT 10 KHZ TO 300 KHZ

May 18, 2021

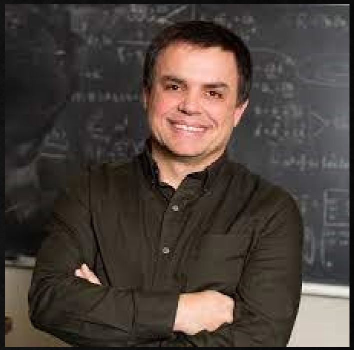
GWADW 2021, The Internets

Nancy Aggarwal
Northwestern University

THANKS…







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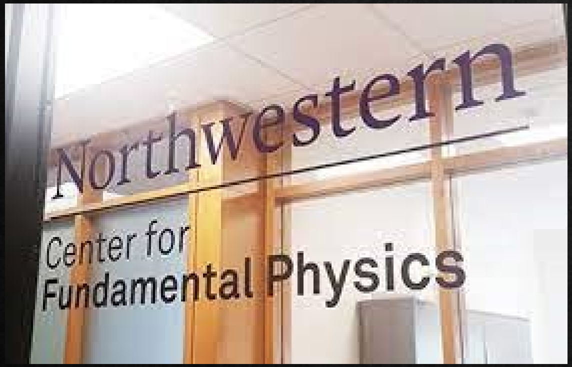


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GRAVITATIONAL WAVES IN OTHER 'COLORS'

Challenges and Opportunities of Gravitational Wave Searches at MHz to GHz Frequencies

N. Aggarwal[a,*], O.D. Aguiar[b], A. Bauswein[c], G. Cella[d], S. Clesse[e], A.M. Cruise[f], V. Domcke[g,h,i,*], D.G. Figueroa[j], A. Geraci[k], M. Goryachev[l], H. Grote[m], M. Hindmarsh[n,o], F. Muia[p,i,*], N. Mukund D. Ottaway[r,s], M. Peloso[t,u], F. Quevedo[p,*], A. Ricciardone[t,u], J. Steinlechner[v,w,x,*], S. Steinlechner S. Sun[y,z], M.E. Tobar[l], F. Torrenti[α], C. Unal[β], G. White[γ]

Aggarwal et al
Arxiv:2011.12414

Abstract

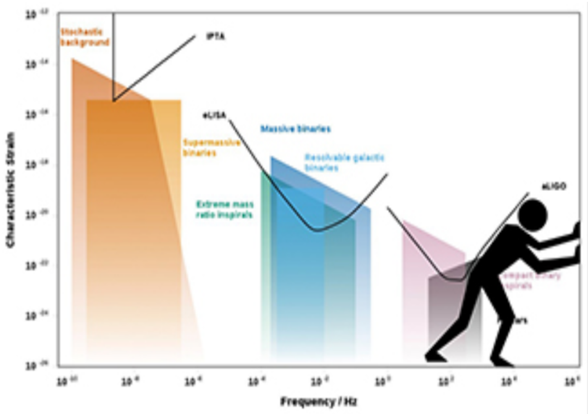
The first direct measurement of gravitational waves by the LIGO and Virgo collaborations has opened up new avenues to explore our Universe. Th… white paper outlines the challenges and gains expected in gravitational wa… …arches at … …ies above the LIGO/Virgo band, with a particular foc… on the MHz and … …e of known astrophysical sources in this frequency rang… …s a uniq… …s beyond the Standard Model operating both … …some of the most promising

See Plenary by Francesco Muia recorded on Monday

Ultra-High-Frequency Gravitational Waves

Goals of the initiative

The first direct detection of gravitational waves by the LIGO and VIRGO collaborations has spawned new avenues for the exploration of the Universe. Currently operating and planned gravitational wave detectors mostly focus on the frequency range below 10 kHz, where signatures from the known astrophysical sources are expected to be discovered. However, based on what happens with the electromagnetic spectrum, there may well be interesting physics to be discovered at every scale of the gravitational wave frequencies. Gravitational waves at frequencies higher than 10 kHz are bound to be sourced by some phenomenon involving beyond the Standard Model physics, such as exotic astrophysical



Background plot generated at gwplotter.com

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

preheating after inflation and phase transitions at high energies - would leave their imprint in the gravitational wave … above the LIGO/VIRGO

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

HIGH FREQUENCY GRAVITATIONAL WAVE DETECTORS

Technical concept	Frequency	Proposed sensitivity (dimensionless)	Proposed sensitivity $\sqrt{S_n(f)}$
Spherical resonant mass, Sec. 4.1.3 [282]			
Mini-GRAIL (built) [289]	2942.9 Hz	10^{-20} $2.3 \cdot 10^{-23}$ $(*)$	$5 \cdot 10^{-20}\,\mathrm{Hz}^{-\frac{1}{2}}$ $10^{-22}\,\mathrm{Hz}^{-\frac{1}{2}}$ $(*)$
Schenberg antenna (built) [286]	3.2 kHz	$2.6 \cdot 10^{-20}$ $2.4 \cdot 10^{-23}$ $(*)$	$1.1 \cdot 10^{-19}\,\mathrm{Hz}^{-\frac{1}{2}}$ $10^{-22}\,\mathrm{Hz}^{-\frac{1}{2}}$ $(*)$
Laser interferometers			
NEMO (devised), Sec. 4.1.1 [25, 272]	[1 – 2.5] kHz	$9.4 \cdot 10^{-26}$	$10^{-24}\,\mathrm{Hz}^{-\frac{1}{2}}$
Akutsu's proposal (built), Sec. 4.1.2 [277, 328]	100 MHz	$7 \cdot 10^{-14}$ $2 \cdot 10^{-19}$ $(*)$	$10^{-16}\,\mathrm{Hz}^{-\frac{1}{2}}$ $10^{-20}\,\mathrm{Hz}^{-\frac{1}{2}}$ $(*)$
Holometer (built), Sec. 4.1.2 [279]	[1 – 13] MHz	$8 \cdot 10^{-22}$	$10^{-21}\,\mathrm{Hz}^{-\frac{1}{2}}$
Optically levitated sensors, Sec. 4.2.1 [59]			
1-meter prototype (under construction)	(10 – 100) kHz	$2.4 \cdot 10^{-20} - 4.2 \cdot 10^{-22}$	$(10^{-19} - 10^{-21})\,\mathrm{Hz}^{-\frac{1}{2}}$
100-meter instrument (devised)	(10 – 100) kHz	$2.4 \cdot 10^{-22} - 4.2 \cdot 10^{-24}$	$(10^{-21} - 10^{-23})\,\mathrm{Hz}^{-\frac{1}{2}}$
Inverse Gertsenshtein effect, Sec. 4.2.2			
GW-OSQAR II (built) [297]	[200 – 800] THz	$h_{c,n} \simeq 8 \cdot 10^{-26}$	×
GW-CAST (built) [297]	$[0.5 - 1.5]\,10^6$ THz	$h_{c,n} \simeq 7 \cdot 10^{-28}$	×
GW-ALPs II (devised) [297]	[200 – 800] THz	$h_{c,n} \simeq 2.8 \cdot 10^{-30}$	×
Resonant polarization rotation, Sec. 4.2.4 [307]			
Cruise's detector (devised) [308]			

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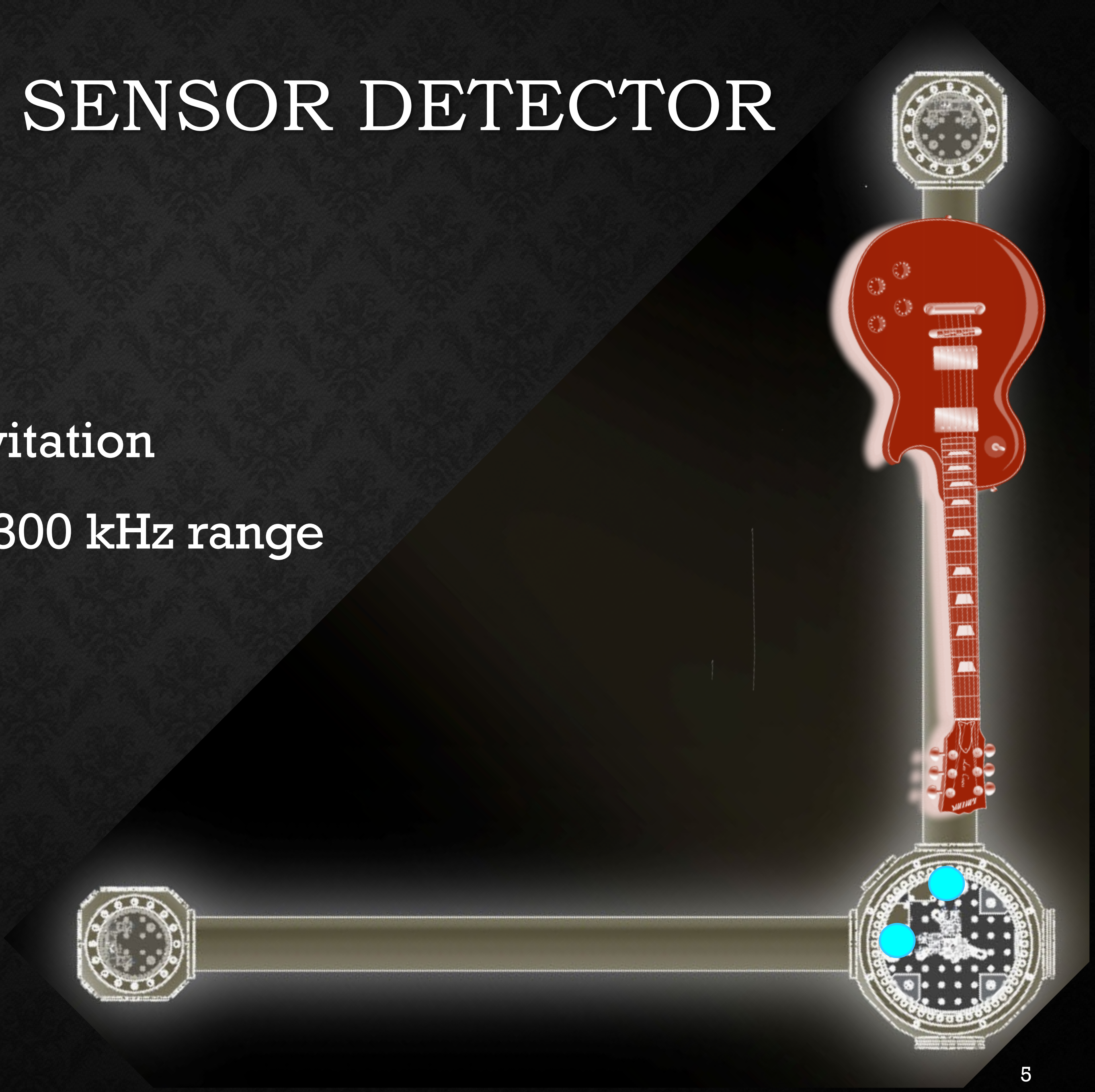
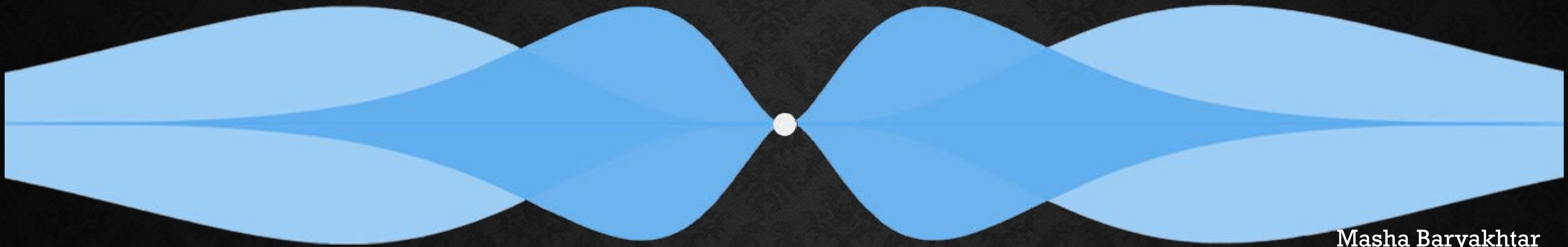
LEVITATED SENSOR DETECTOR

- Miniature GW detector
- Based on optical trapping/levitation
- Tunable resonance in the 10-300 kHz range



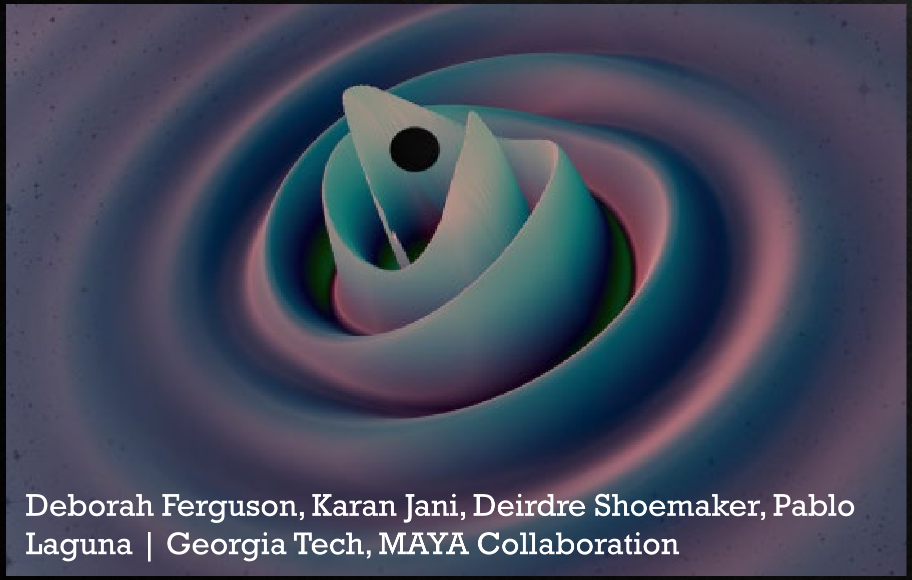
SCIENCE CASE

BH Superradiance



Masha Baryakhtar

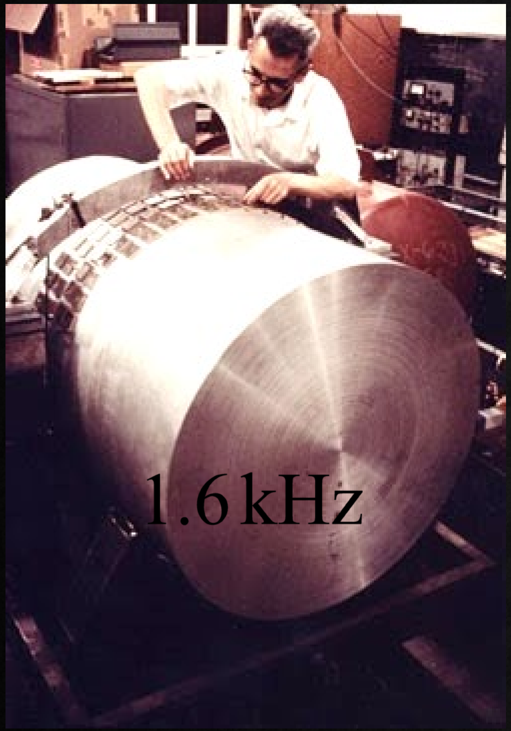
Primordial black holes

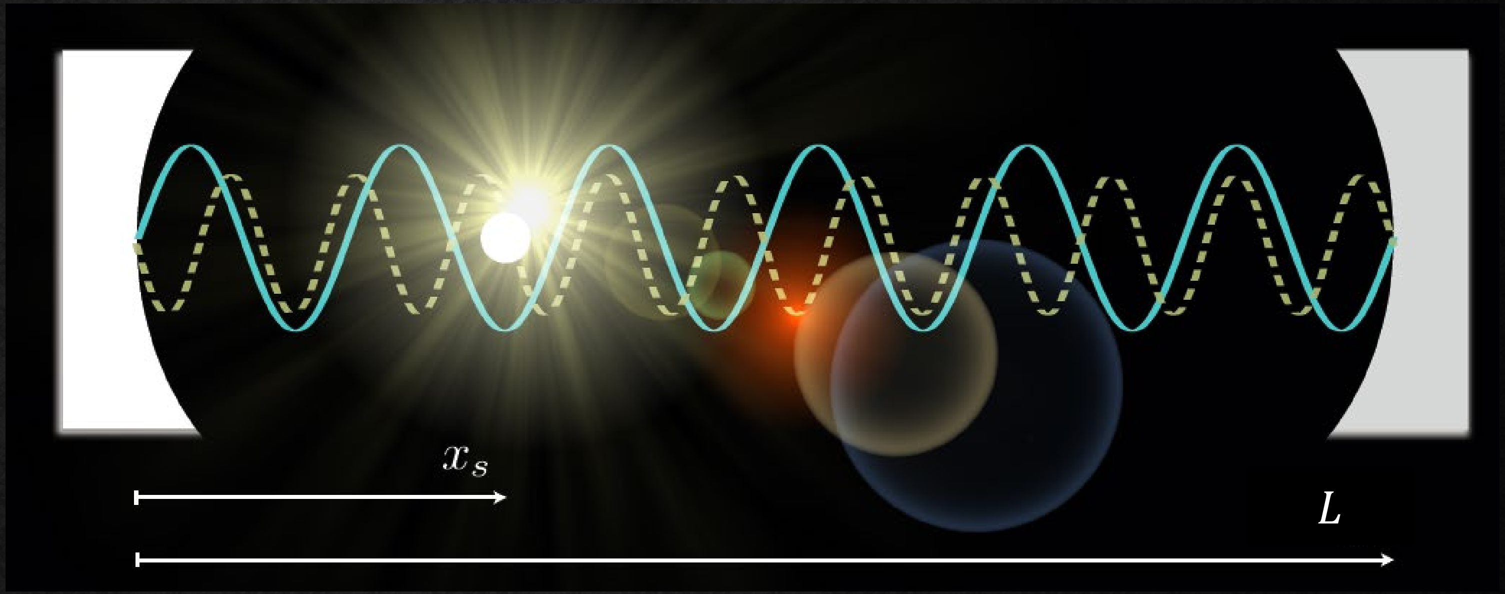


Deborah Ferguson, Karan Jani, Deirdre Shoemaker, Pablo Laguna | Georgia Tech, MAYA Collaboration

The unknown unknowns???

GW DETECTOR USING OPTICAL TRAPS





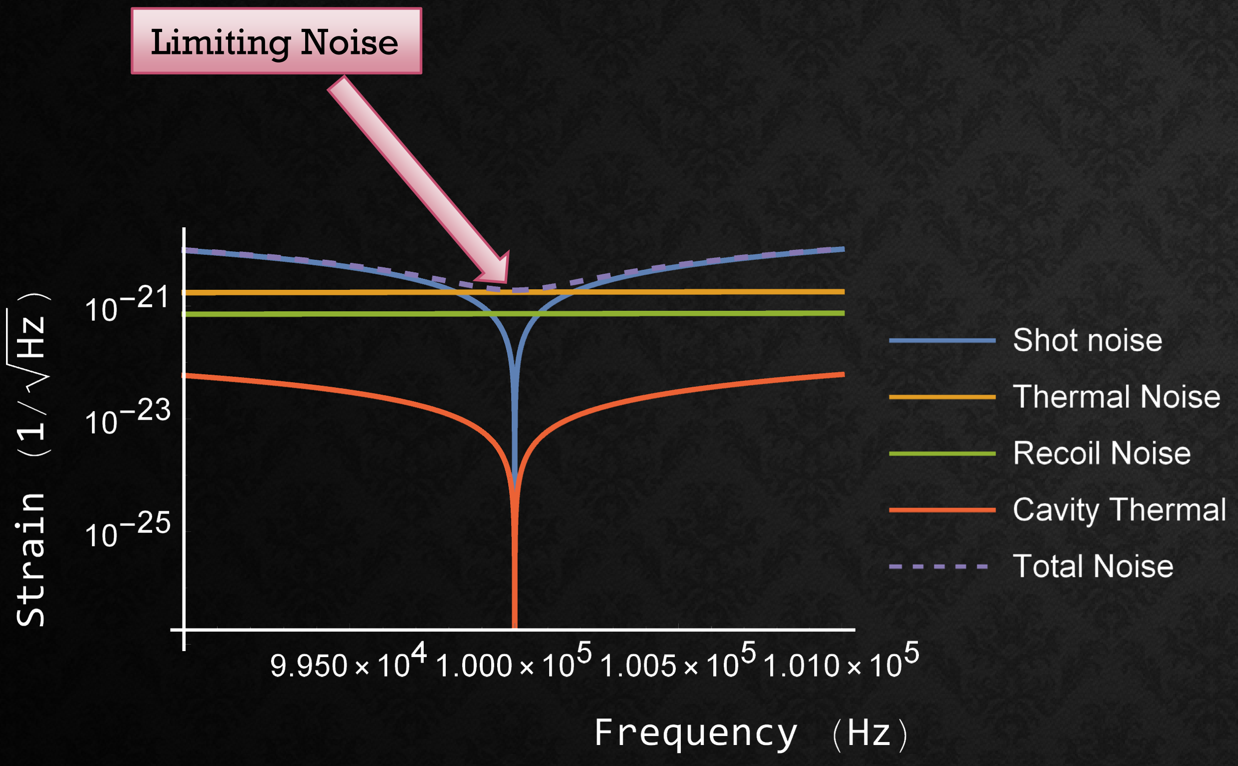
Arvanitaki and Geraci, PRL 110, 071105 (2013)

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

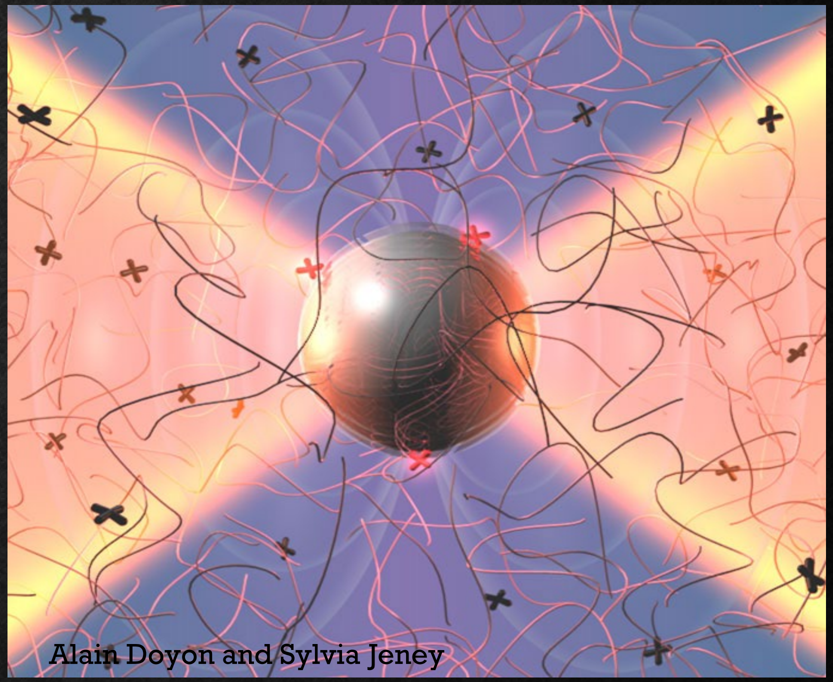
$$\Delta x_{GW} = \Delta x_s - \Delta x_a = \frac{h}{2}(x_s - L), \text{ maximized at } x_s \to 0$$

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

NOISE



Preliminary Aggarwal et al



- Thermal noise from gas damping
  - $S_{FF,thermal} = 4\, k_B\, T\, m\, \gamma_g$
- Quantum noise from photon recoil
  - $S_{FF,Recoil} = 4\, \hbar\omega\, m\, \gamma_{sc}$

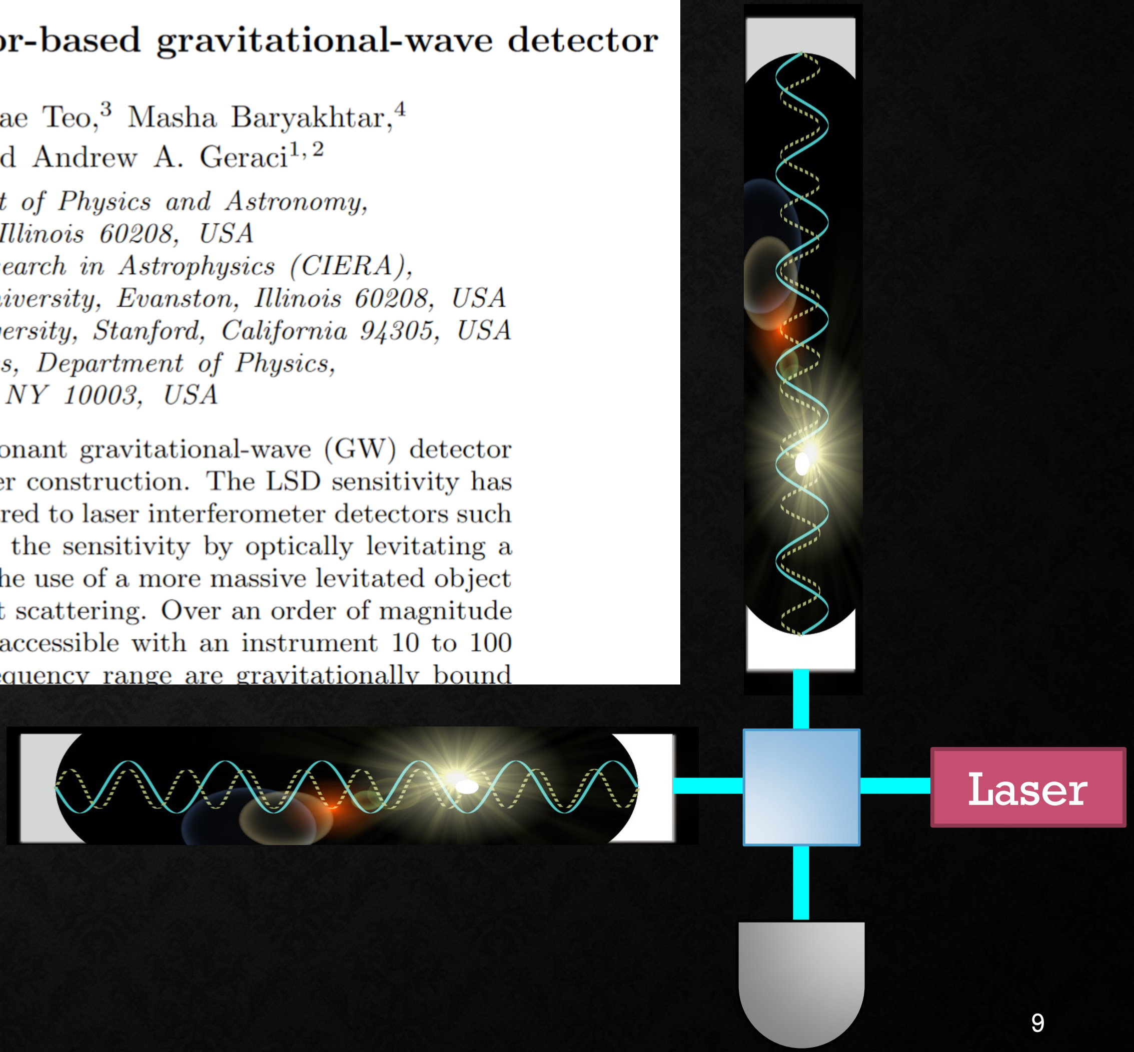
HONING THE NOISE AND REFINING SIGNAL CALCULATIONS

Searching for new physics with a levitated-sensor-based gravitational-wave detector

Nancy Aggarwal,[1,2] George P. Winstone,[1] Mae Teo,[3] Masha Baryakhtar,[4]
Shane L. Larson,[2] Vicky Kalogera,[2] and Andrew A. Geraci[1,2]

[1] *Center for Fundamental Physics, Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA*
[2] *Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA*
[3] *Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA*
[4] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*

The Levitated Sensor Detector (LSD) is a compact resonant gravitational-wave (GW) detector based on optically trapped dielectric particles that is under construction. The LSD sensitivity has more favorable frequency scaling at high frequencies compared to laser interferometer detectors such as LIGO. We propose a method to substantially improve the sensitivity by optically levitating a multi-layered stack of dielectric discs. These stacks allow the use of a more massive levitated object while exhibiting minimal photon recoil heating due to light scattering. Over an order of magnitude of unexplored frequency space for GWs above 10 kHz is accessible with an instrument 10 to 100 meters in size. Particularly motivated sources in this frequency range are gravitationally bound



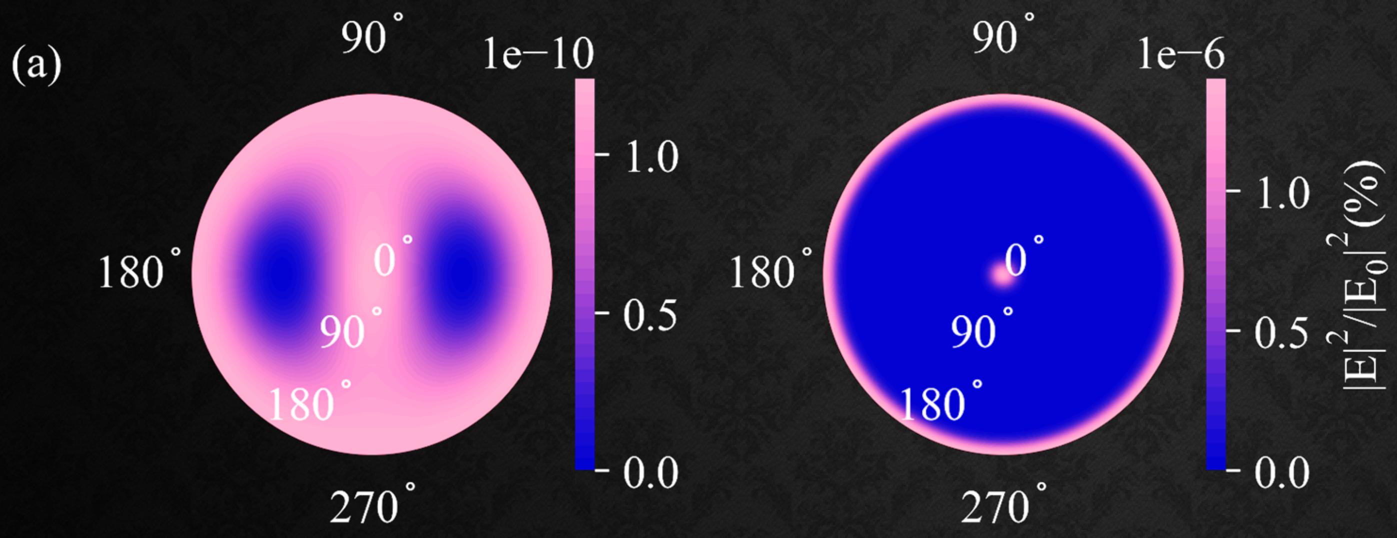
Aggarwal et al
arxiv:2010.13157

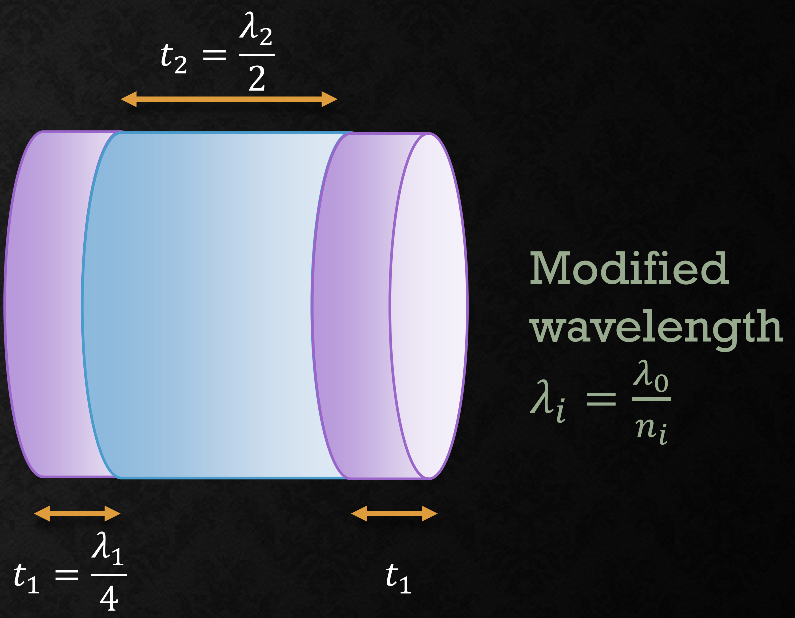
LIMITING NOISE

- Limiting noise source is gas damping and photon recoil.
- $S_{FF} = 4\,M\,(k_B T\ \gamma_g + \hbar\,\omega\,\gamma_{sc})$
- Limit on resonance $(\Omega \to \Omega_T)$, $S_{hh} \sim 16\,\frac{1}{\Omega_T^2}\frac{1}{M}\frac{1}{L^2}(\hbar\,\omega\,\gamma_{sc} + k_B T\,\gamma_g)$

temperature T ↓ length L ↑ recoil γ_{sc} ↓ mass M ↑

REDUCING LIMITING NOISES

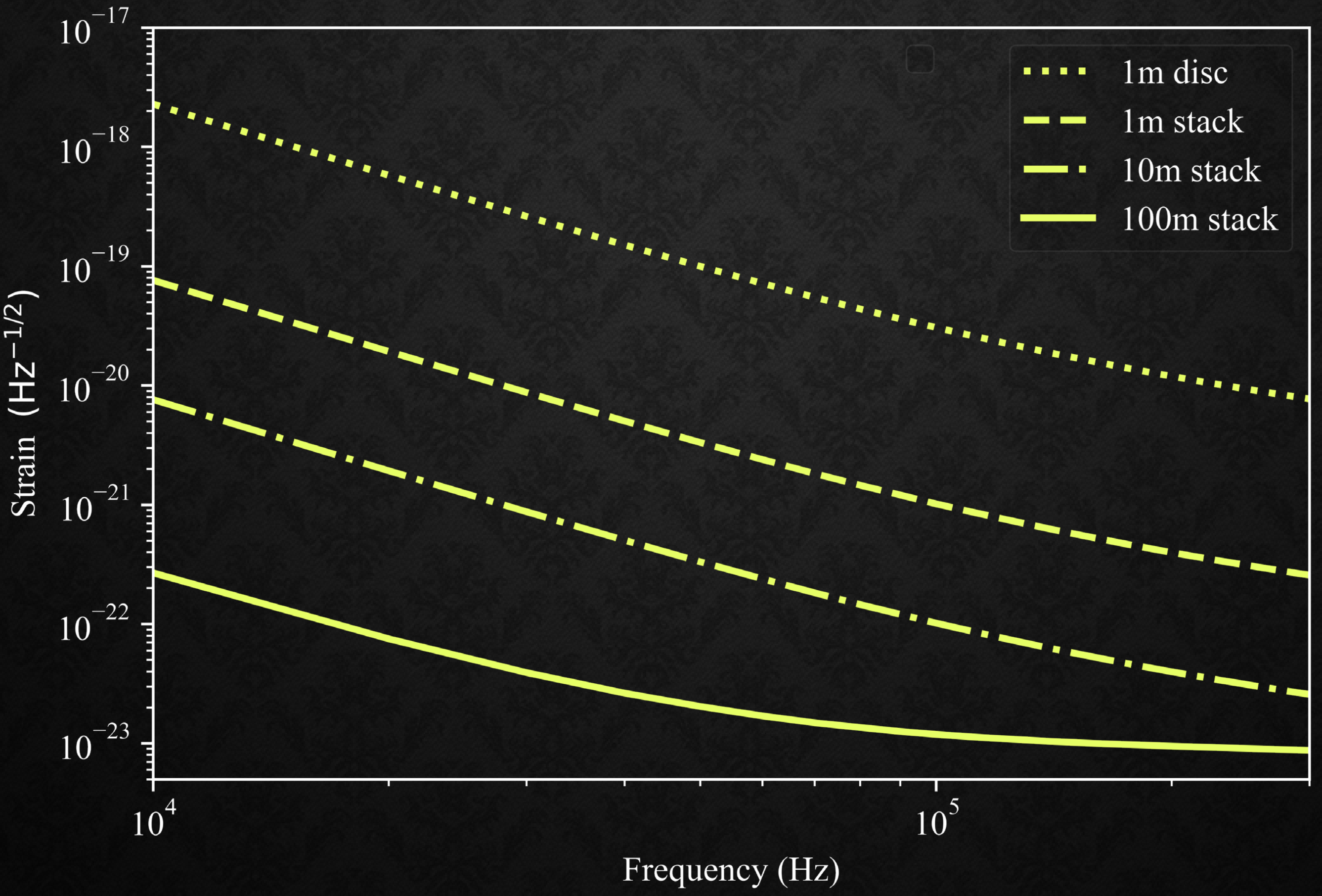




- Sphere scatters light in all directions
- Disk scatters light in the beam direction (low γ_{sc})
- Numerical simulations of scattering from disks show low scattering loss, hence low recoil heating
- Diffraction-limited mirror sizes big enough to achieve negligible scattering loss
- Stacked disks to increase mass (high M)

Aggarwal et al arxiv:2010.13157

IMPROVED SENSITIVITY



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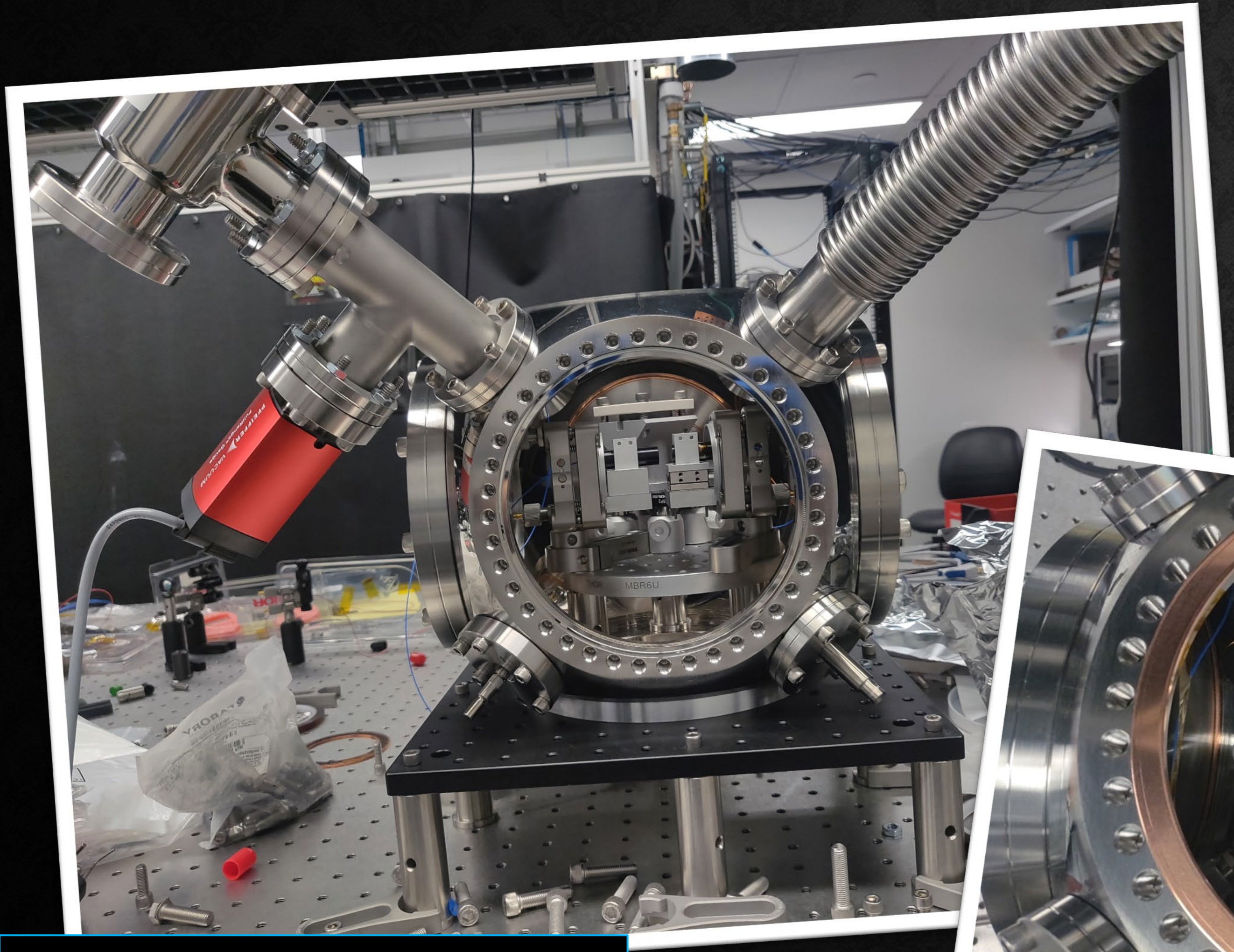
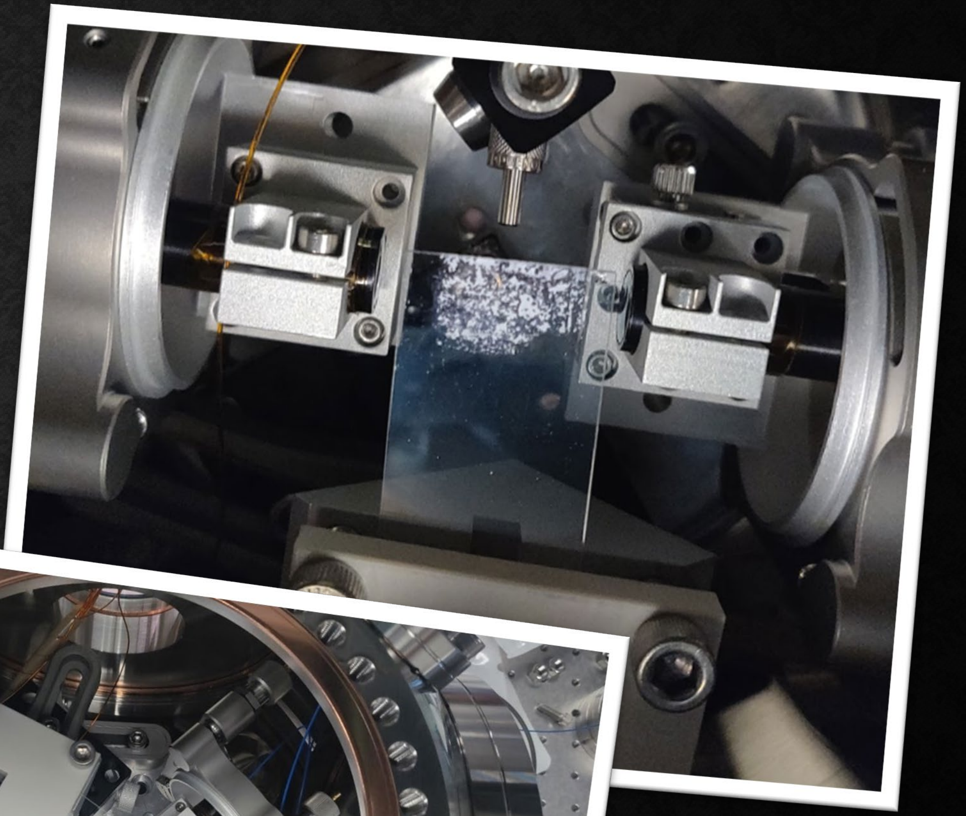
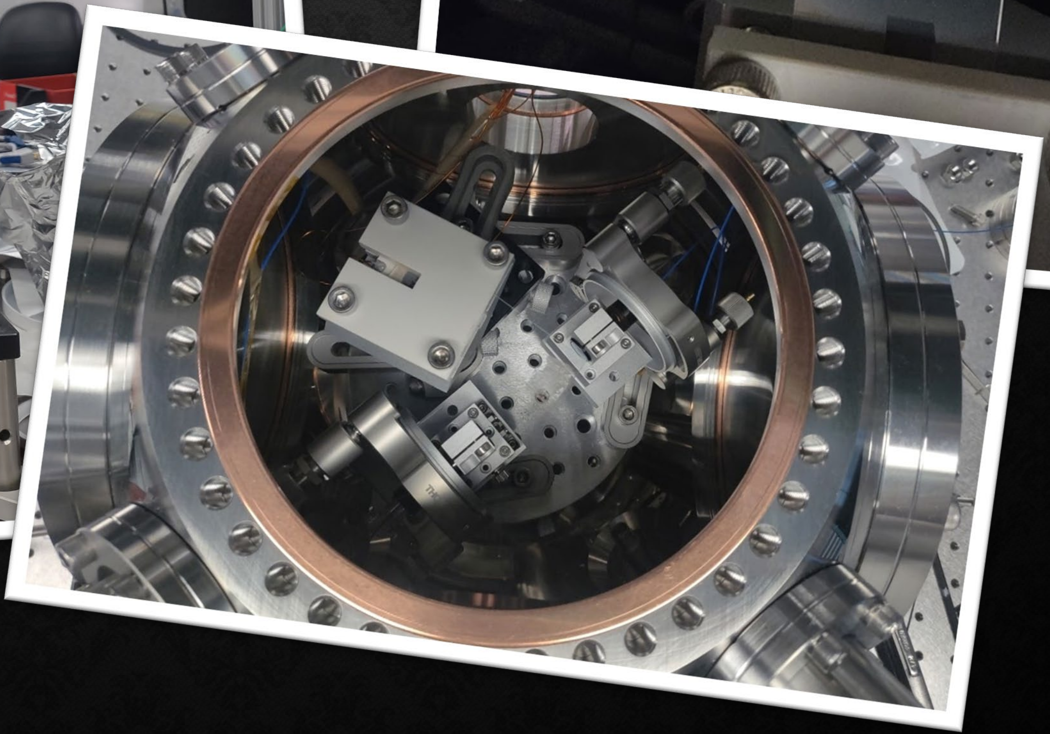
IN THE LAB…

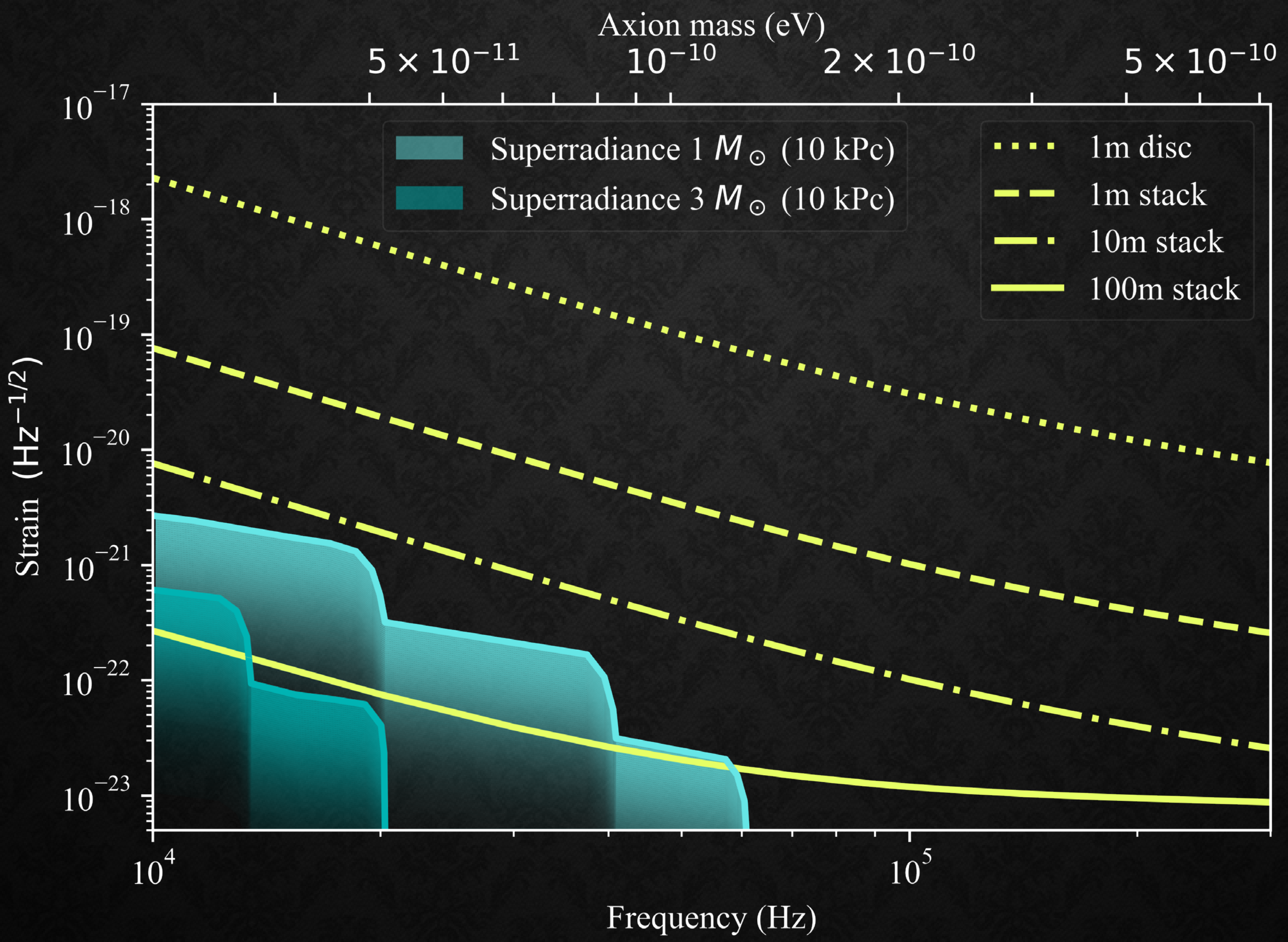






Picture Credits: George Winstone, Daniel Grass, Aaron Wang, and Shelby Klomp

SENSITIVITY TO BH SUPERRADIANCE



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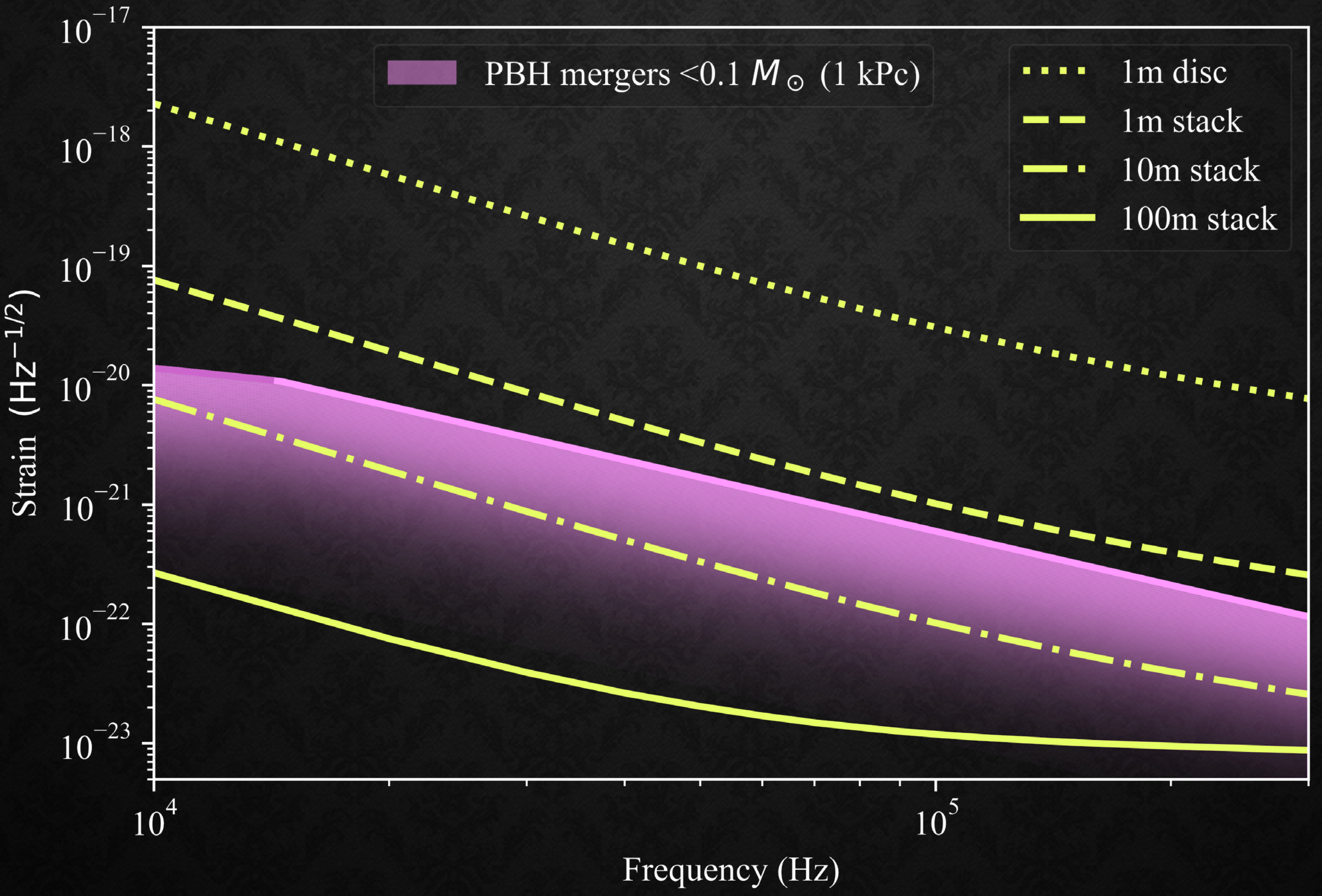
SENSITIVITY TO BLACKHOLE MERGERS



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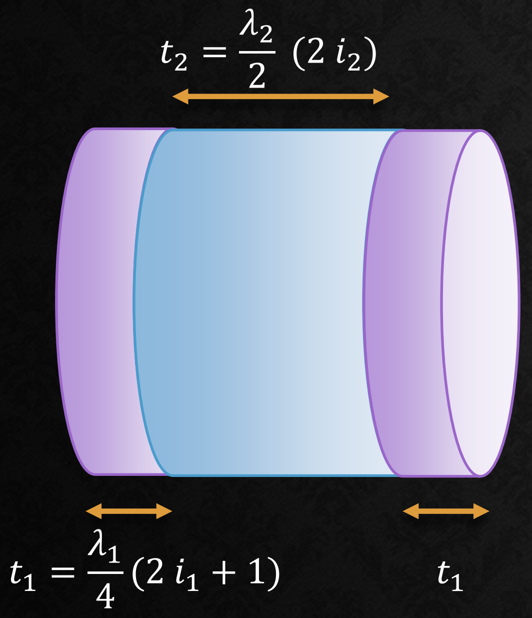
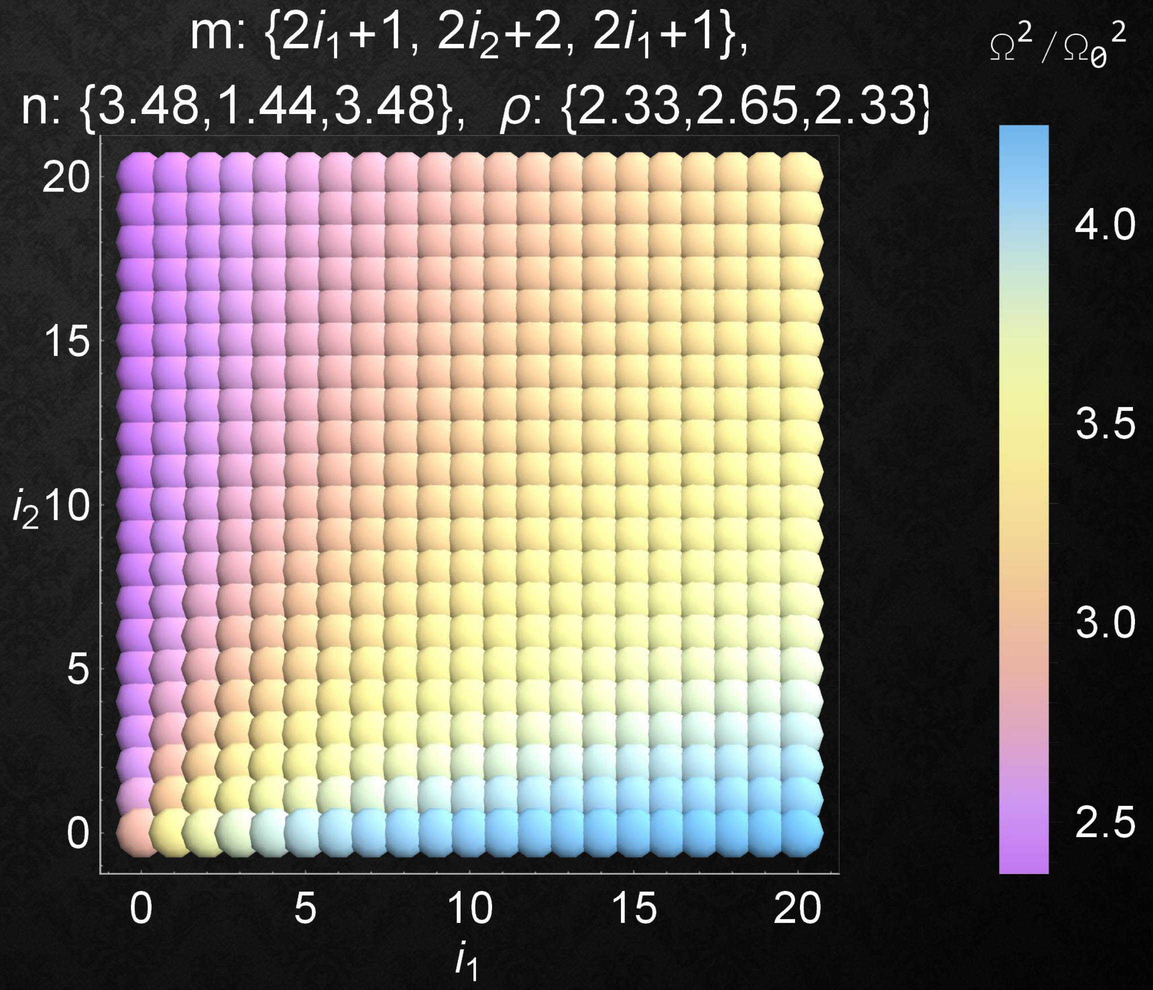
ADD MORE MASS!!



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

$$\Omega_0^2 = \frac{8\pi P\left(1 - e^{-2R^2/w^2}\right)}{c\lambda^2 \rho_0 R^2}$$



Preliminary: Aggarwal et al.

SUMMARY

- New initiative for high-frequency GW detectors
- Miniature GW detector based on levitated nanoparticles to probe GWs in 10 kHz – 300 kHz band
- Limited by gas damping and photon recoil
- Proposed new design with 20 times improved sensitivity and theoretically verified feasibility
- Will set independent limits on BH superradiance and Primordial black holes
- Further improvements can be achieved by xylophone configuration and/or increasing the mass

THANK YOU