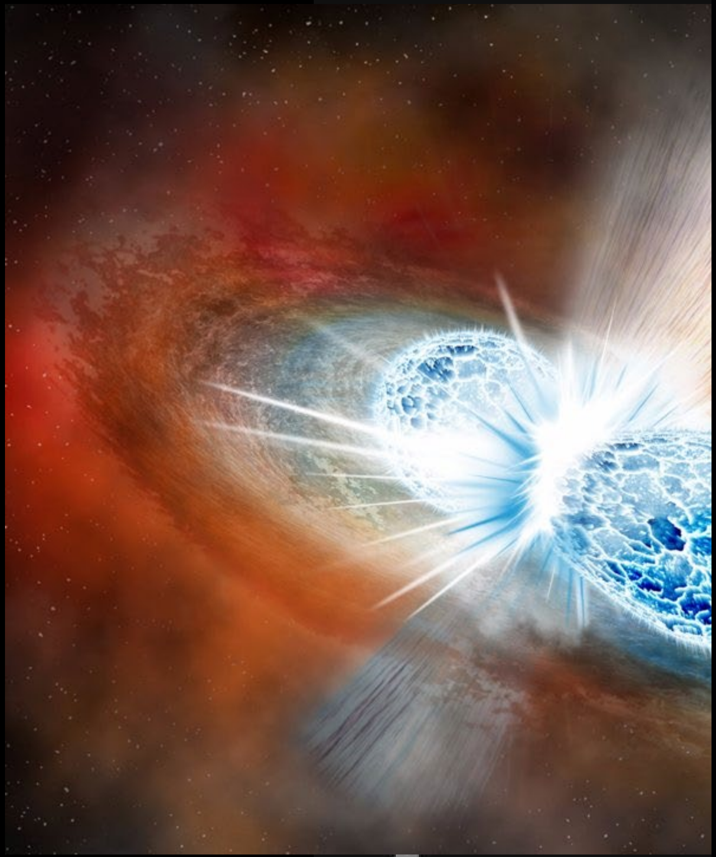
Gravitational waves unlocking fundamental physics

CMSA Workshop on Phase Transitions and Topological Defects

Aug 2, 2022

Nancy Aggarwal
Northwestern University

ASTROPHYSICS AND COSMOLOGY USING LIGO-VIRGO



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

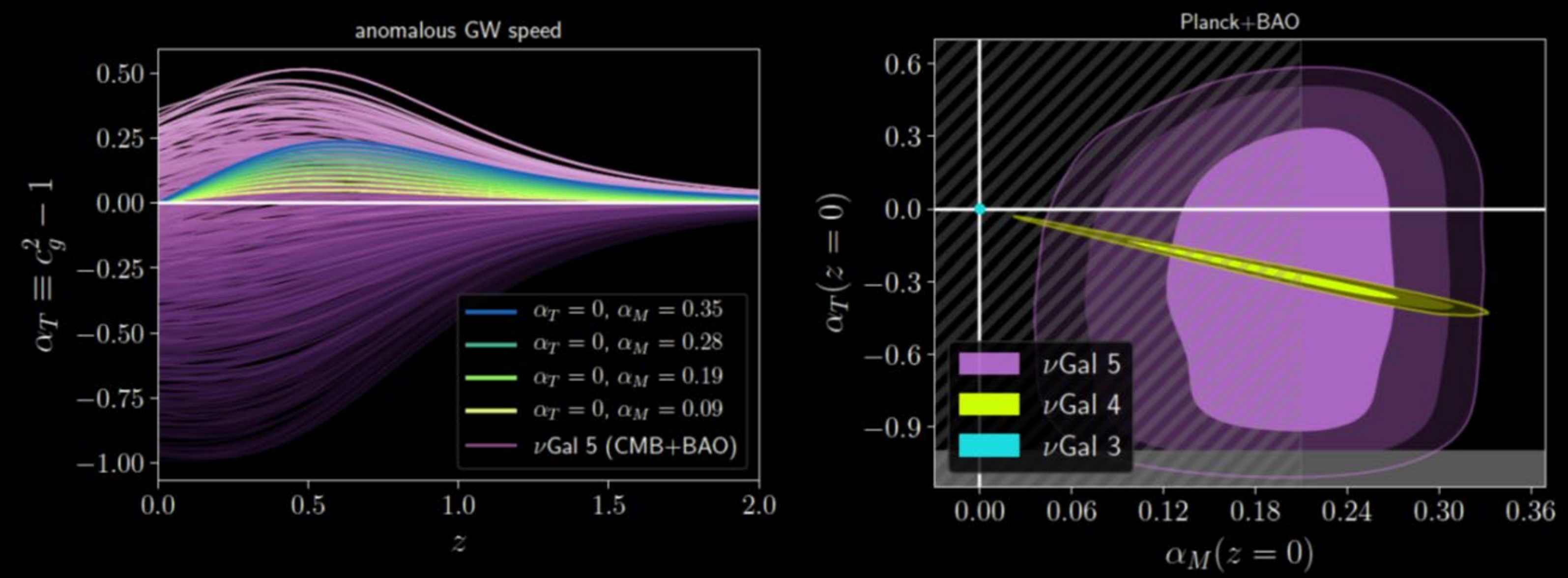
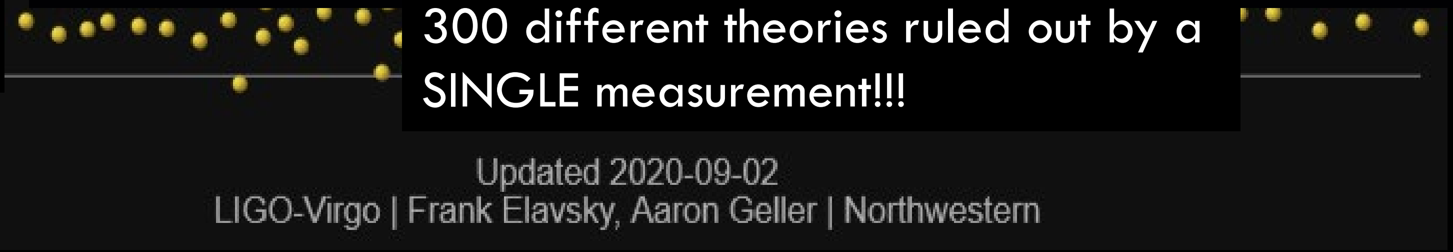


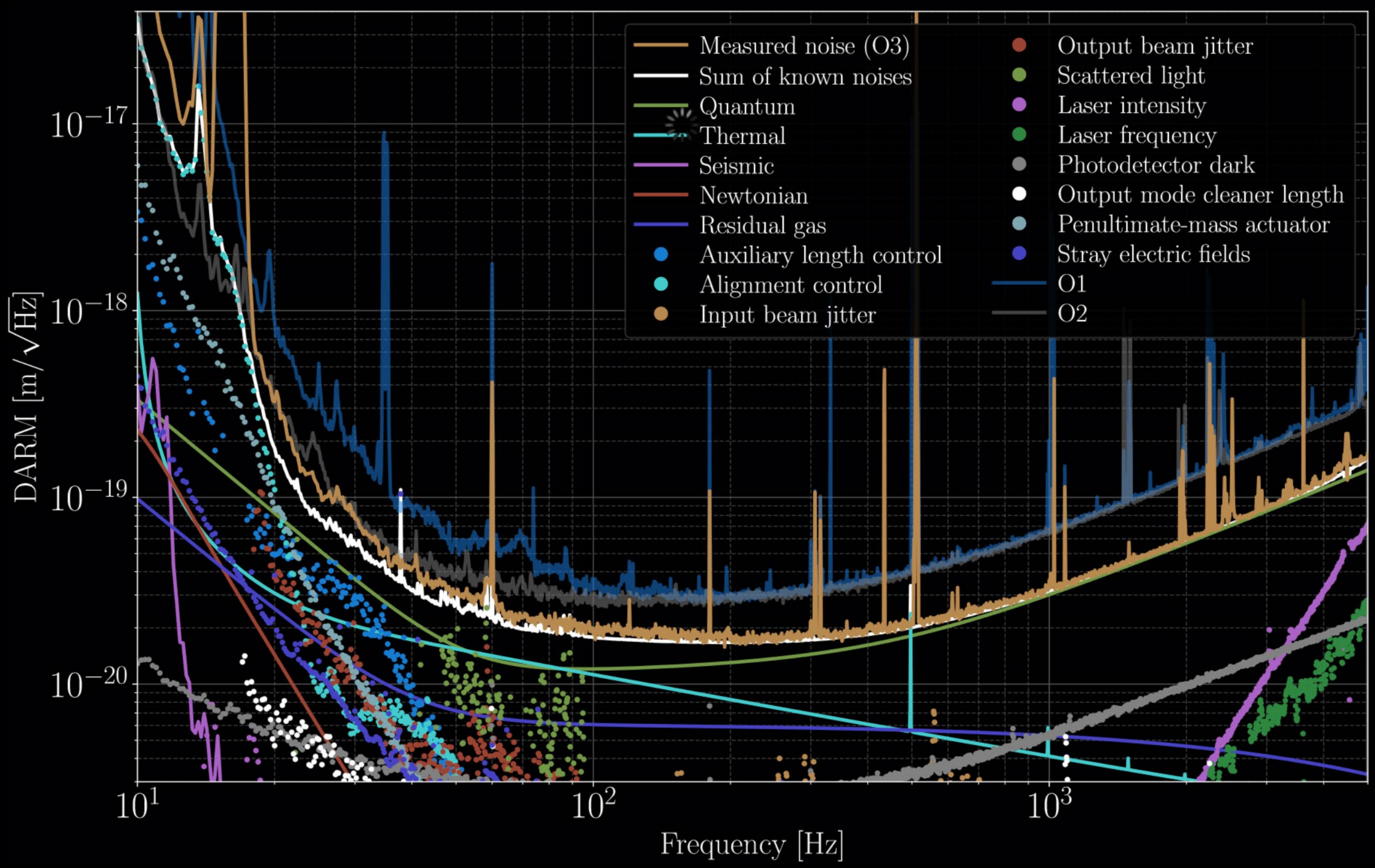
FIG. 1: **Left:** time evolution of the tensor speed excess α_T as a function of redshift for 300 different realizations of viable quintic Galileon cosmologies. Only quintic fine tuned cases (colored) predict $\alpha_T(z=0) \approx 0$. **Right:** 1, 2 and 3σ confidence regions of the parameter space 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.

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



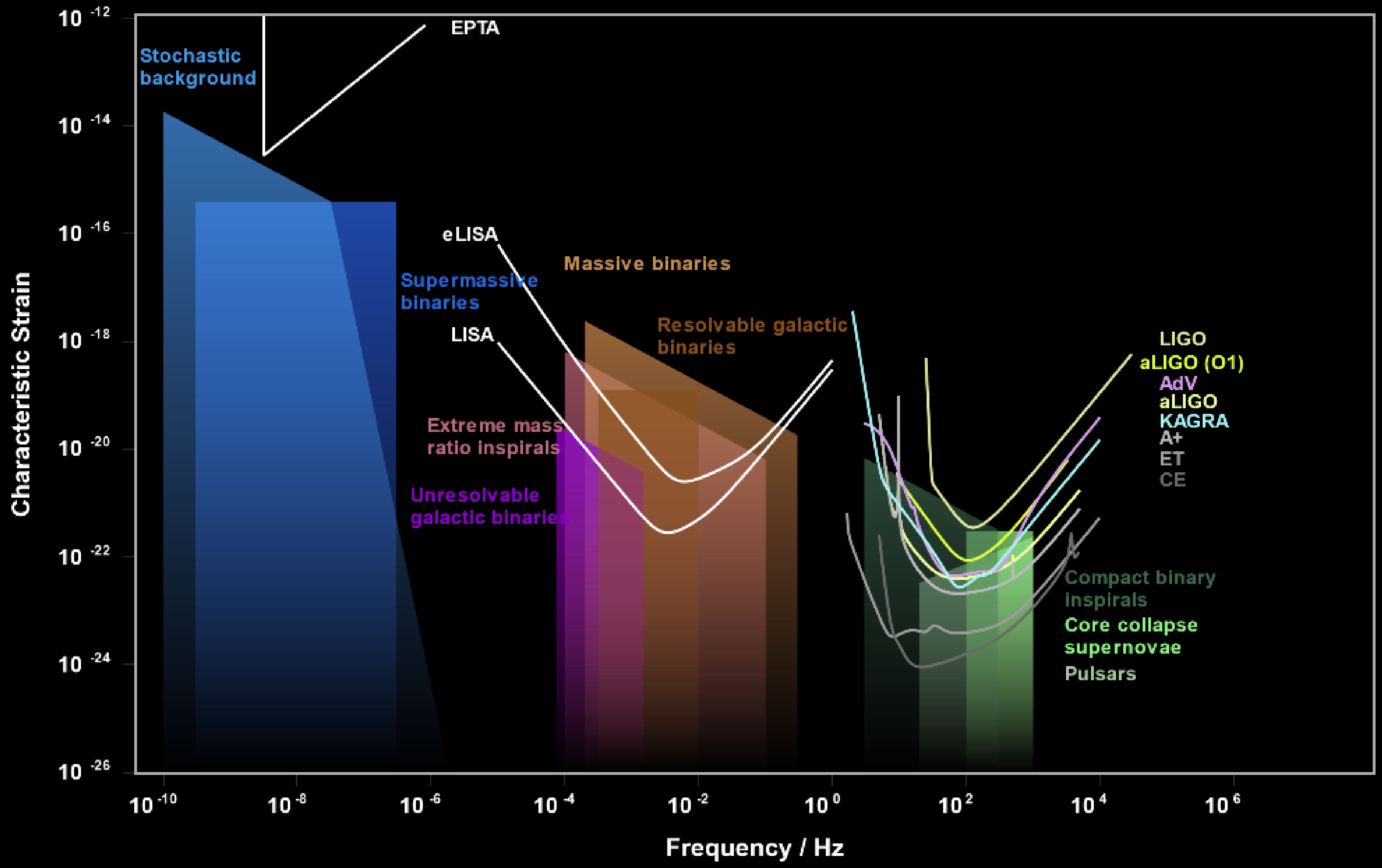
Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

MOST SENSITIVE DISPLACEMENT MEASUREMENT



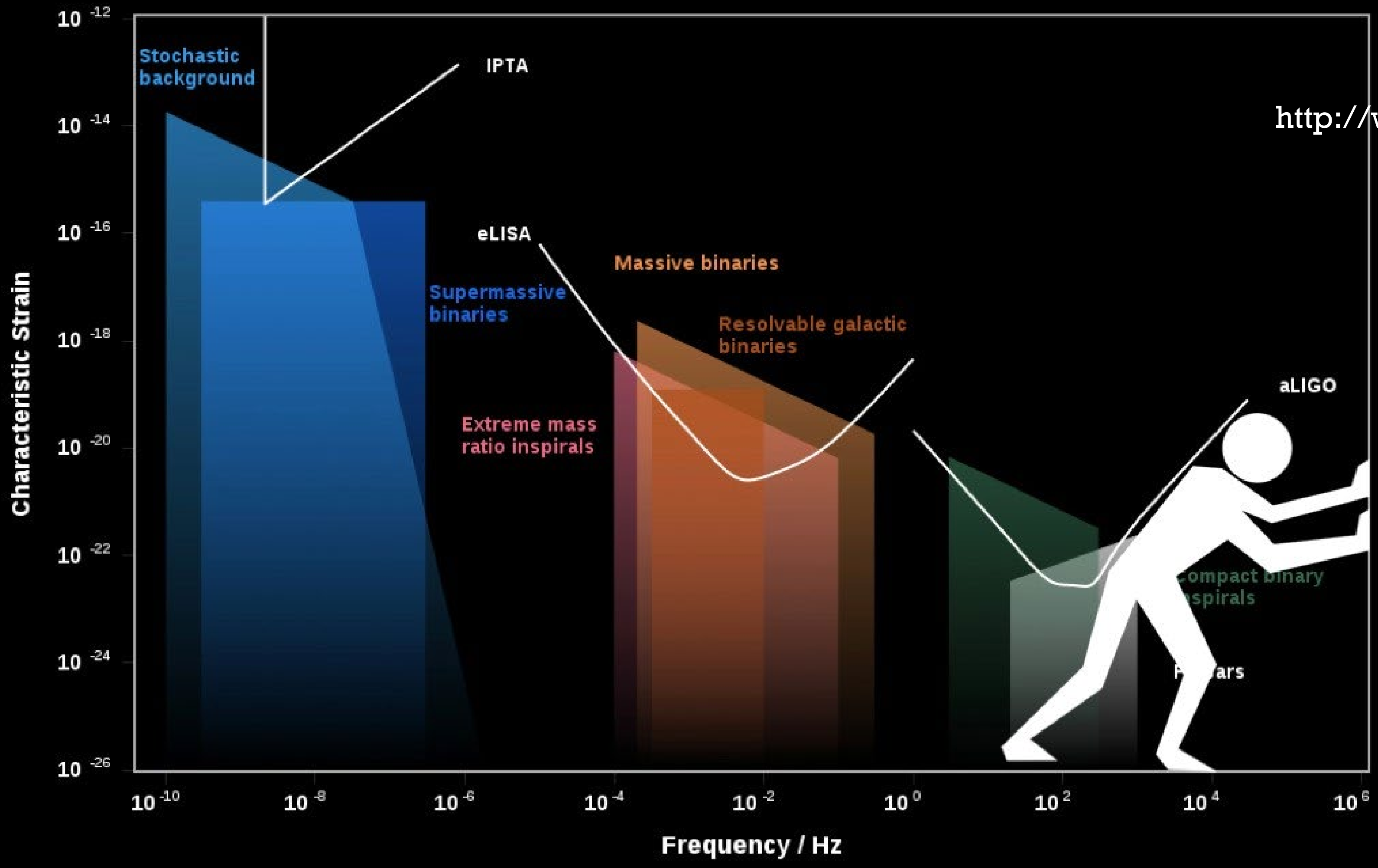
Sensitivity and performance of the Advanced LIGO detectors in the third observing run
A. Buikema *et al.*
Phys. Rev. D 102, 062003 – Published 11 September 2020

GW ASTRONOMY & COSMOLOGY BELOW THE AUDIO BAND



Credit: gwplotter

GWS ABOVE THE AUDIO BAND?

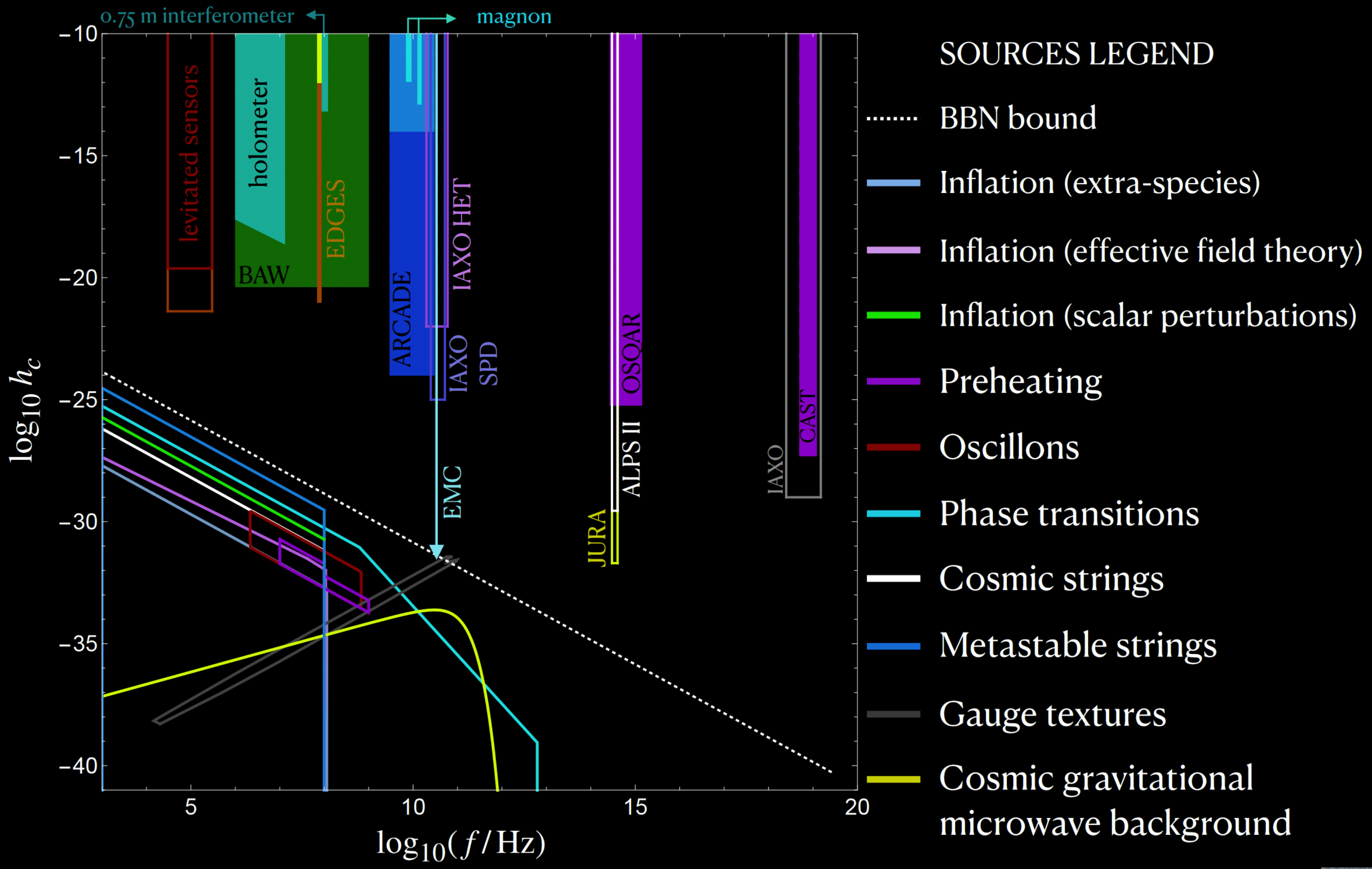


http://www.ctc.cam.ac.uk/activities/UHF-GW.php

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

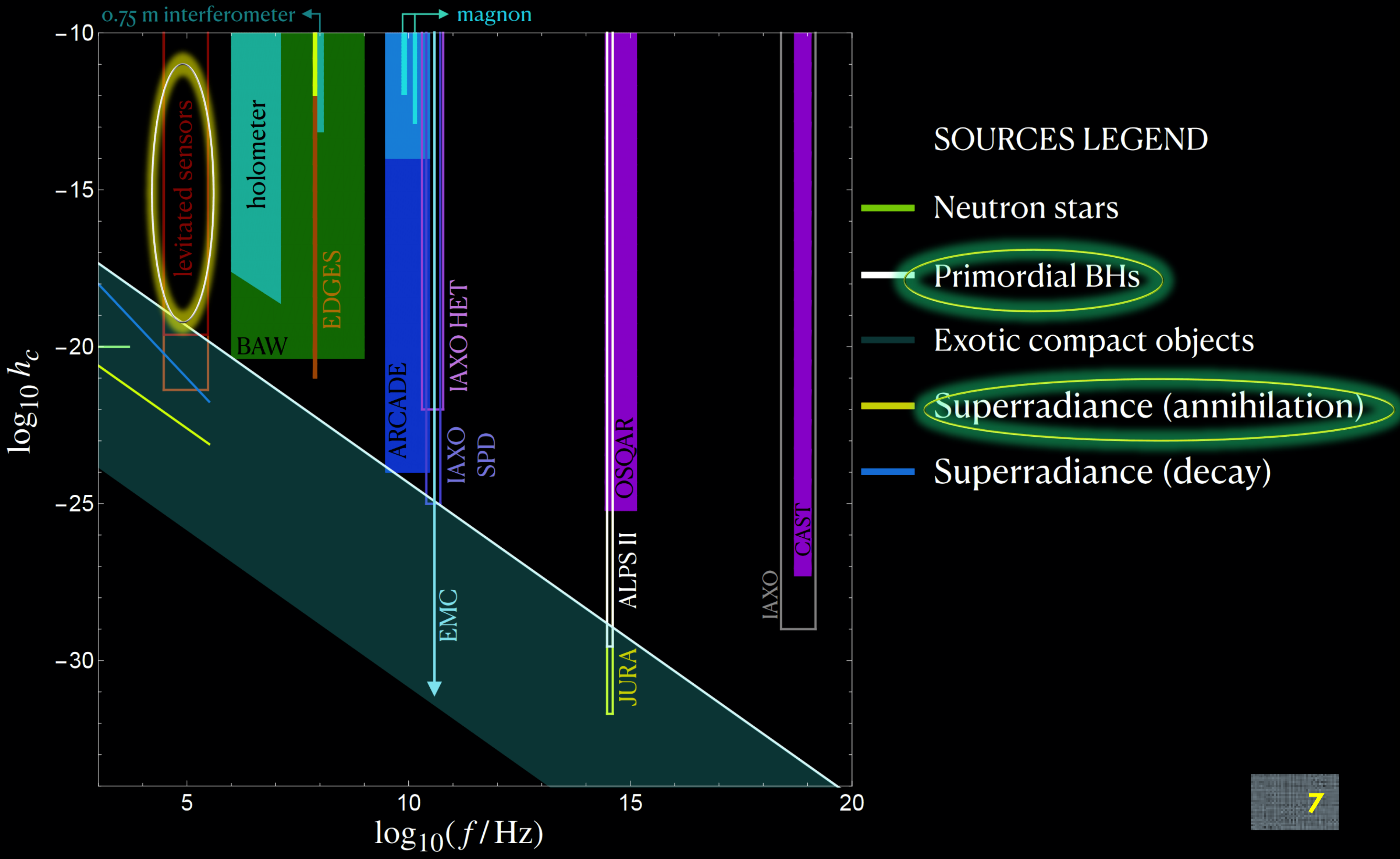
NEW INITIATIVE FOCUSES ON GWS ABOVE AUDIO BAND

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).

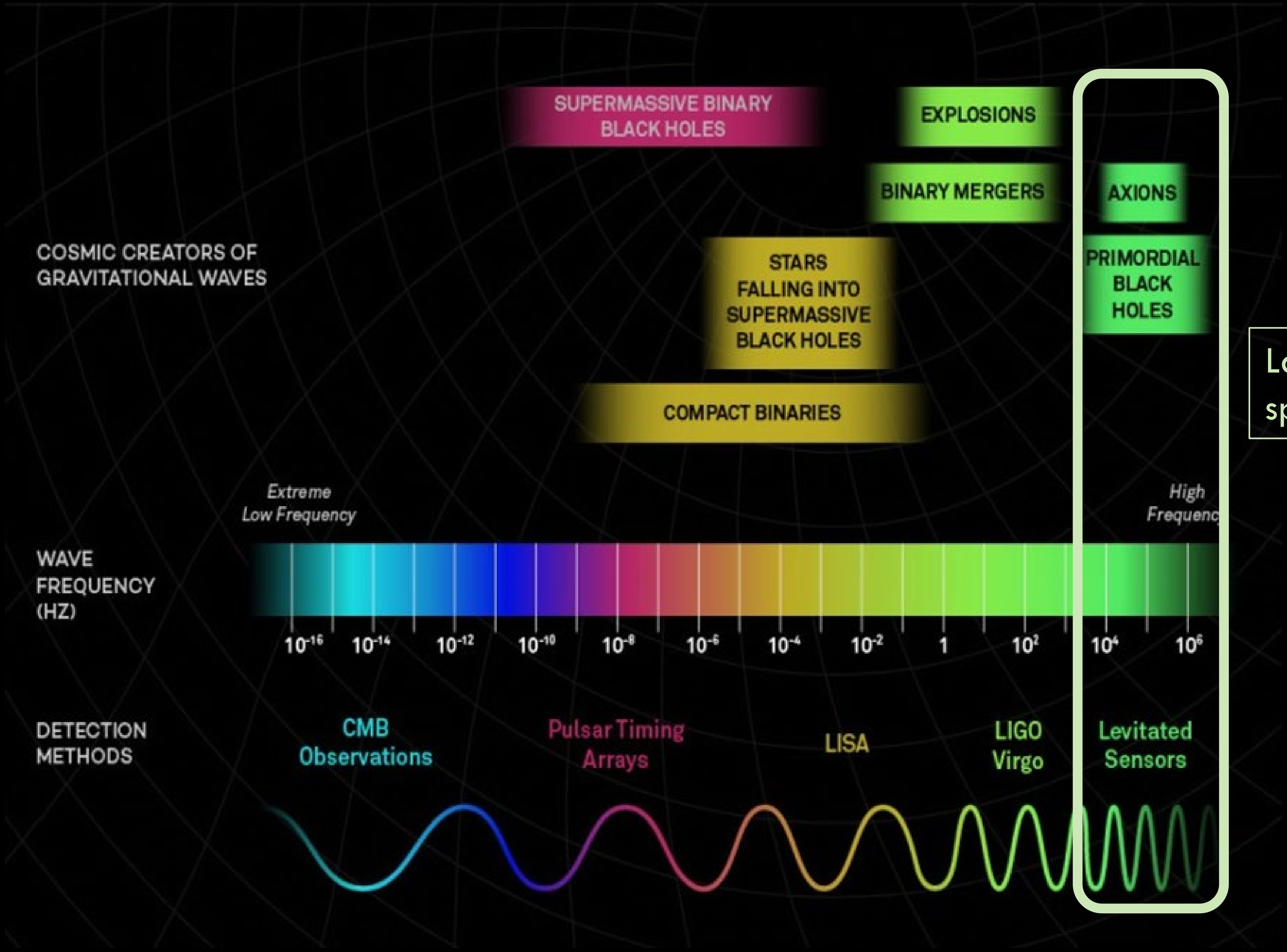


NUMEROUS INTERESTING SOURCES & PROMISING TECHS!!!

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).

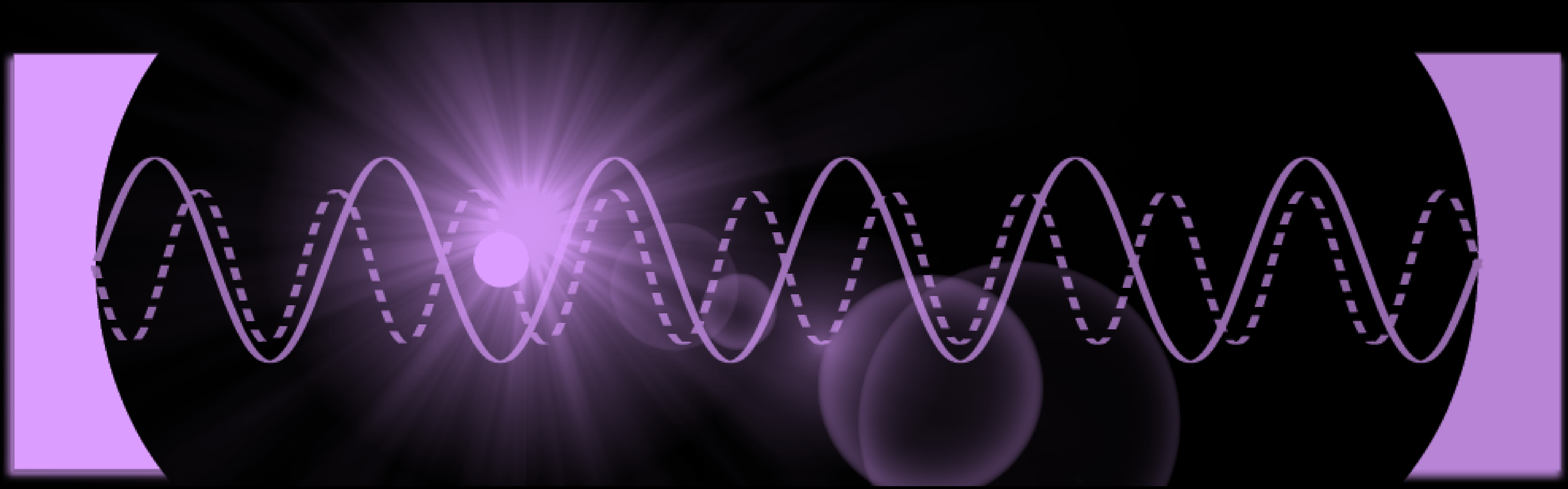


GW DETECTOR AT 10-300 KHZ



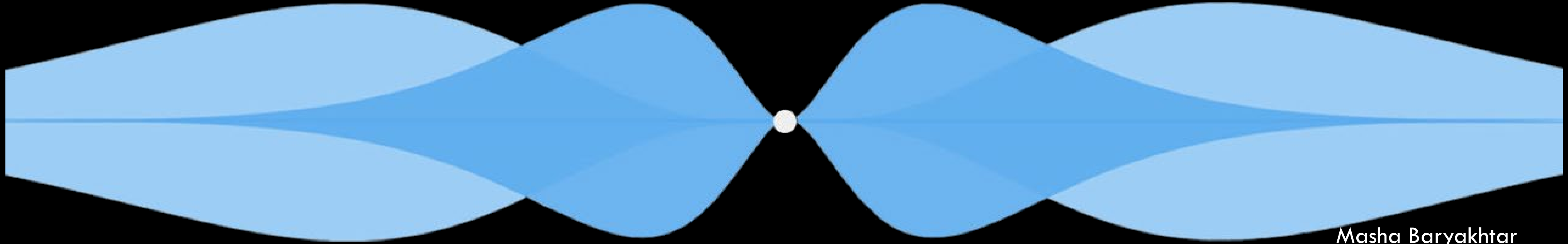
Latest addition to the spectrum!

LEVITATED SENSOR DETECTOR



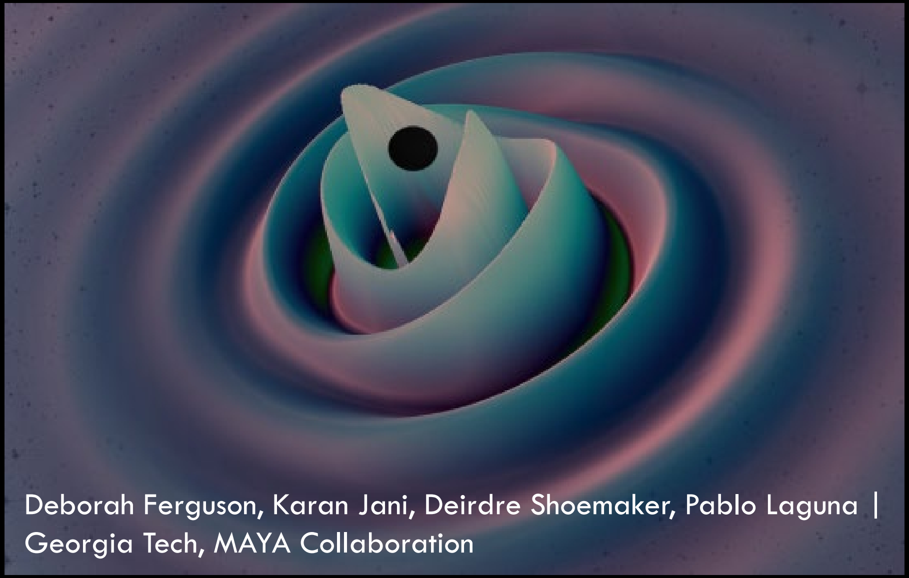
SCIENCE CASE

BH Superradiance



Masha Baryakhtar

Primordial black holes

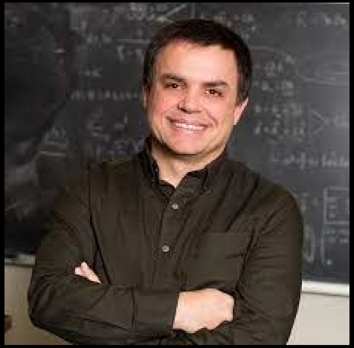


Deborah Ferguson, Karan Jani, Deirdre Shoemaker, Pablo Laguna | Georgia Tech, MAYA Collaboration

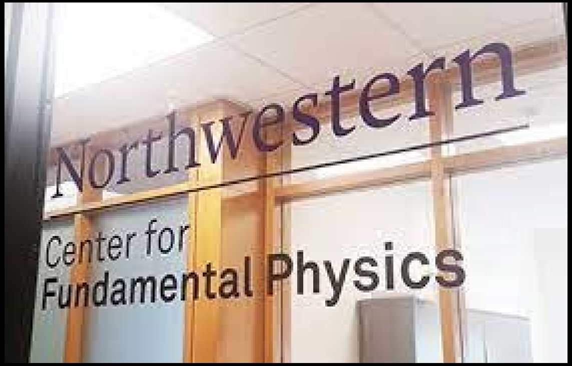
The unknown unknowns???







Office of Naval Research
ONR
Science & Technology





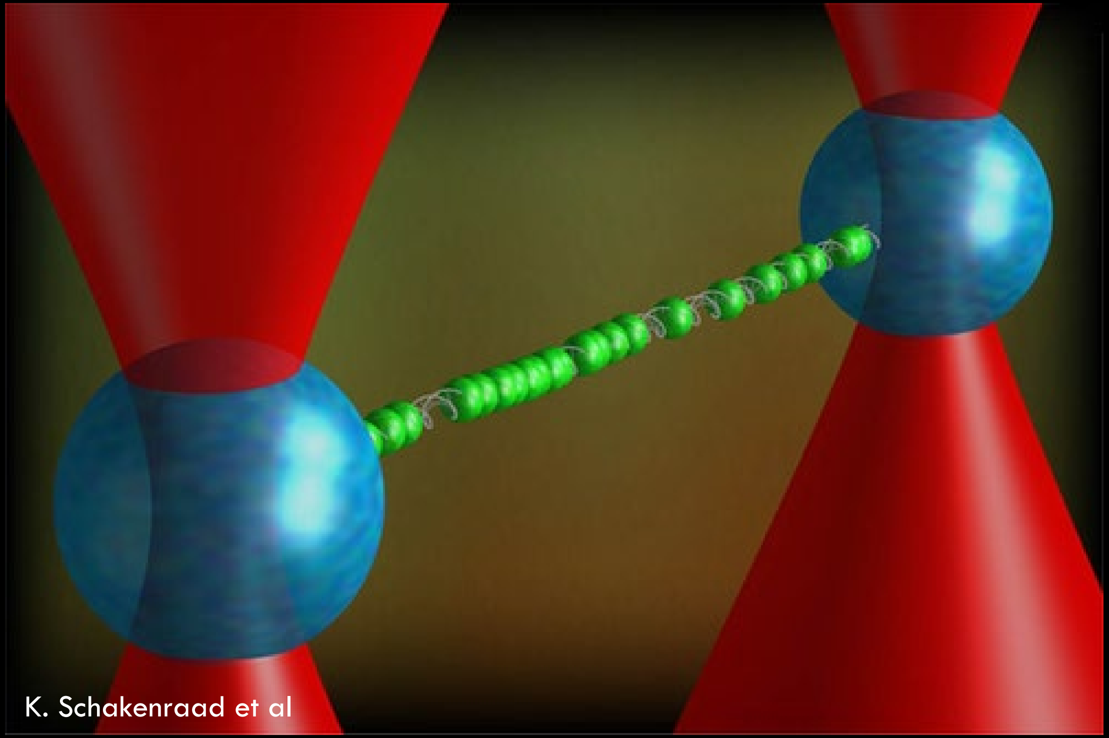

W.M. KECK FOUNDATION

CIERA
Center for Interdisciplinary Exploration and Research in Astrophysics

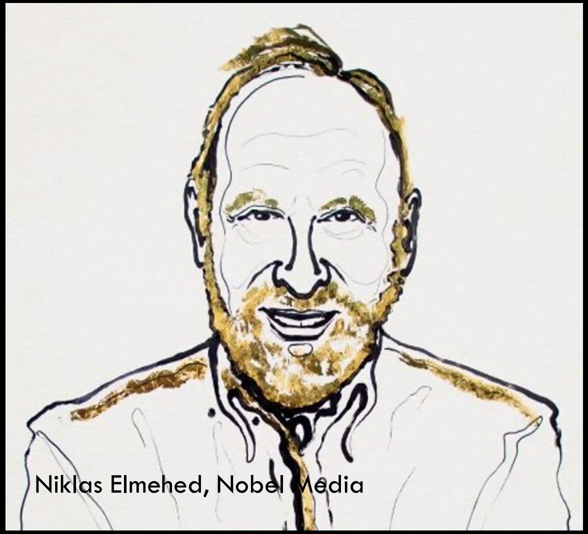
NSF

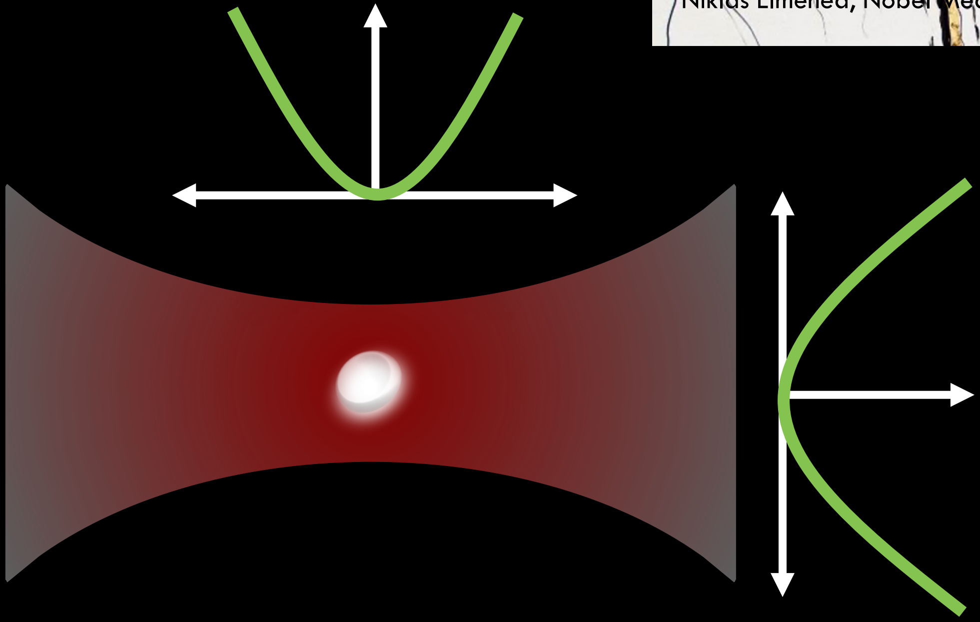
Northwestern

OPTICAL TRAPPING

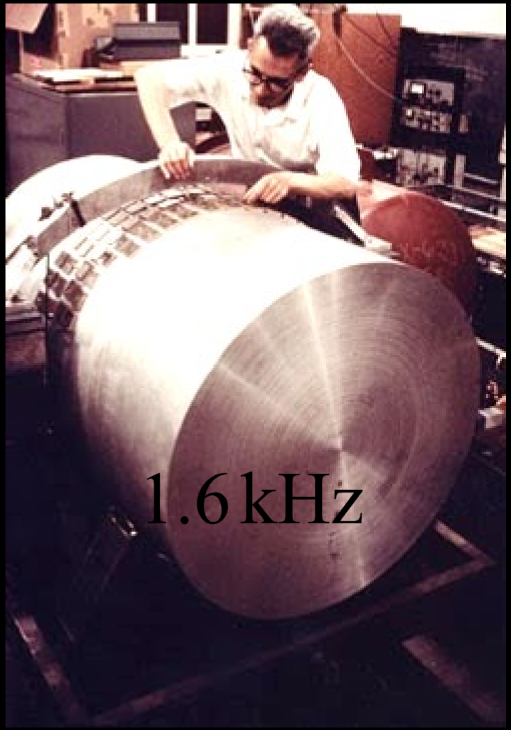

K. Schakenraad et al

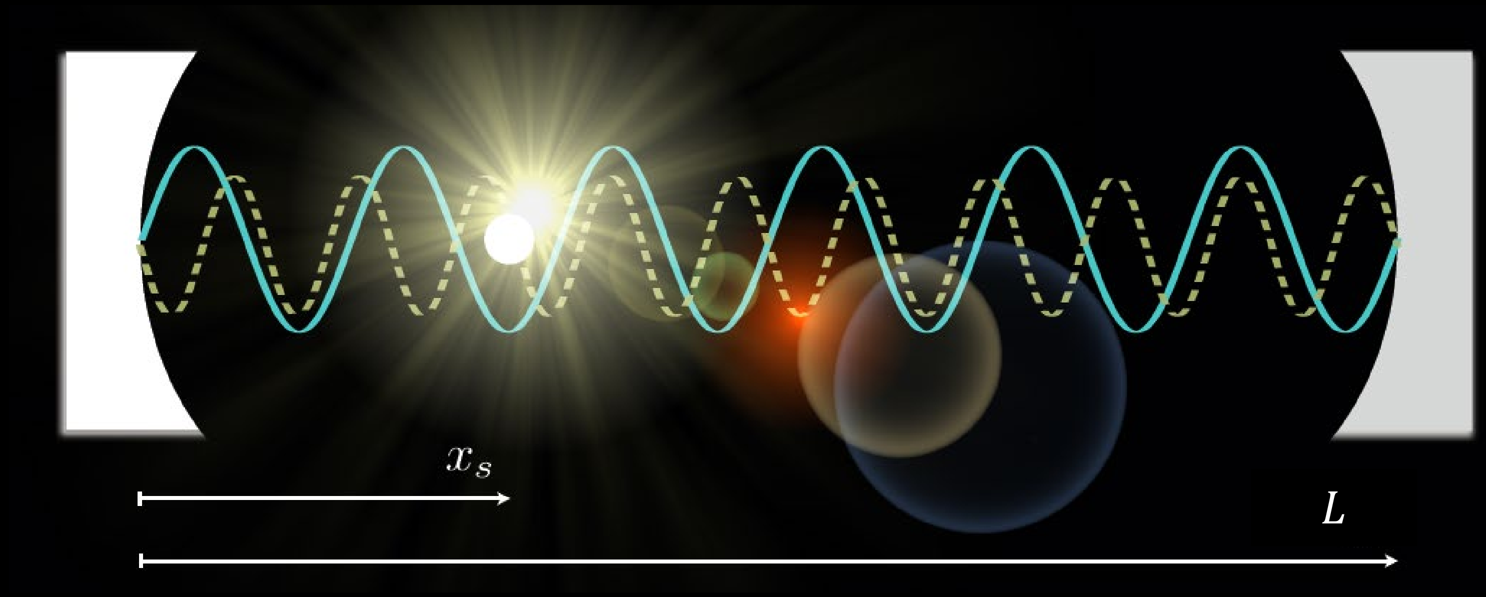
$$U(\vec{r}) = -\frac{1}{2}\alpha(\vec{r})\,E^2(\vec{r})$$


Niklas Elmehed, Nobel Media



GW DETECTOR USING OPTICAL TRAPS





Arvanitaki and Geraci,
PRL 110, 071105 (2013)

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

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

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

LIMITING NOISE: GAS DAMPING AND PHOTON RECOIL HEATING

- $S_{FF} = 4\,M(\,k_B T\ \gamma_g + \ \hbar\,\omega\,\gamma_{sc})$
- Limit on resonance $(\Omega \to \Omega_T)$, $S_{hh} \sim 16\,\frac{1}{\Omega_T^2}\frac{1}{M}\frac{1}{L^2}(\hbar\,\omega\,\gamma_{sc} + k_B T\,\gamma_g)$

temperature T ↓

length L ↑

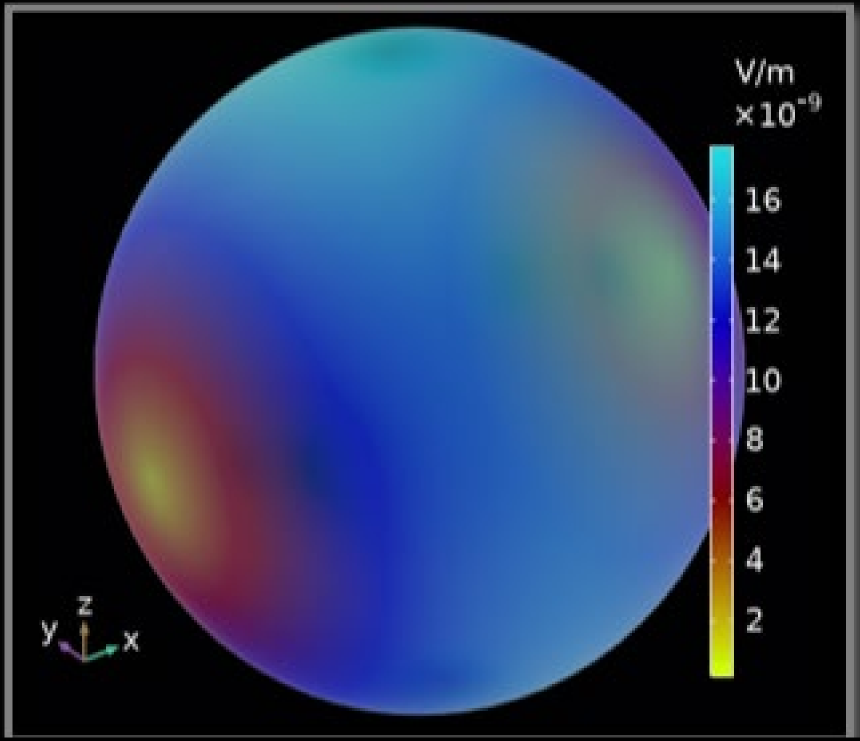
recoil γ_{sc} ↓

mass M ↑

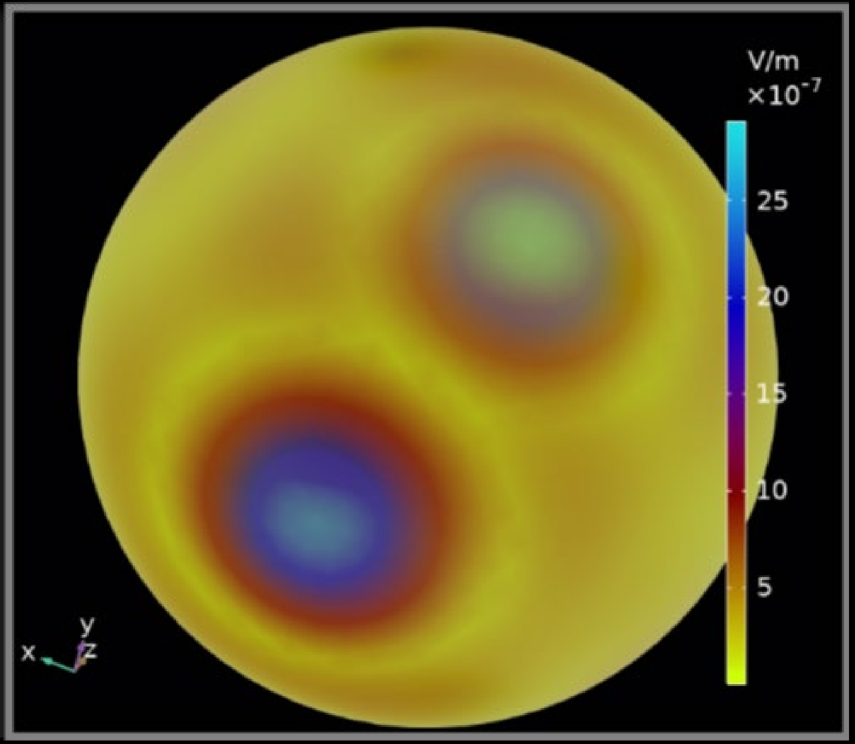
PARTICLE GEOMETRY AFFECTS SCATTER

- 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: $\vec{E} = 1\, Vm^{-1}\, \hat{x} \cos kz$



SiO2 Sphere (d=300 nm)

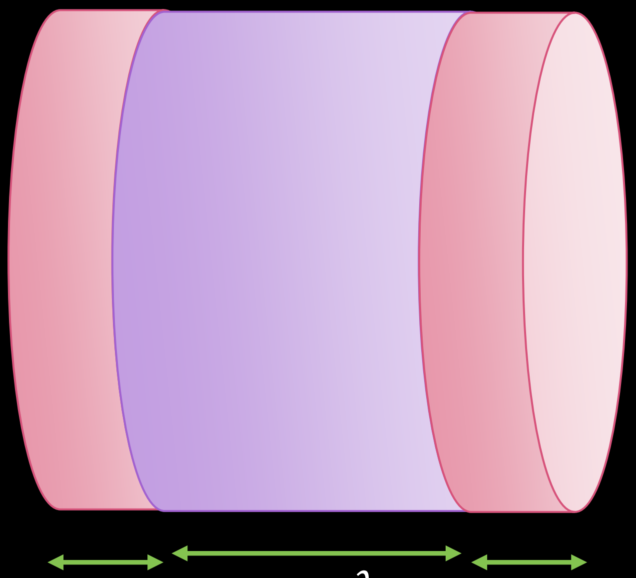


NaYF Hexagon (d=4 um, τ =200 nm),
300 times more mass

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

INCREASE PARTICLE MASS WHILE KEEPING SCATTER LOW?

- Stacked disks to increase mass (high M)



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

Modified wavelength

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

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?

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

INCREASE PARTICLE MASS WHILE KEEPING SCATTER LOW?

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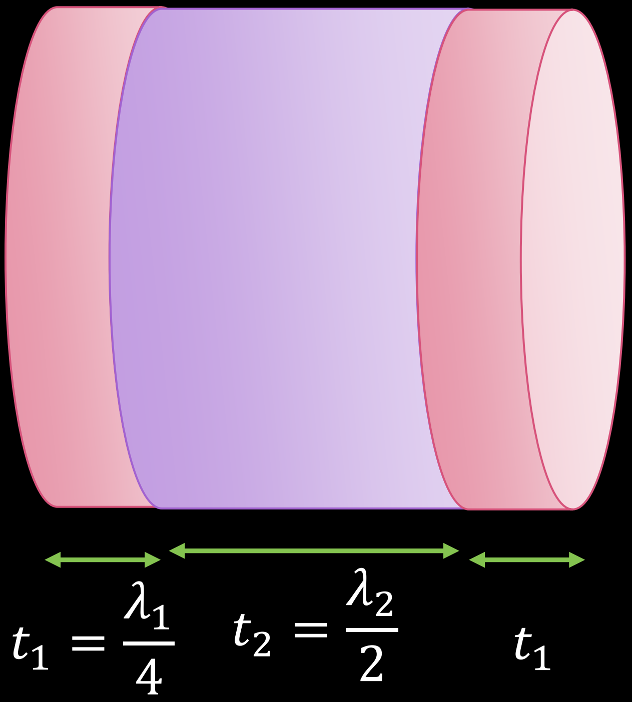
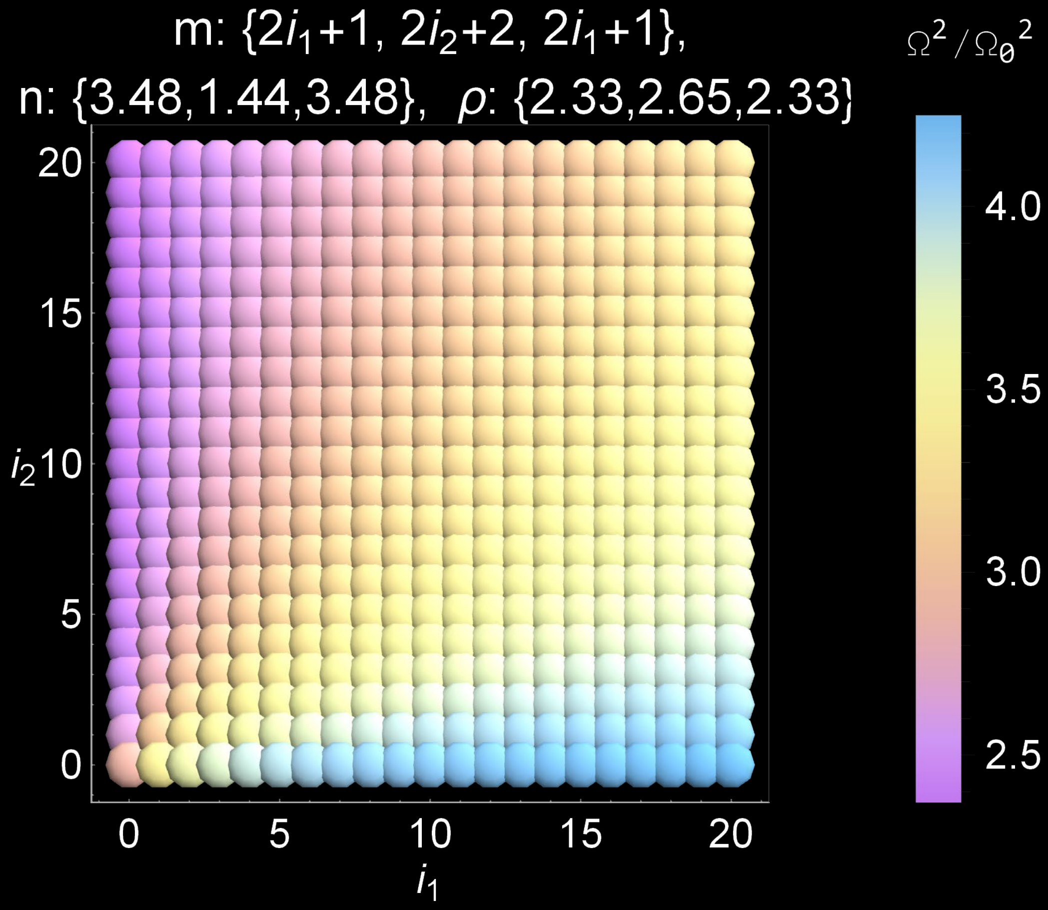


Modified wavelength

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


m: $\{2i_1+1, 2i_2+2, 2i_1+1\}$,

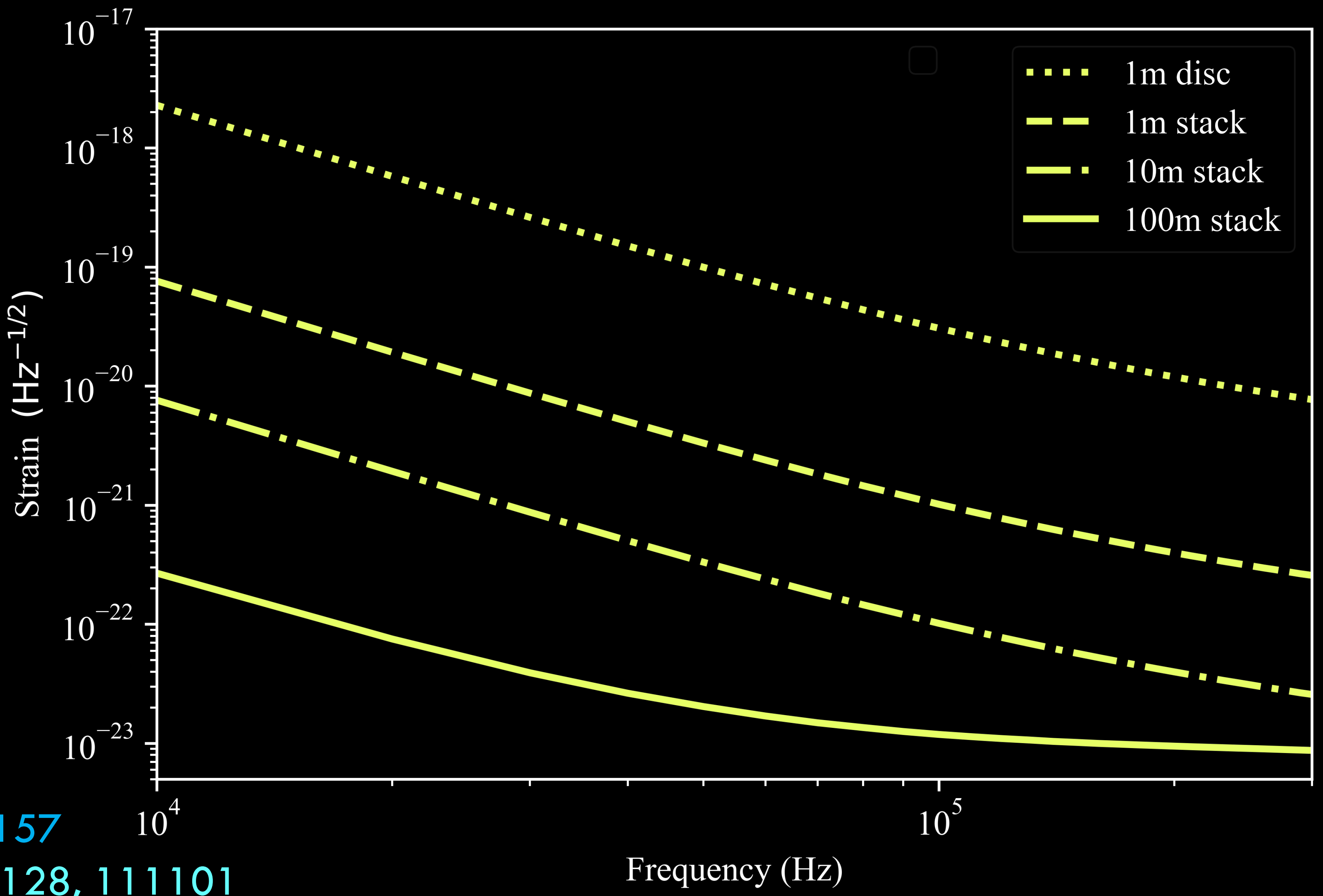
n: {3.48,1.44,3.48}, ρ: {2.33,2.65,2.33}

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

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

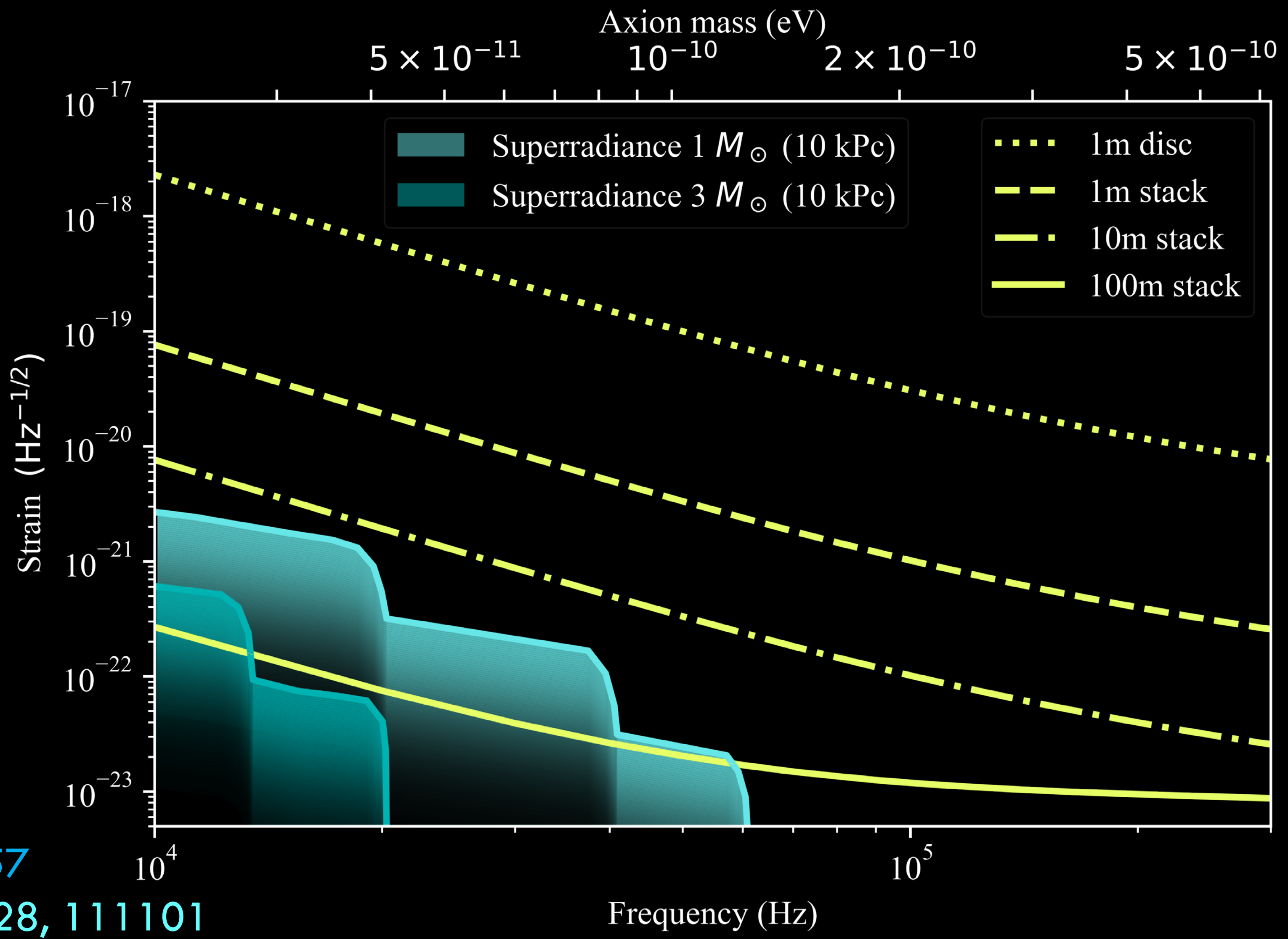
In prep: Aggarwal et al.

IMPROVED SENSITIVITY



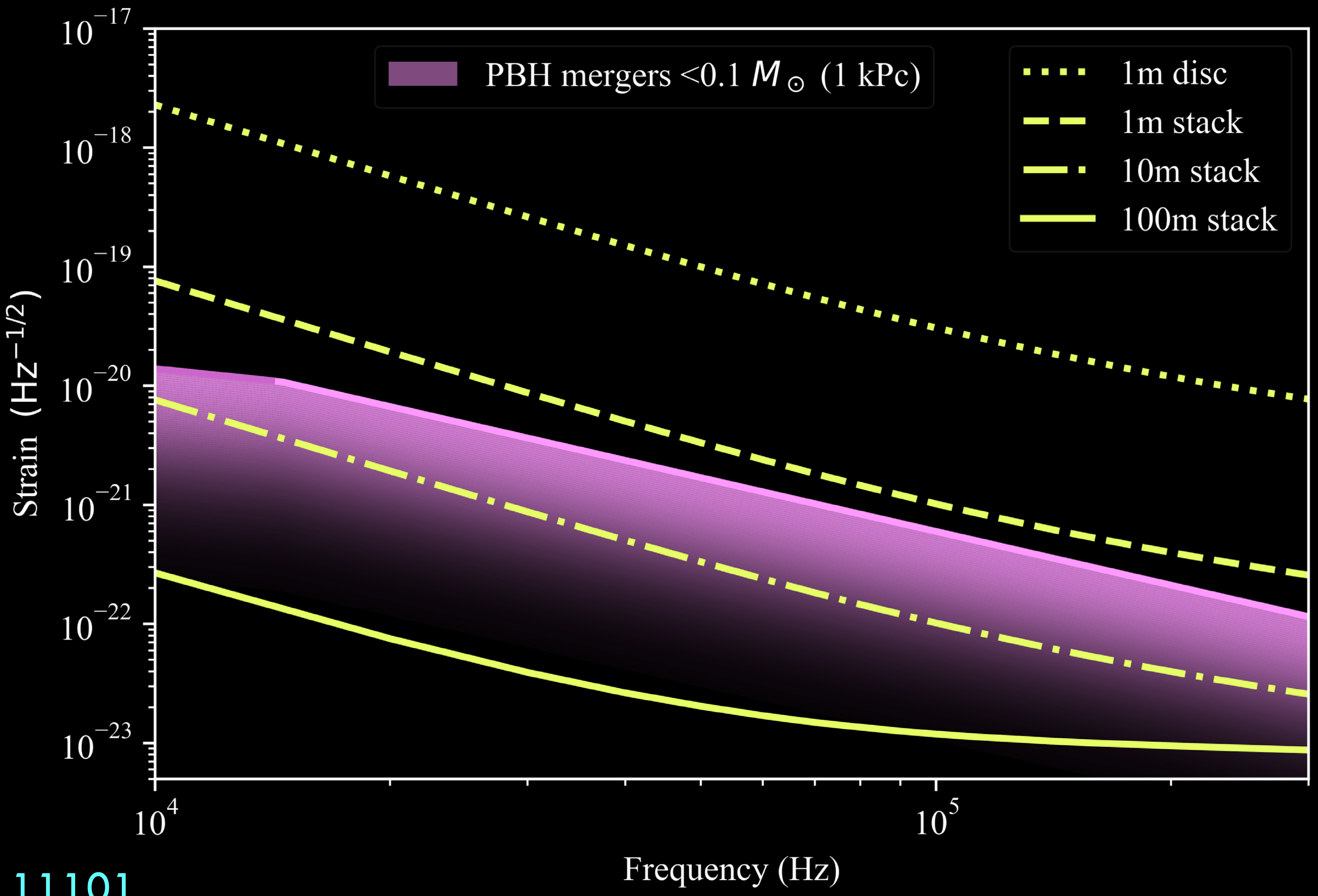
Aggarwal et al
arxiv:2010.13157
Phys. Rev. Lett. 128, 111101

SENSITIVITY TO BH SUPERRADIANCE



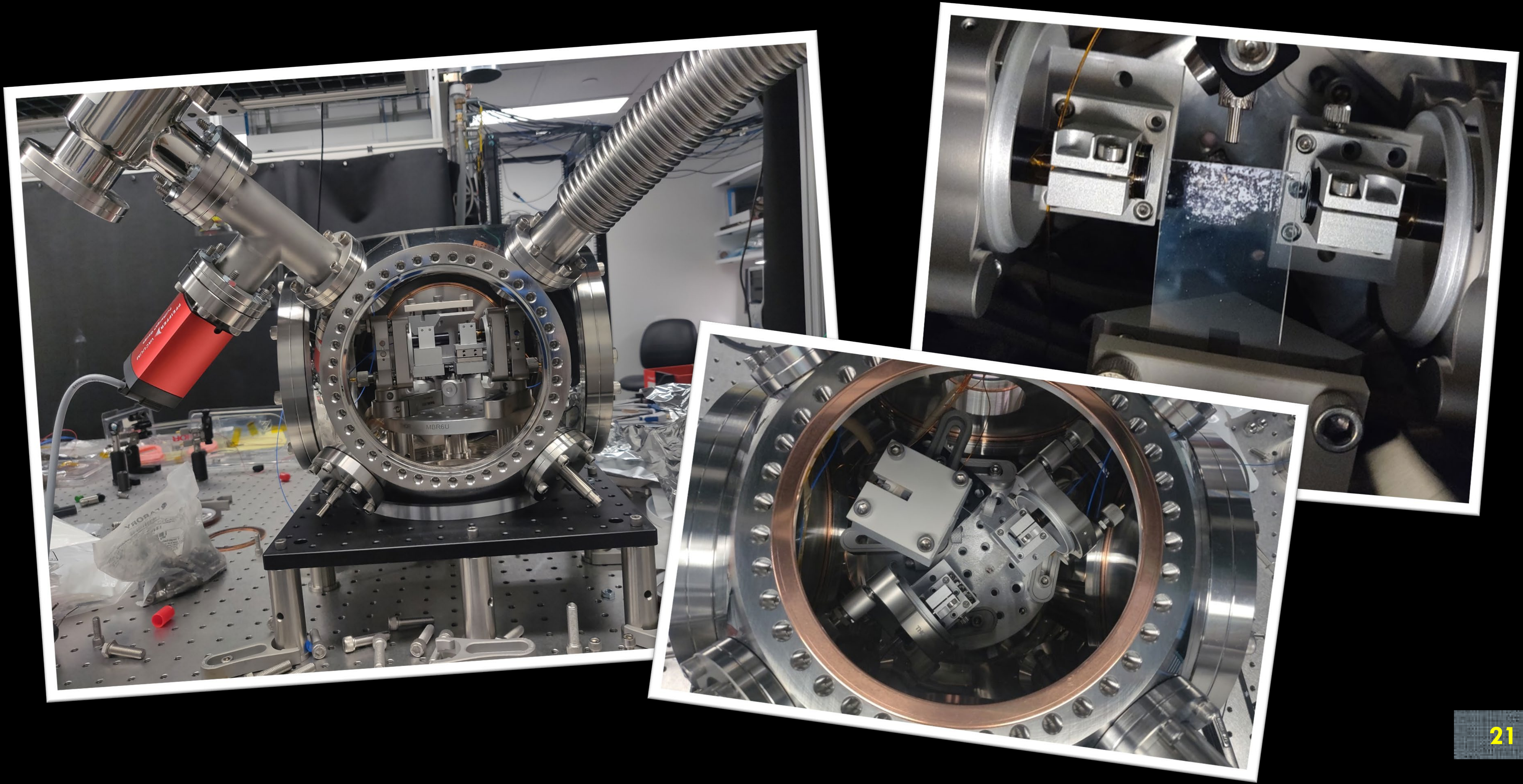
Aggarwal et al
arxiv:2010.13157
Phys. Rev. Lett. 128, 111101

SENSITIVITY TO BLACKHOLE MERGERS

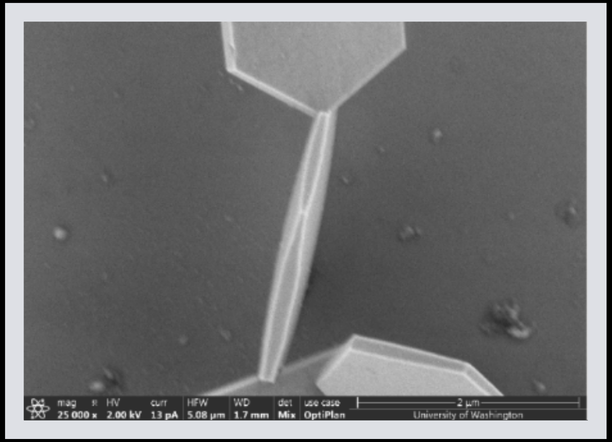


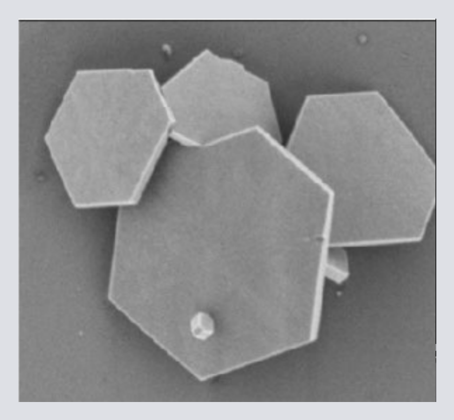
Aggarwal et al
arxiv:2010.13157
Phys. Rev. Lett. 128, 111101

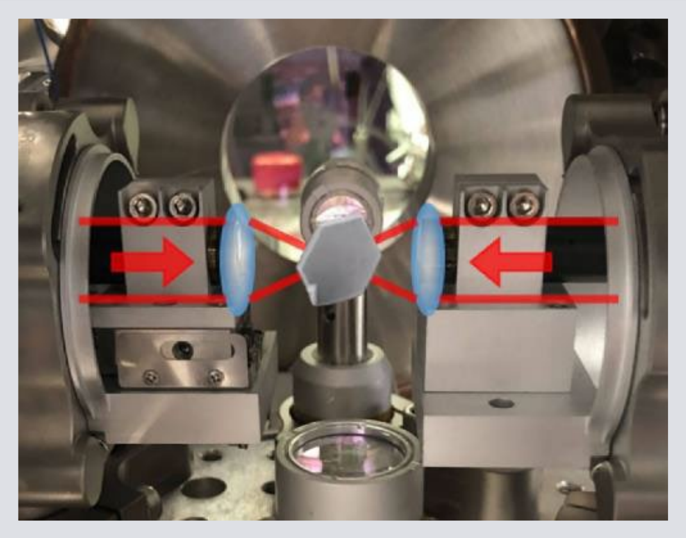
TRAPPING OF FLAT OBJECTS IN THE LAB…

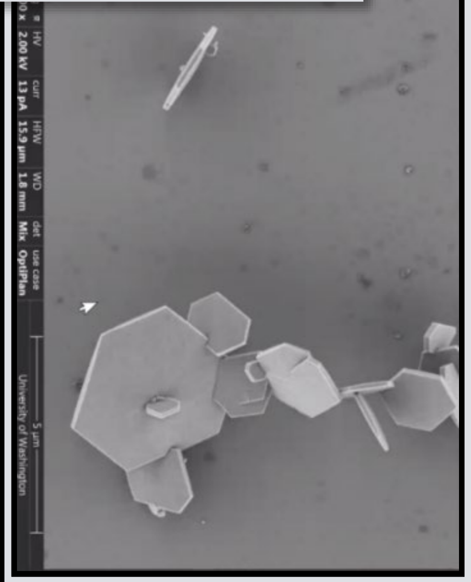


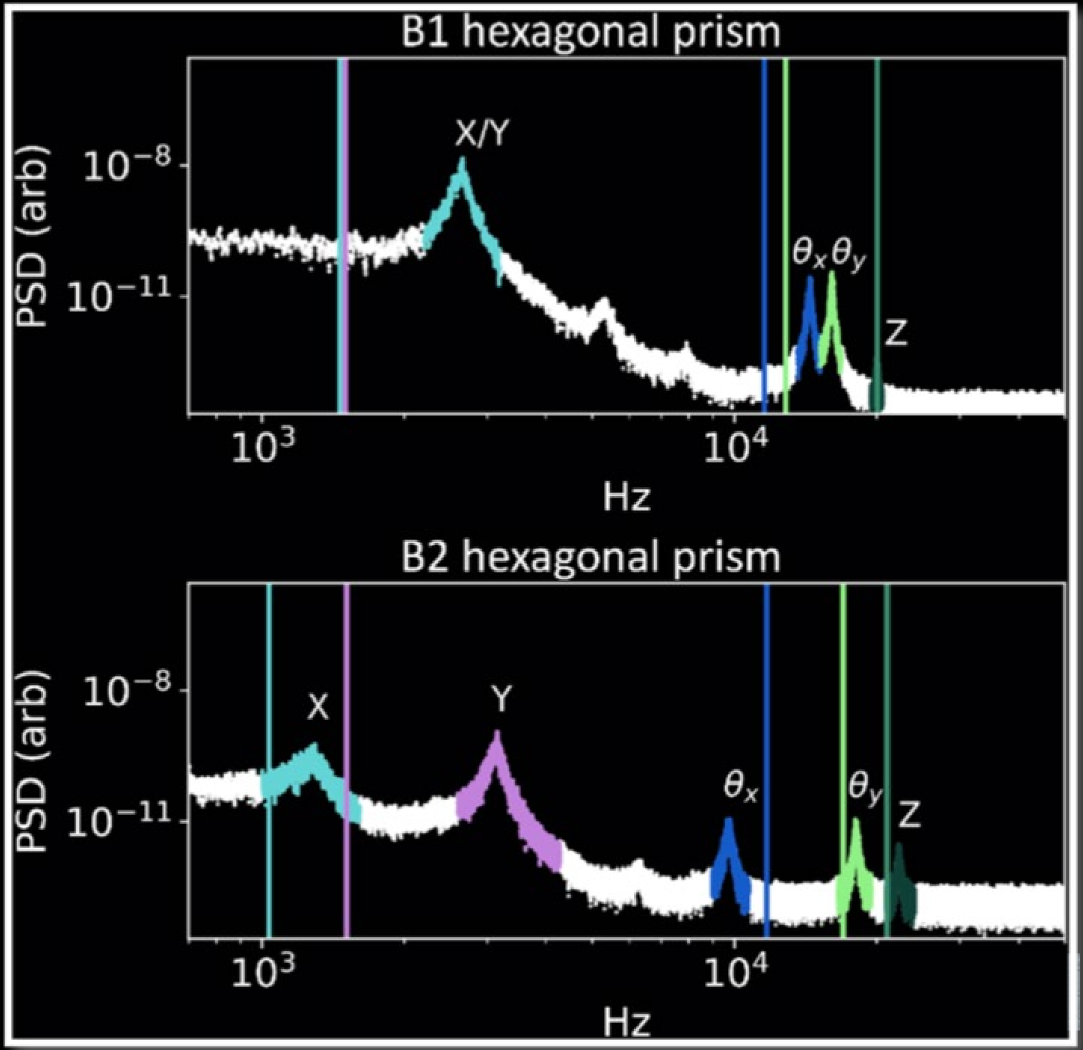
FIRST SPECTRA, TRAPPING OF NAYF HEXAGON PLATES



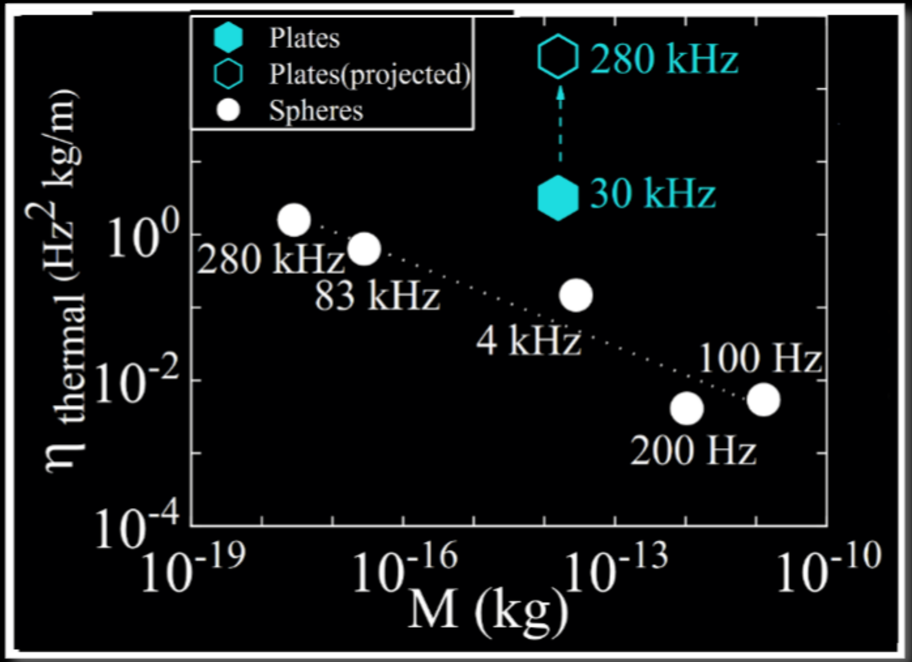


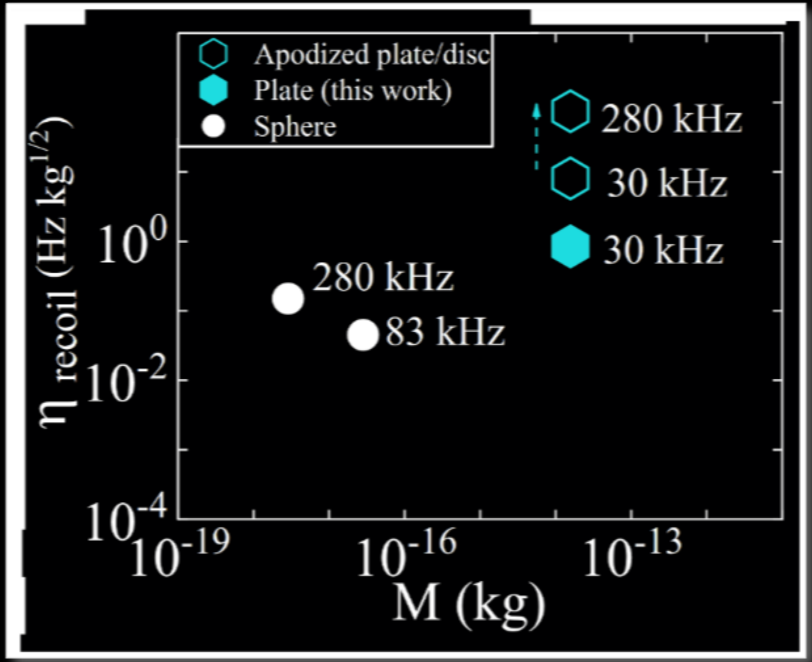






STATE OF THE ART IN OPTICAL TRAPPING





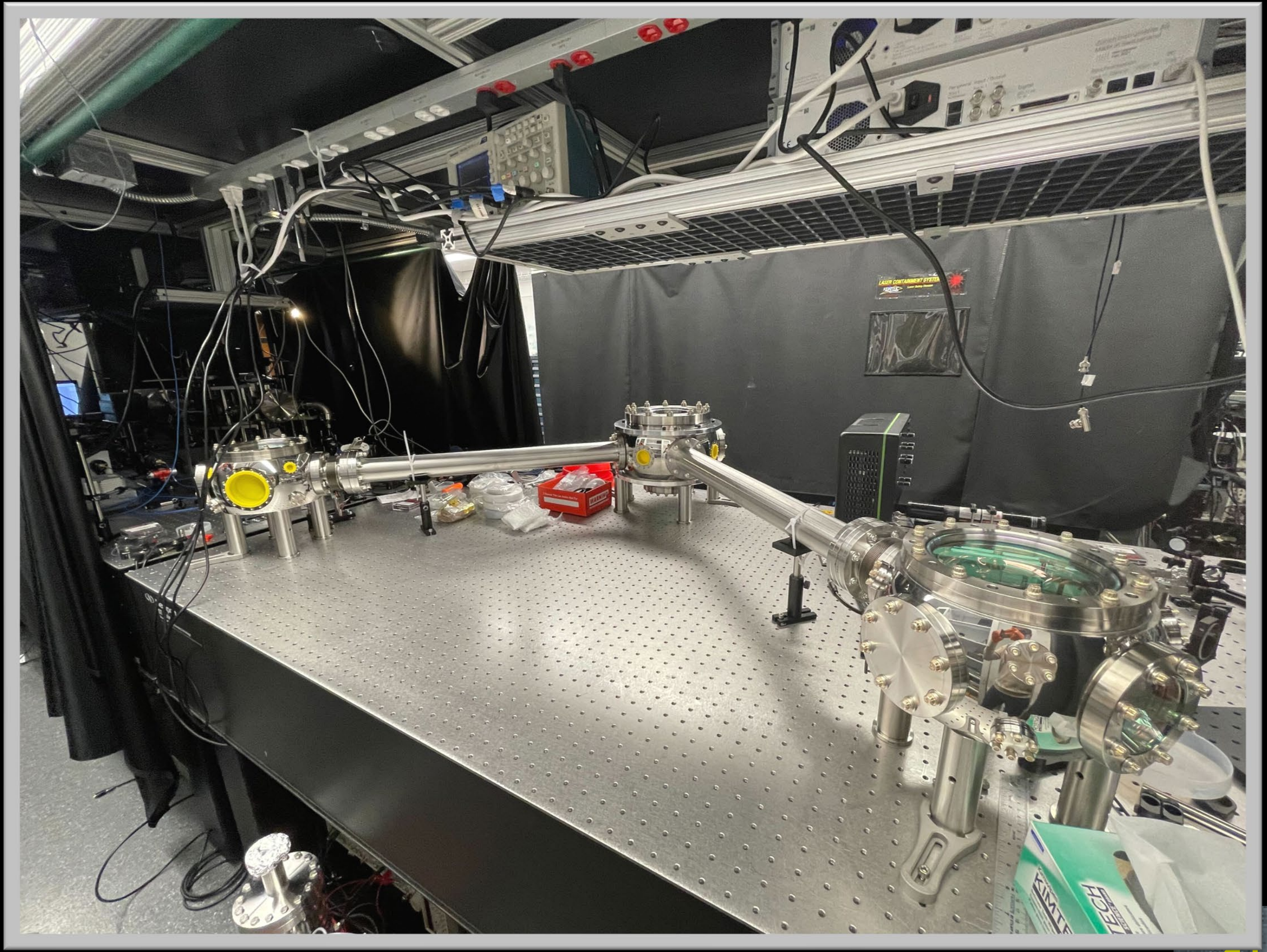
$$\eta_{\text{thermal}} = \left(\frac{\Omega_z}{2\pi}\right)^2 \sqrt{M\rho\tau}$$

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

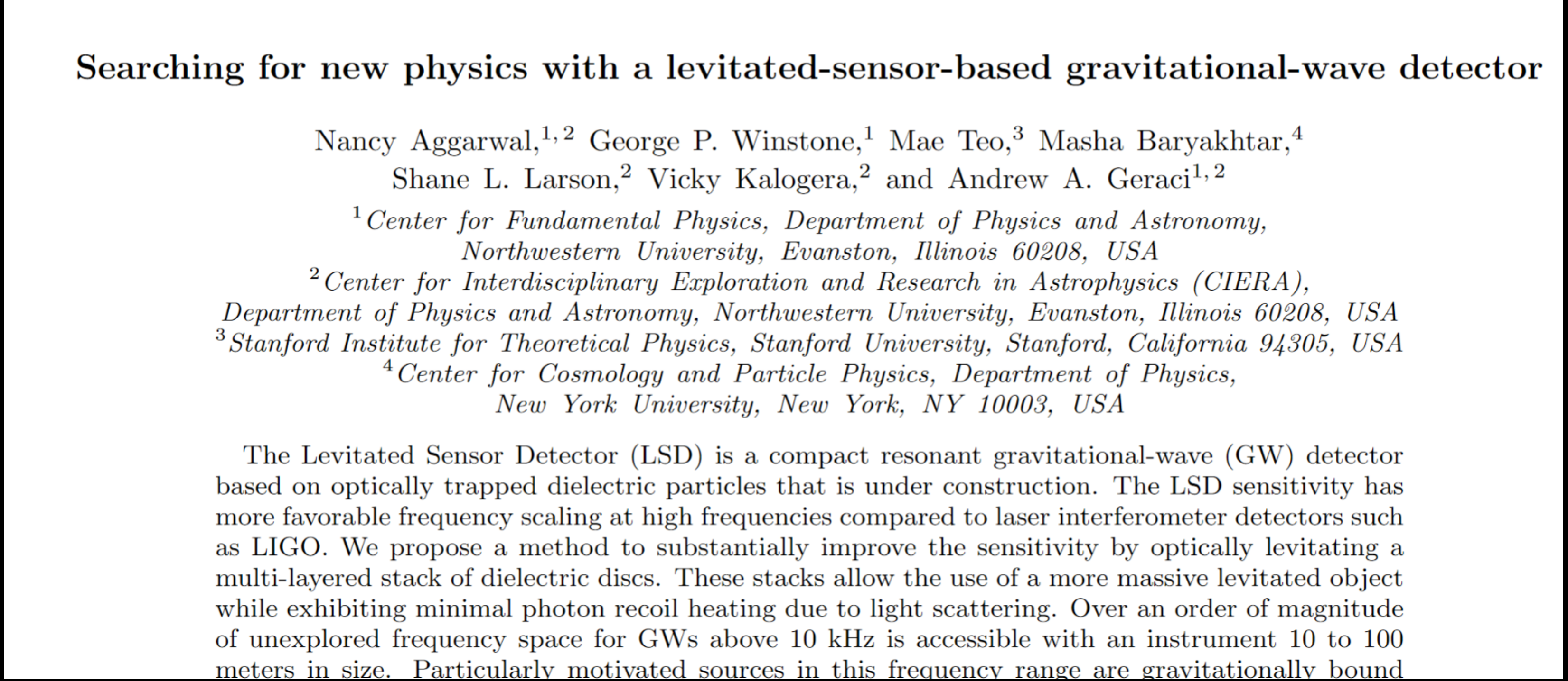
$$\eta_{\text{recoil}} = \left(\frac{\Omega_z}{2\pi}\right)^{3/2} \sqrt{\frac{M}{\gamma_{sc}}}$$

STAY TUNED…

- New initiative for building 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



HONING THE NOISE AND REFINING SOURCE ESTIMATE

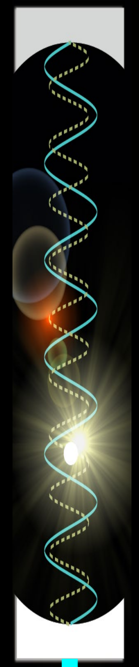


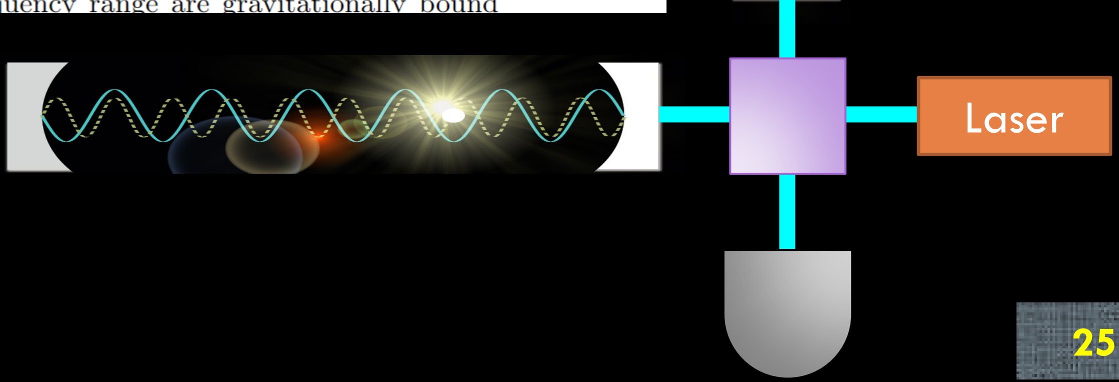
Searching for new physics with a levitated-sensor-based gravitational-wave detector

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

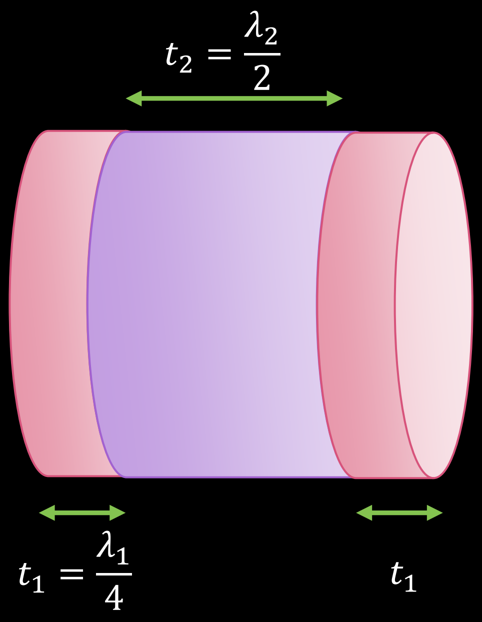
The Levitated Sensor Detector (LSD) is a compact resonant gravitational-wave (GW) detector based on optically trapped dielectric particles that is under construction. The LSD sensitivity has more favorable frequency scaling at high frequencies compared to laser interferometer detectors such as LIGO. 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



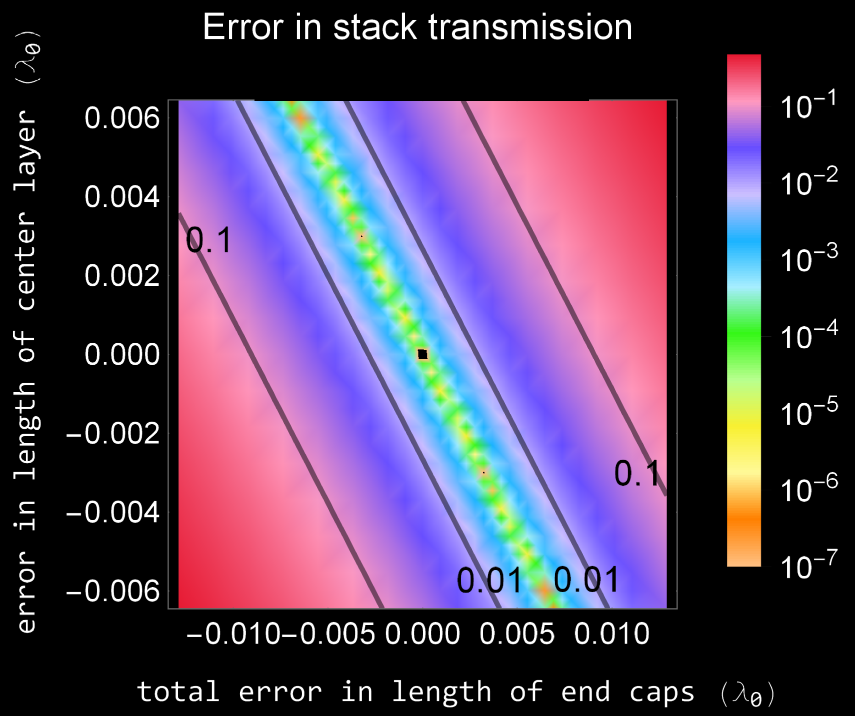


Aggarwal et al
arxiv:2010.13157
Phys. Rev. Lett. 128, 111101

1. EXAMINE TRANSMISSION THROUGH STACKS



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



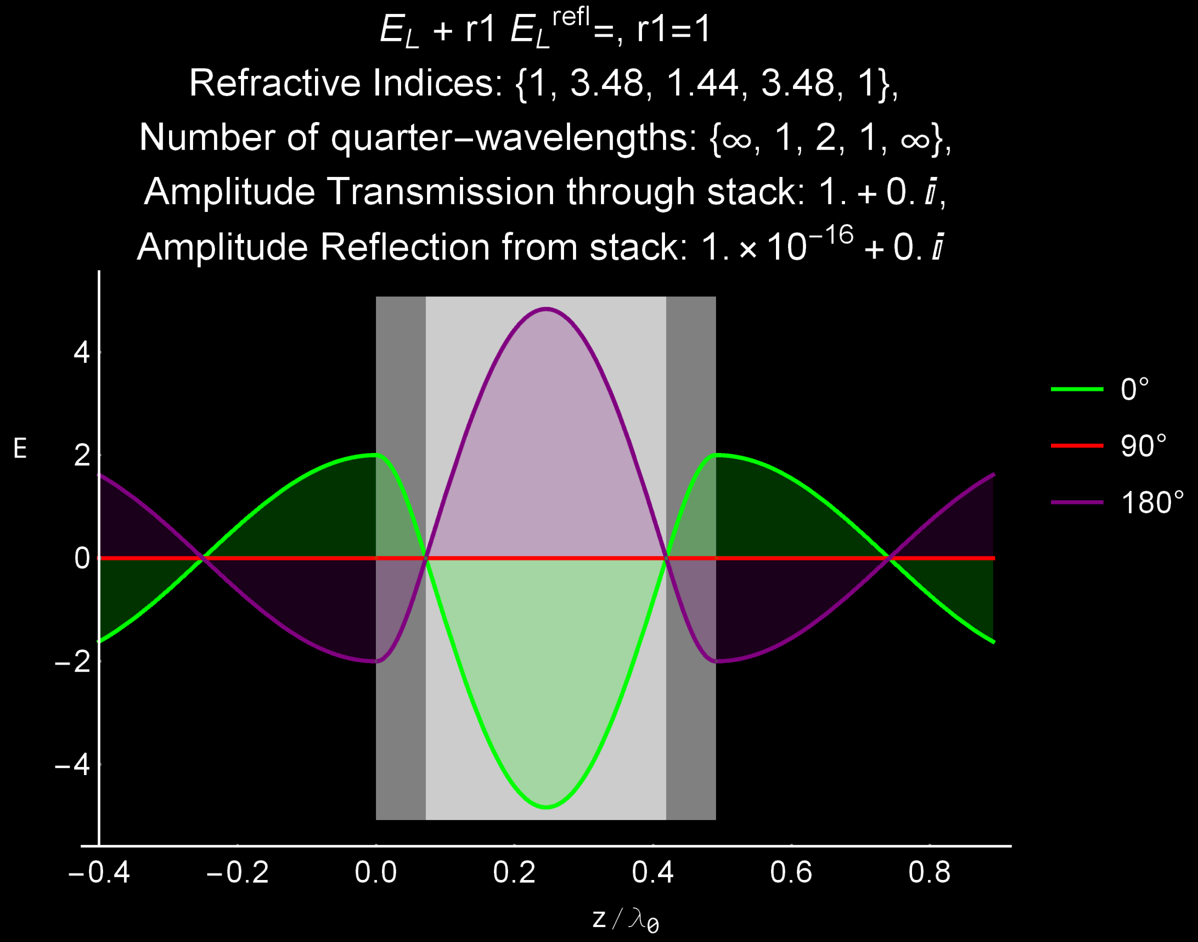
- Symmetric
- Whole number of quarter wavelengths in end caps
- Even number of quarter wavelengths in center

$$\delta T_{OEO} = -1218.31(1.000(\epsilon_1 + \epsilon_3) + 1.075\epsilon_2)^2$$

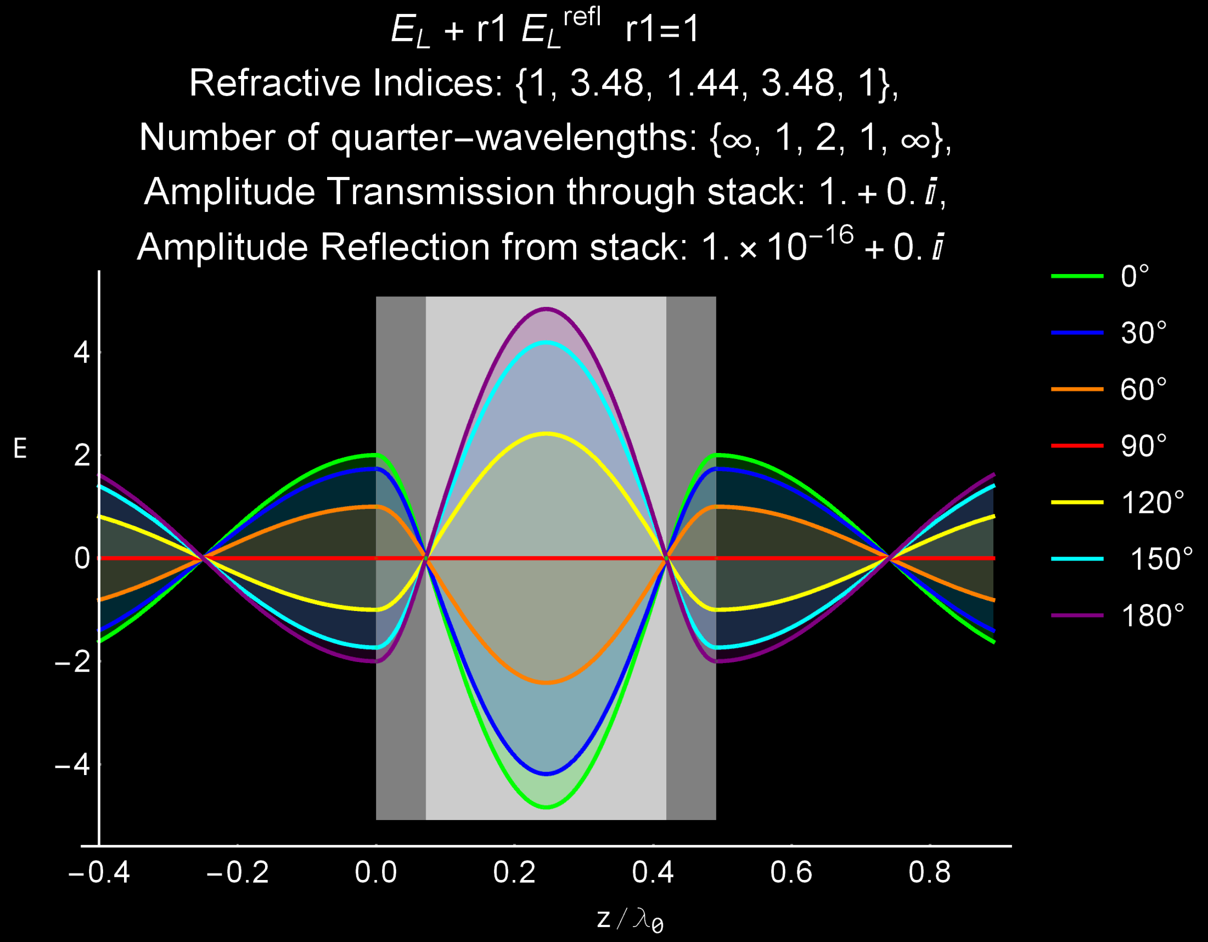
1.5 nm precision for 99%
0.5 nm precision for 99.9%

Preliminary: Aggarwal et al.

2. ELECTRIC FIELD INSIDE STACKS



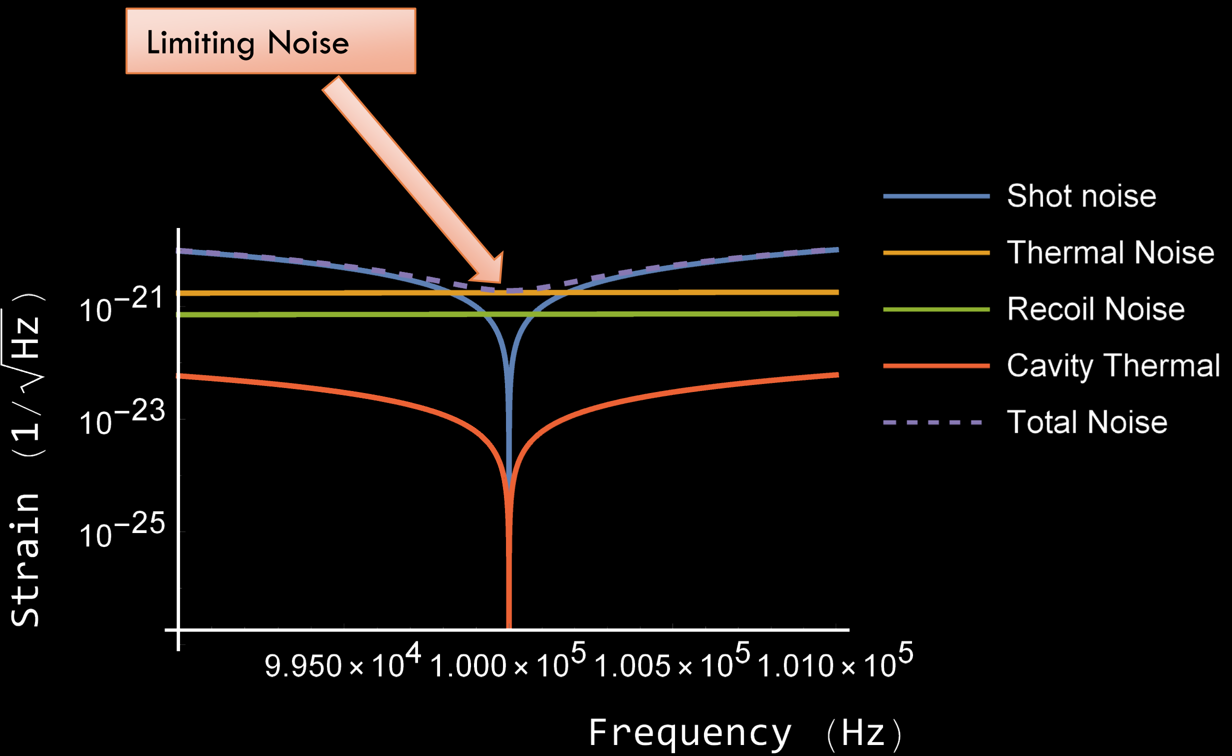
E_L + r1 E_L^{refl}=, r1=1
Refractive Indices: {1, 3.48, 1.44, 3.48, 1},
Number of quarter−wavelengths: {∞, 1, 2, 1, ∞},
Amplitude Transmission through stack: $1. + 0.\,i$,
Amplitude Reflection from stack: $1. \times 10^{-16} + 0.\,i$



E_L + r1 E_L^{refl} r1=1
Refractive Indices: {1, 3.48, 1.44, 3.48, 1},
Number of quarter−wavelengths: {∞, 1, 2, 1, ∞},
Amplitude Transmission through stack: $1. + 0.\,i$,
Amplitude Reflection from stack: $1. \times 10^{-16} + 0.\,i$

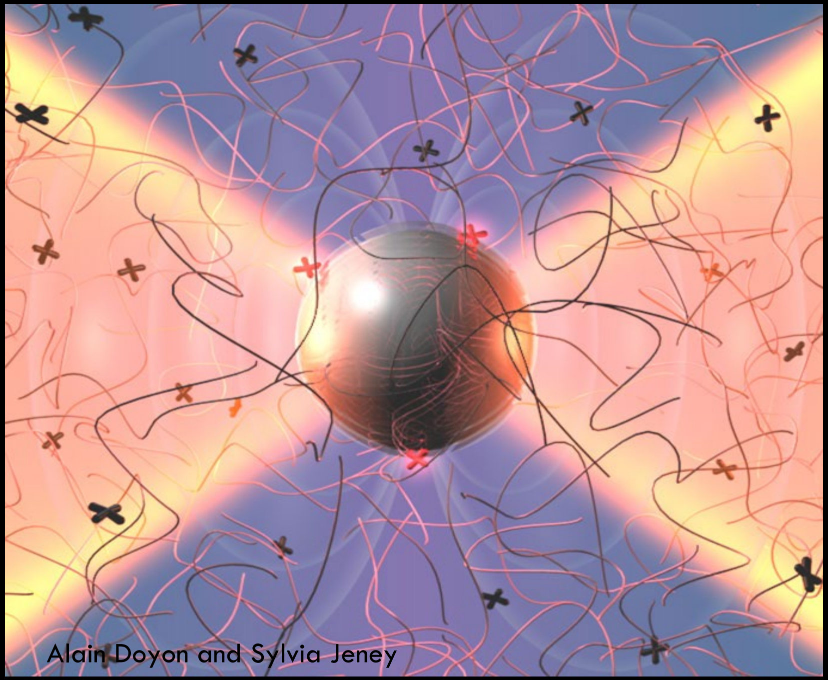
Preliminary: Aggarwal et al.

ANTICIPATED NOISES



Limiting Noise

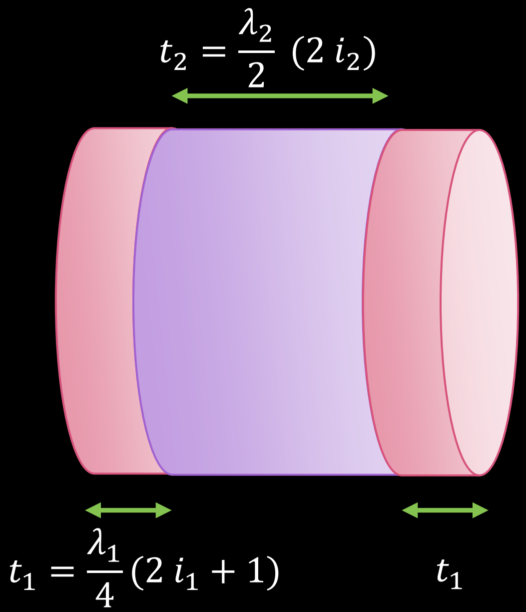
Preliminary Aggarwal et al



Alain Doyon and Sylvia Jeney

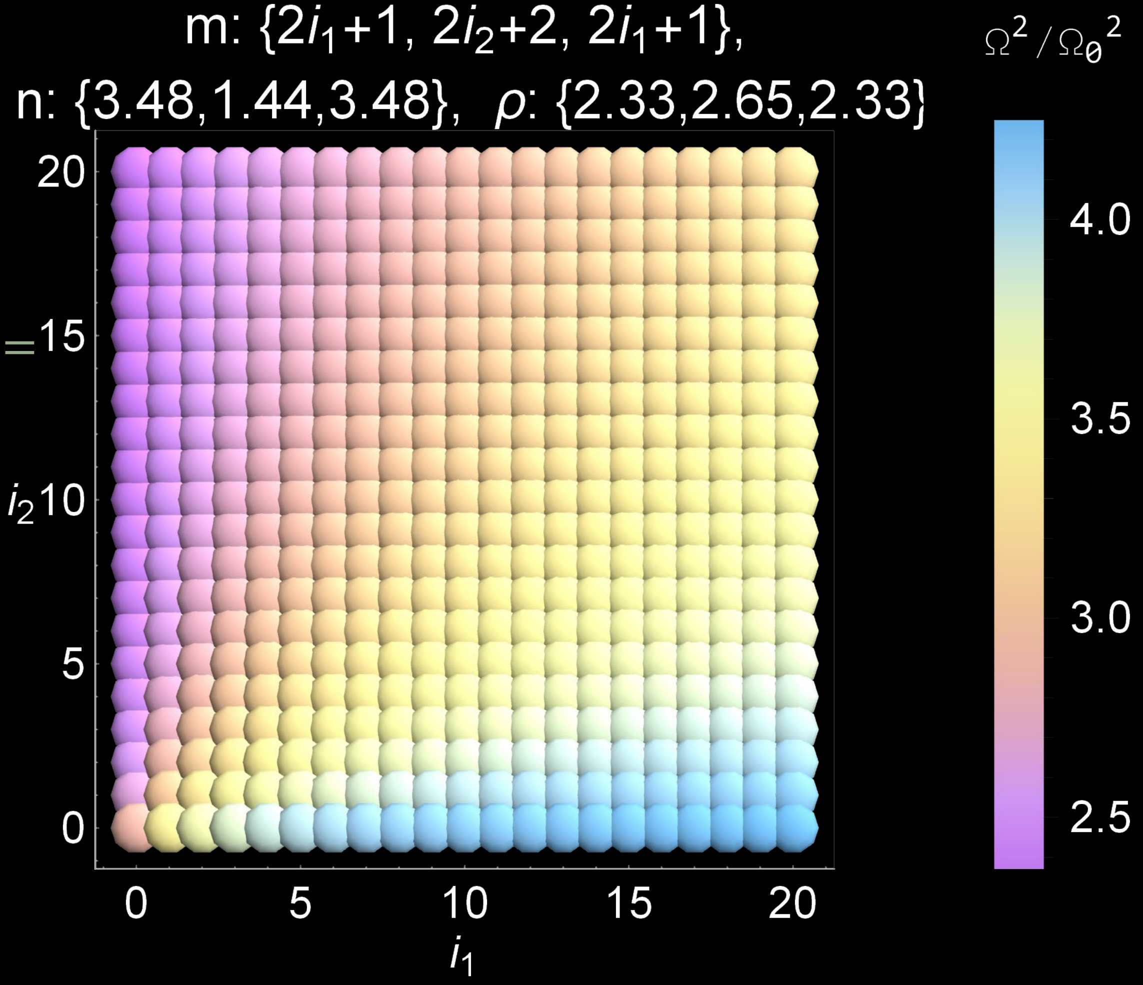
- Thermal noise from gas damping
  - $S_{FF,thermal} = 4\, k_B\, T\, M\, \gamma_g$
- Quantum noise from photon recoil
  - $S_{FF,Recoil} = 4\, \hbar\omega\, M\, \gamma_{sc}$

3. FEASIBLE TRAP FREQUENCY



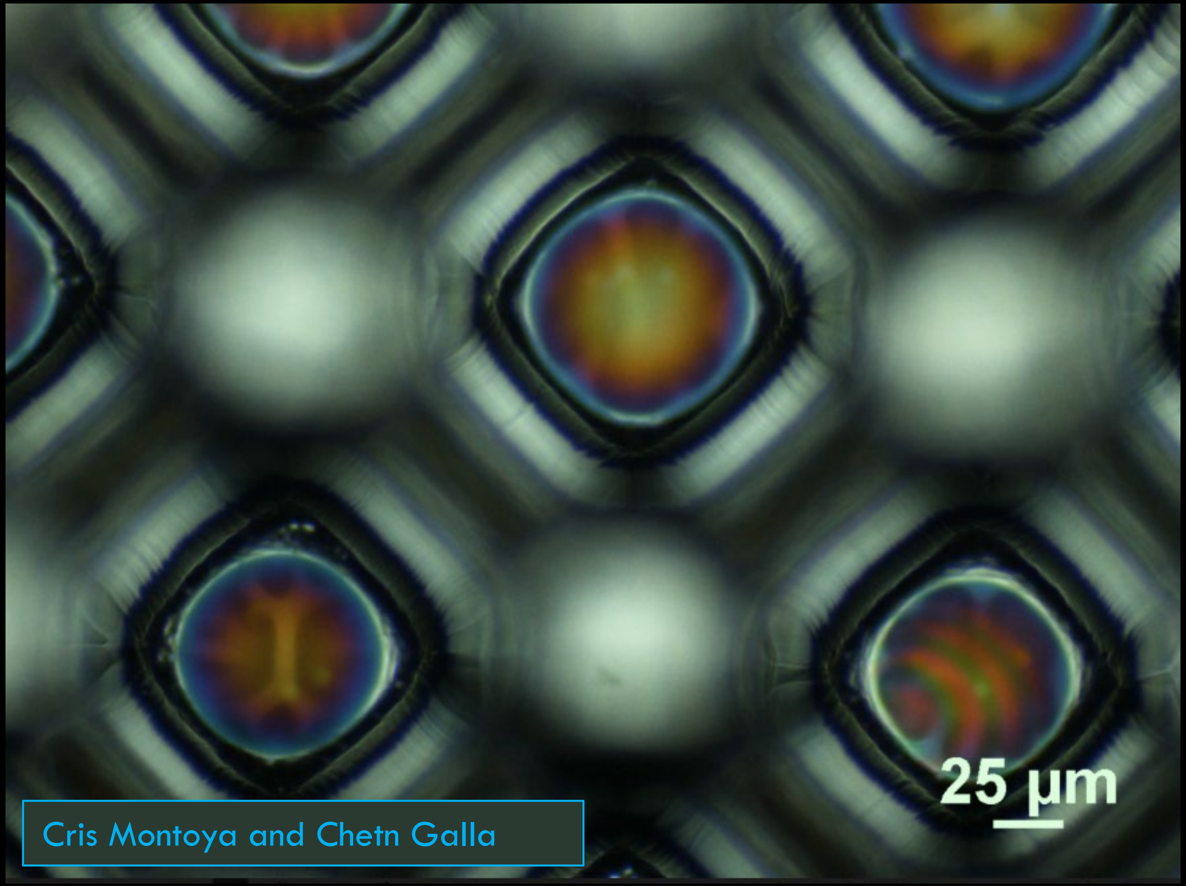
Modified wavelength $\lambda_i = \frac{\lambda_0}{n_i}$

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

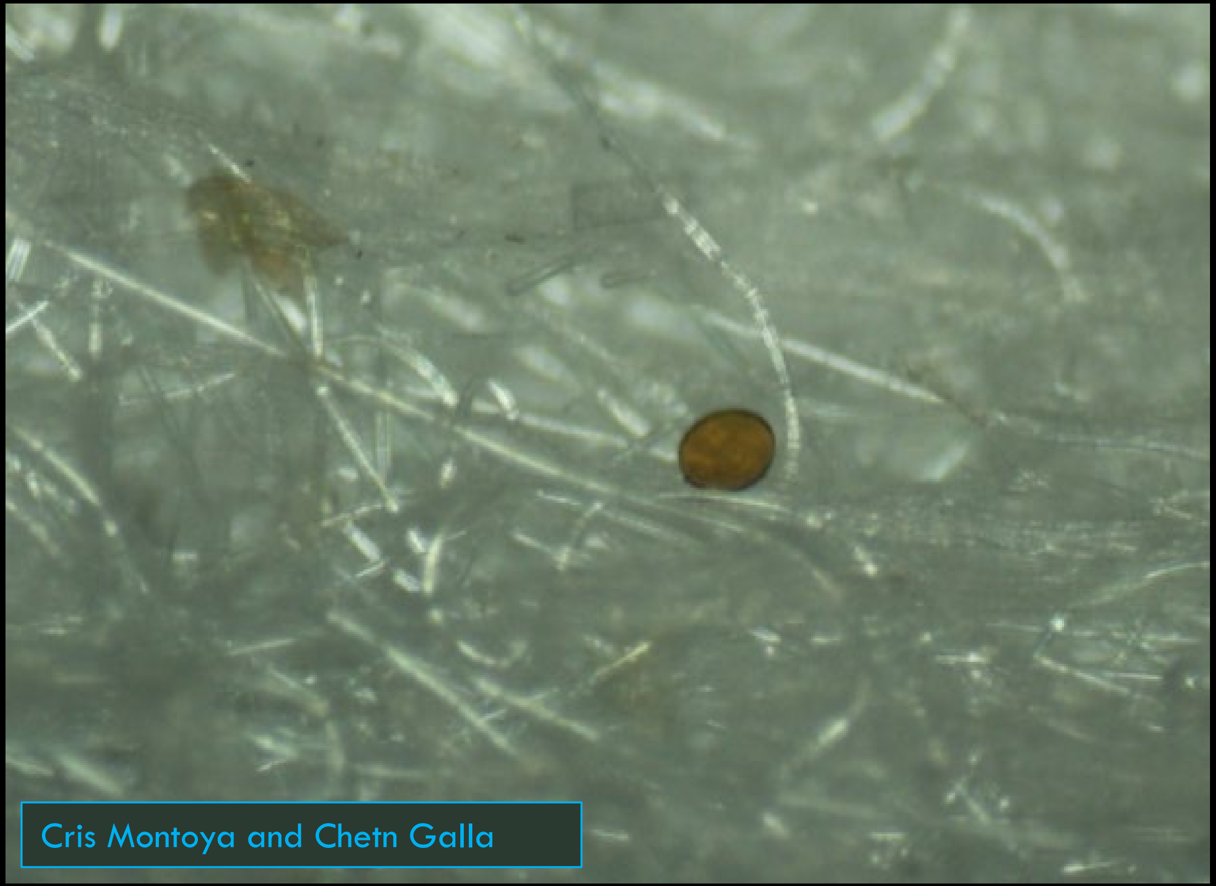

m: $\{2i_1+1,\ 2i_2+2,\ 2i_1+1\}$,
n: {3.48,1.44,3.48}, ρ: {2.33,2.65,2.33}

Preliminary: Aggarwal et al.

4. FABRICATING THE DISKS

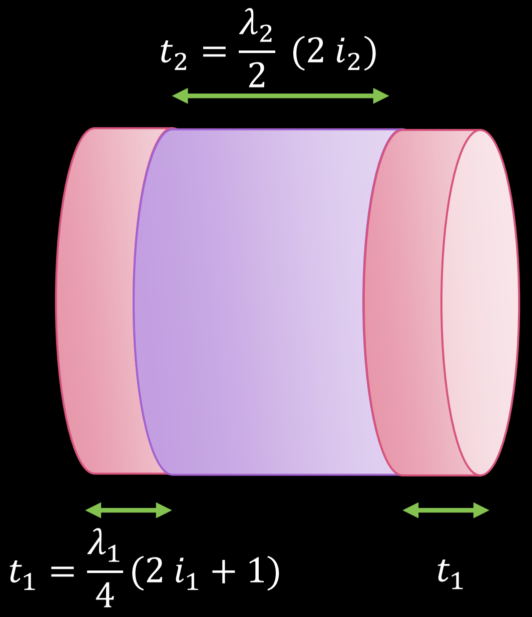


Cris Montoya and Chetn Galla



Cris Montoya and Chetn Galla

FUTURE DIRECTION2: ADD MORE MASS!!



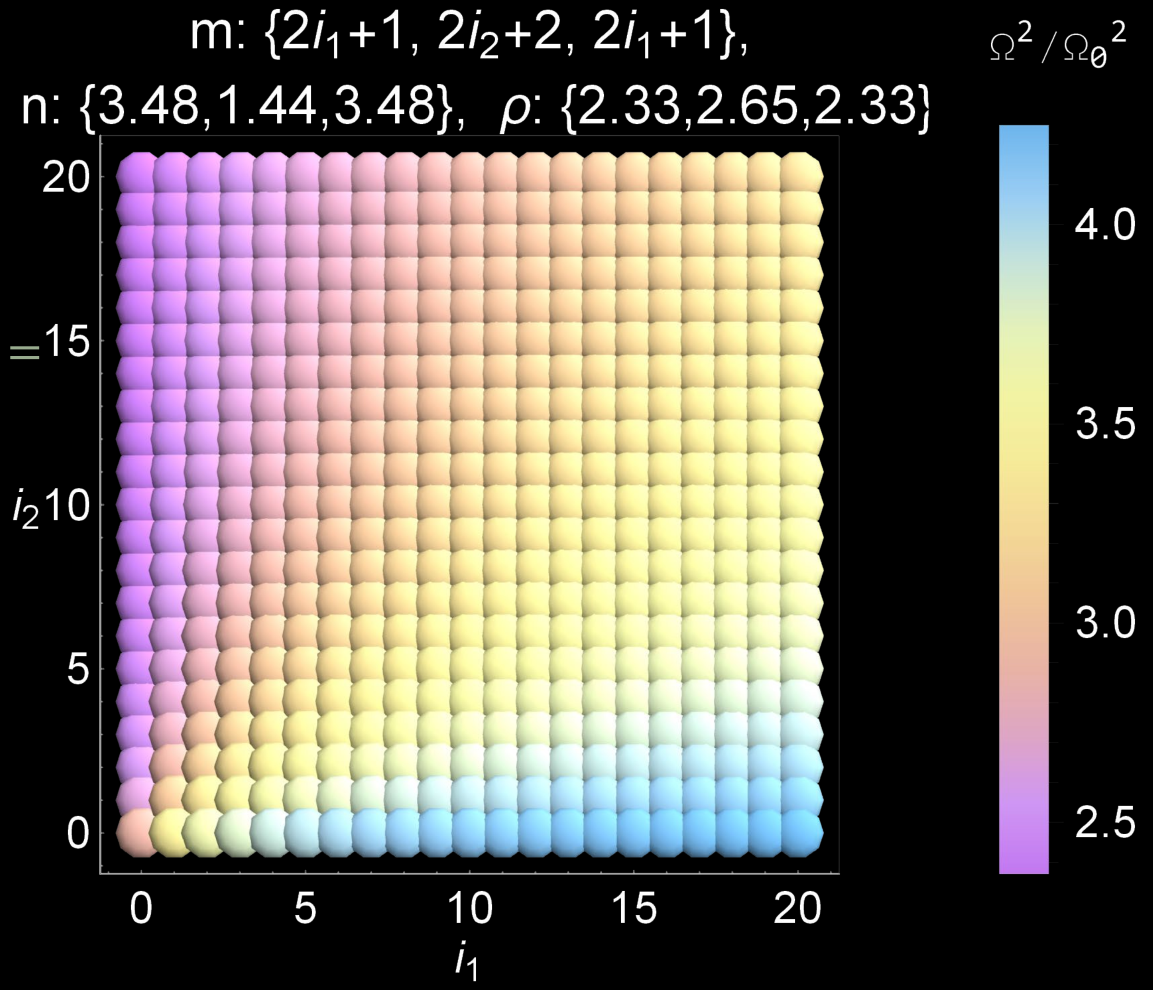
$t_2 = \frac{\lambda_2}{2}(2\,i_2)$

$t_1 = \frac{\lambda_1}{4}(2\,i_1 + 1)$

t_1

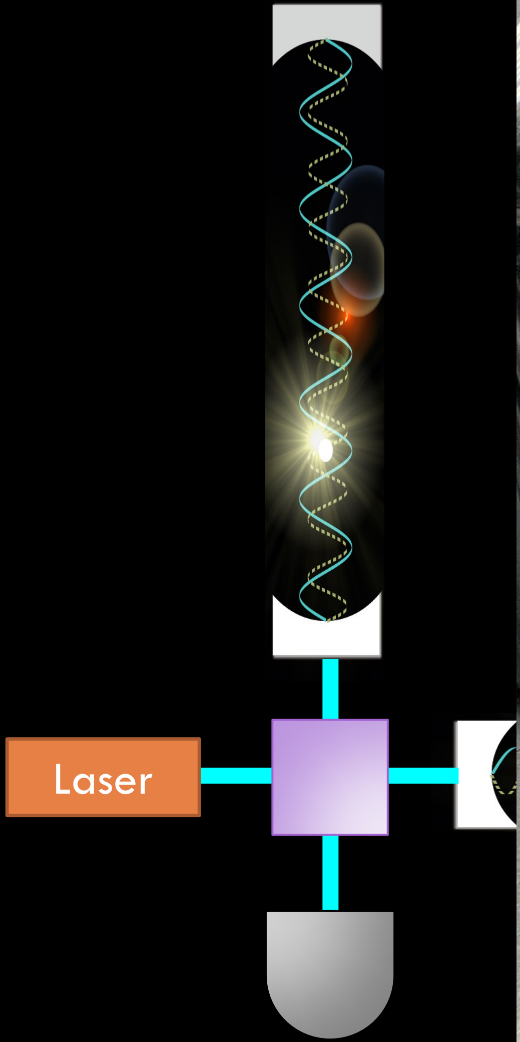
Modified wavelength$\lambda_i = \frac{\lambda_0}{n_i}$

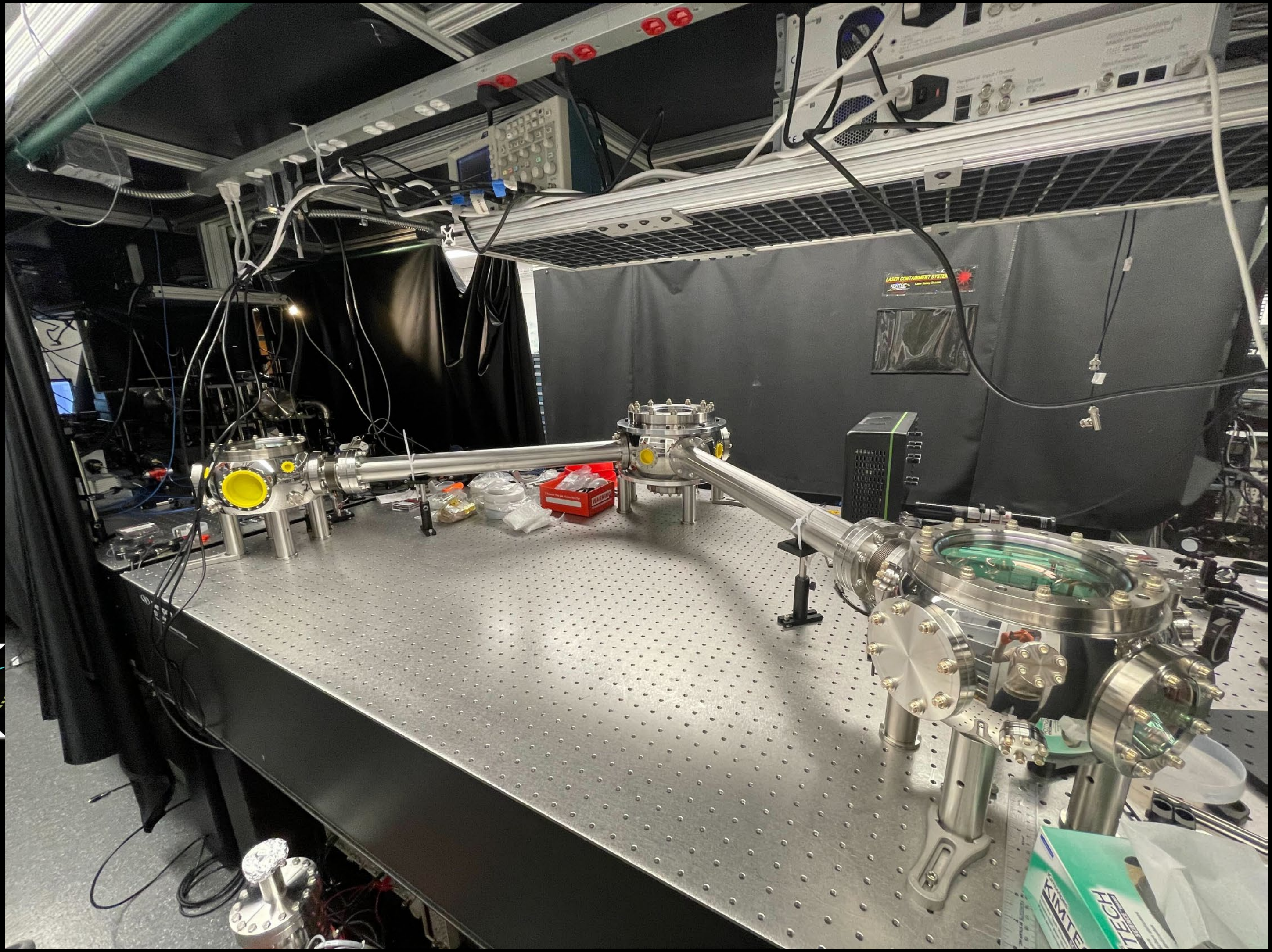
$$\Omega_0^2 = \frac{8\pi P(1 - e^{-2R^2/w^2})}{c\lambda^2 \rho_0 R^2}$$



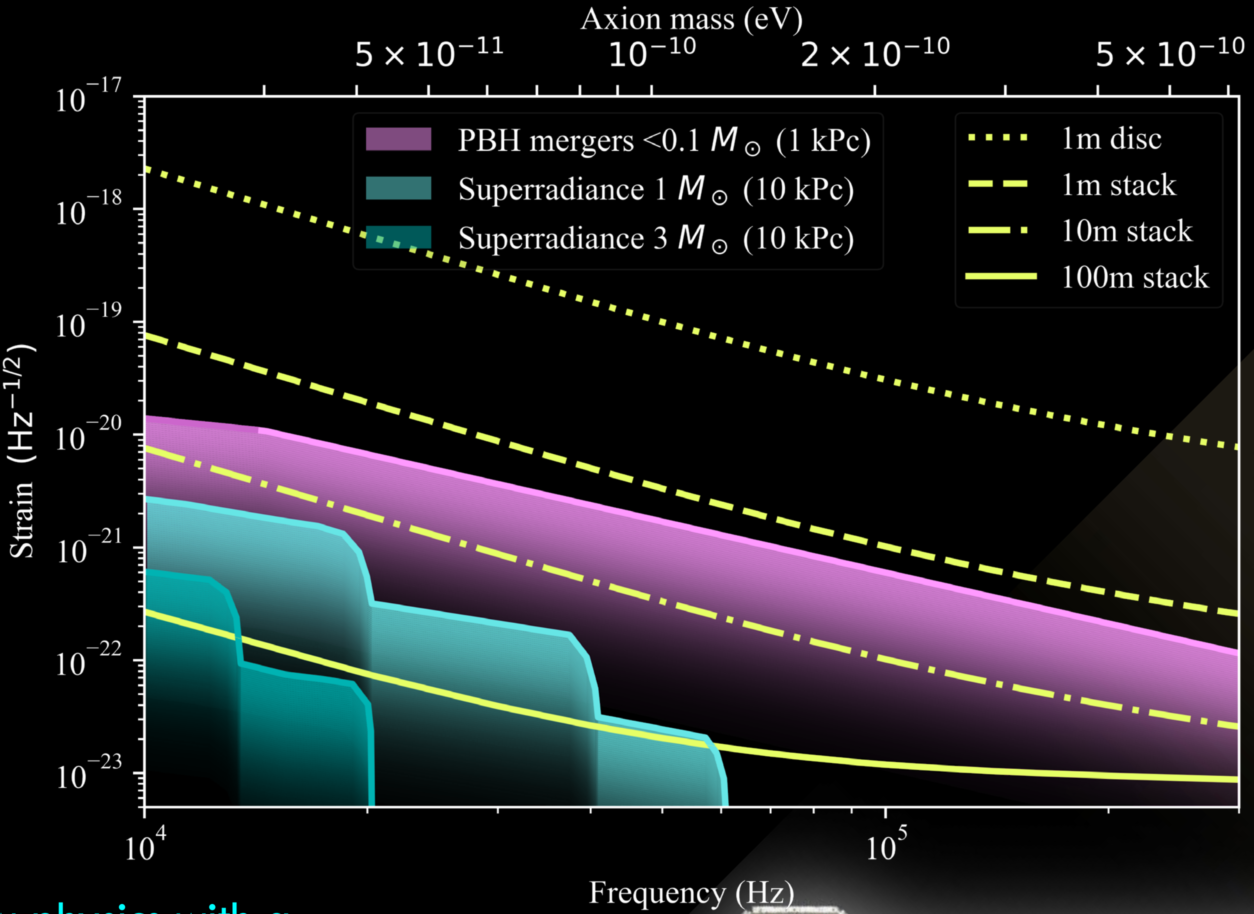
Preliminary: Aggarwal et al.

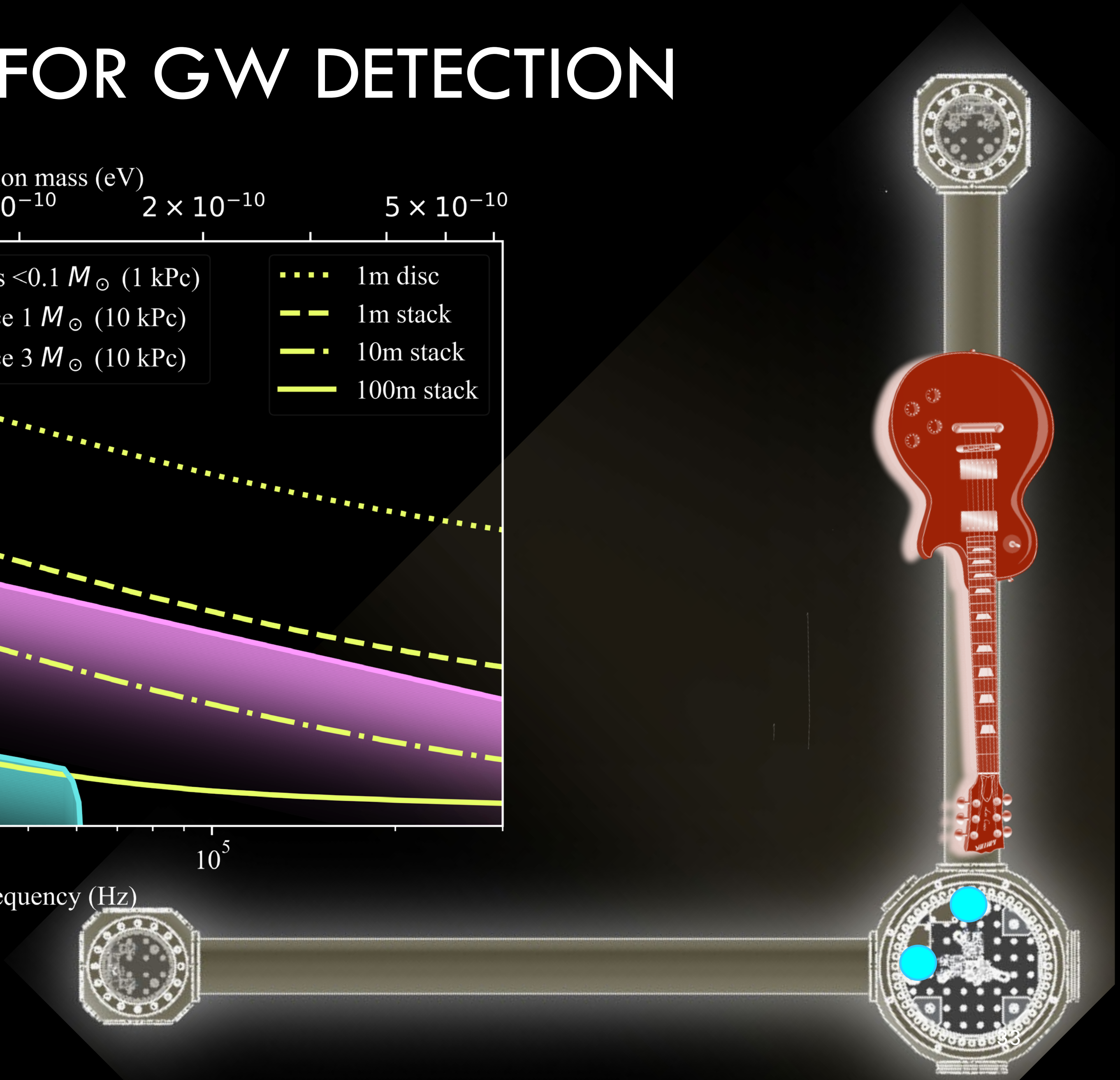
TABLETOP DETECTOR





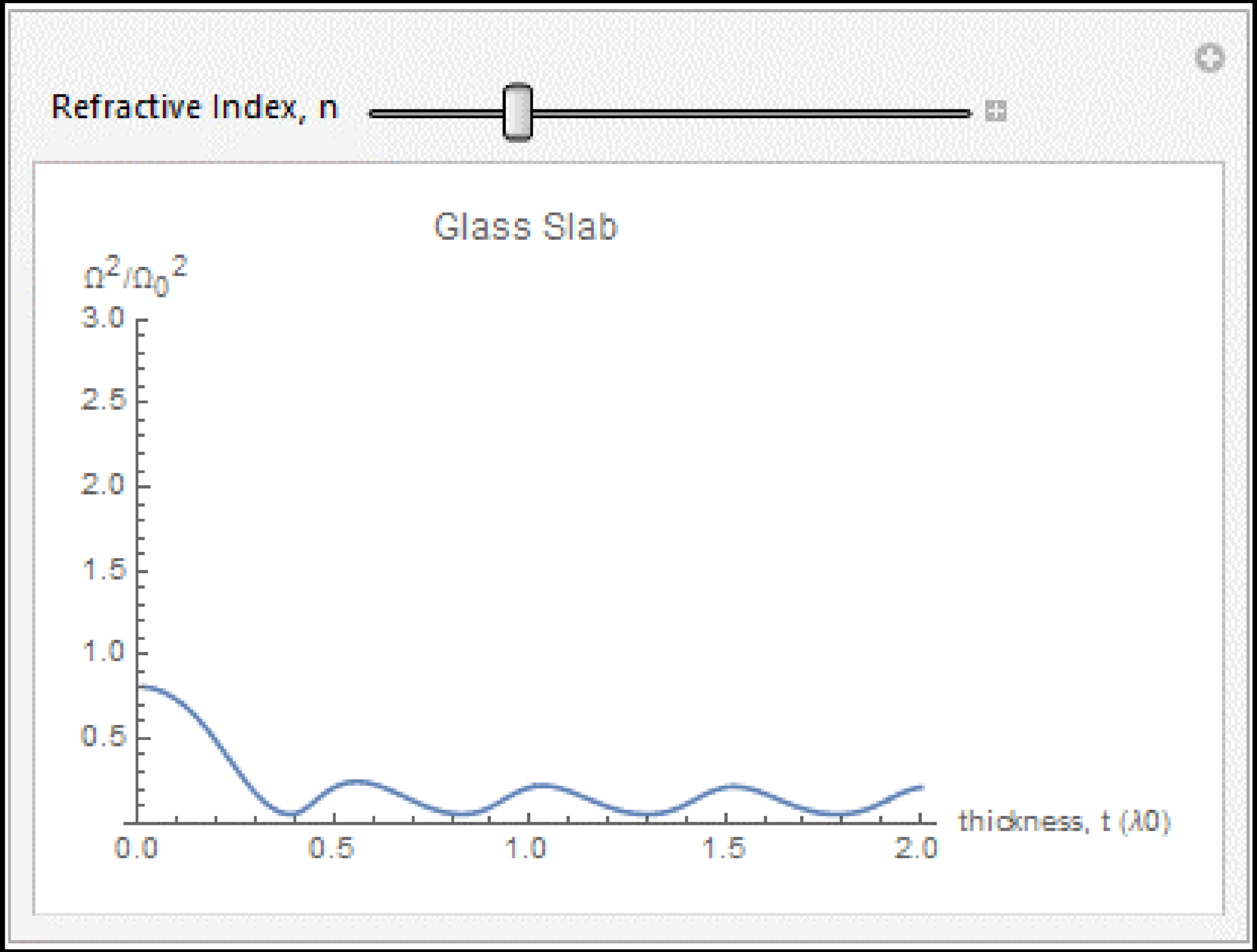
OPTICAL TRAPPING FOR GW DETECTION



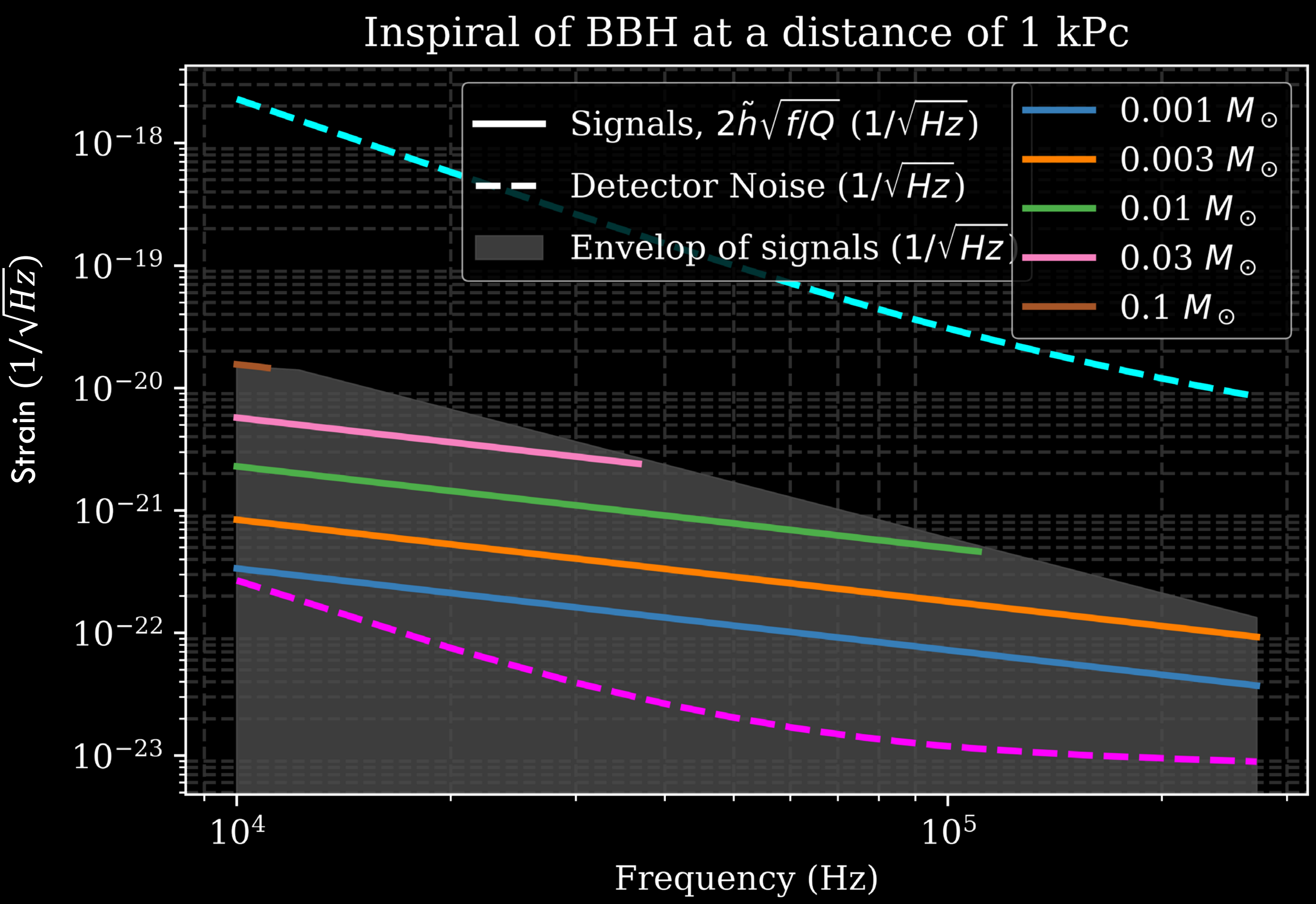


Searching for new physics with a levitated-sensor-based GW detector
NA, G. Winstone, M. Teo et al
arxiv:2010.13157

TRAP FREQUENCY FOR SINGLE CYLINDER

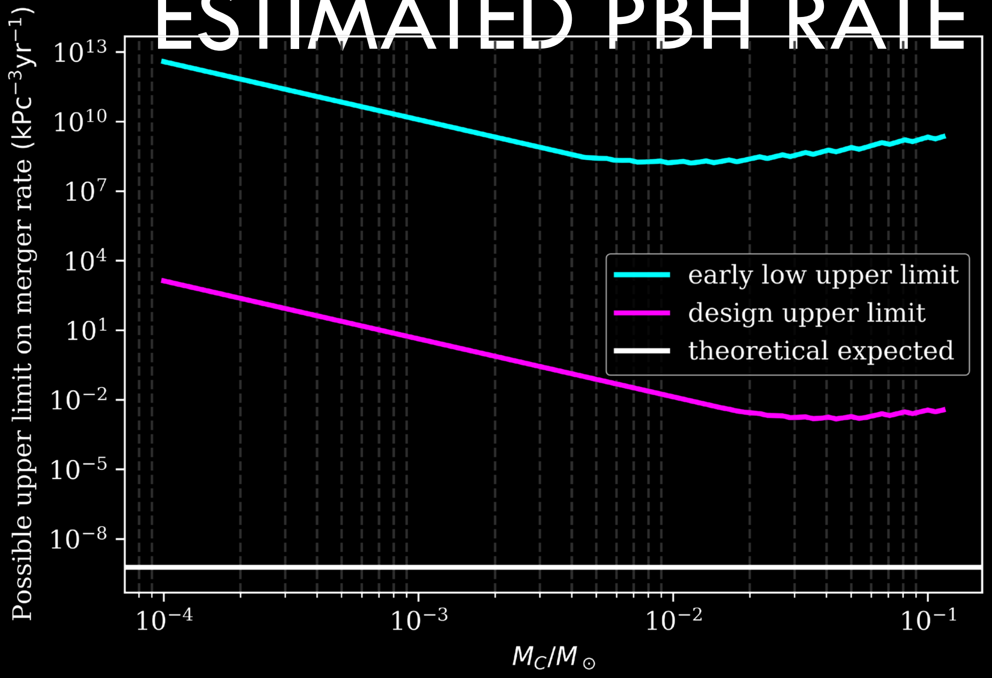


DETAILED PBH STRAIN

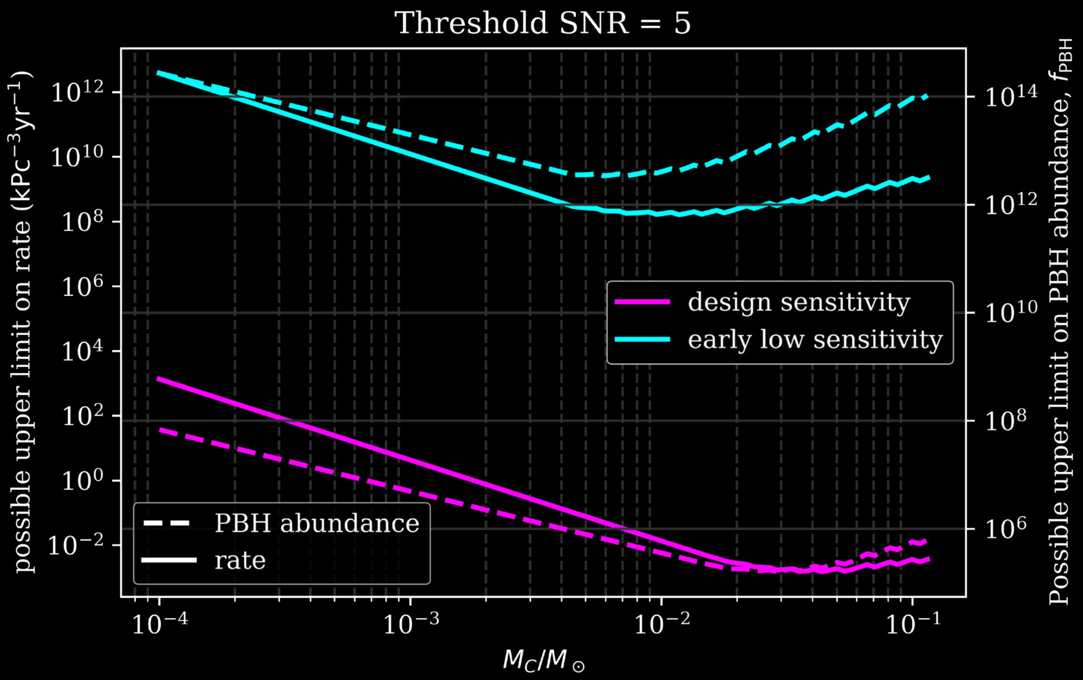


Preliminary: Aggarwal et al.

ESTIMATED PBH RATE UPPER LIMIT

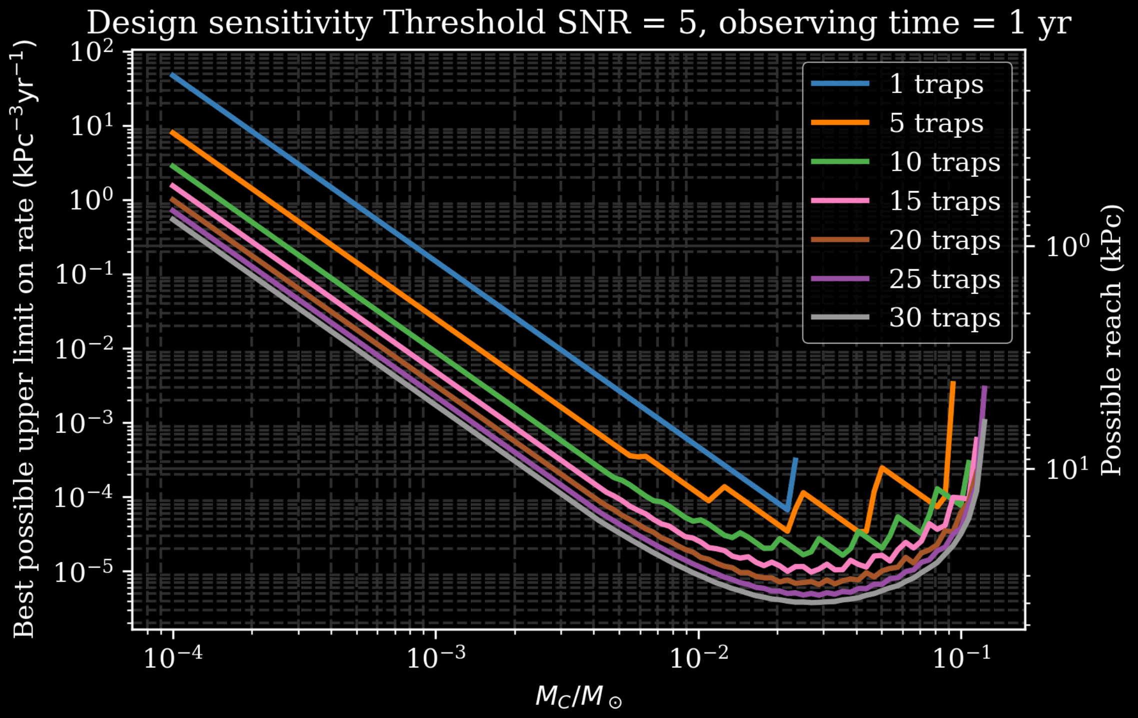


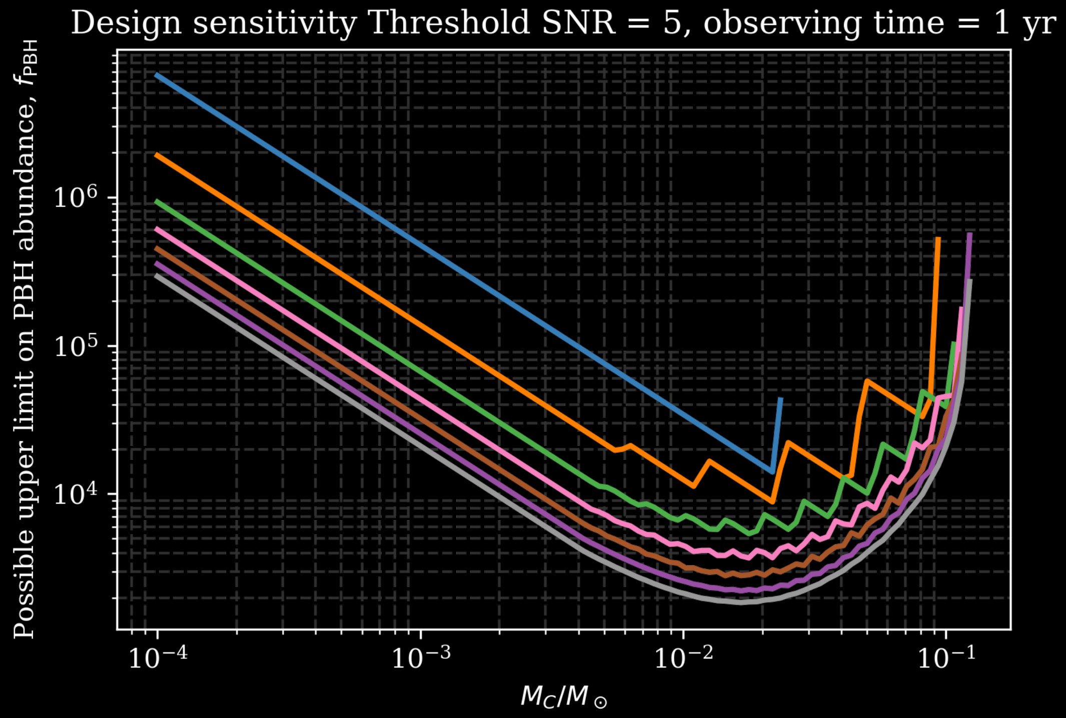
PBH binary formation+merger models



Preliminary: Aggarwal et al.

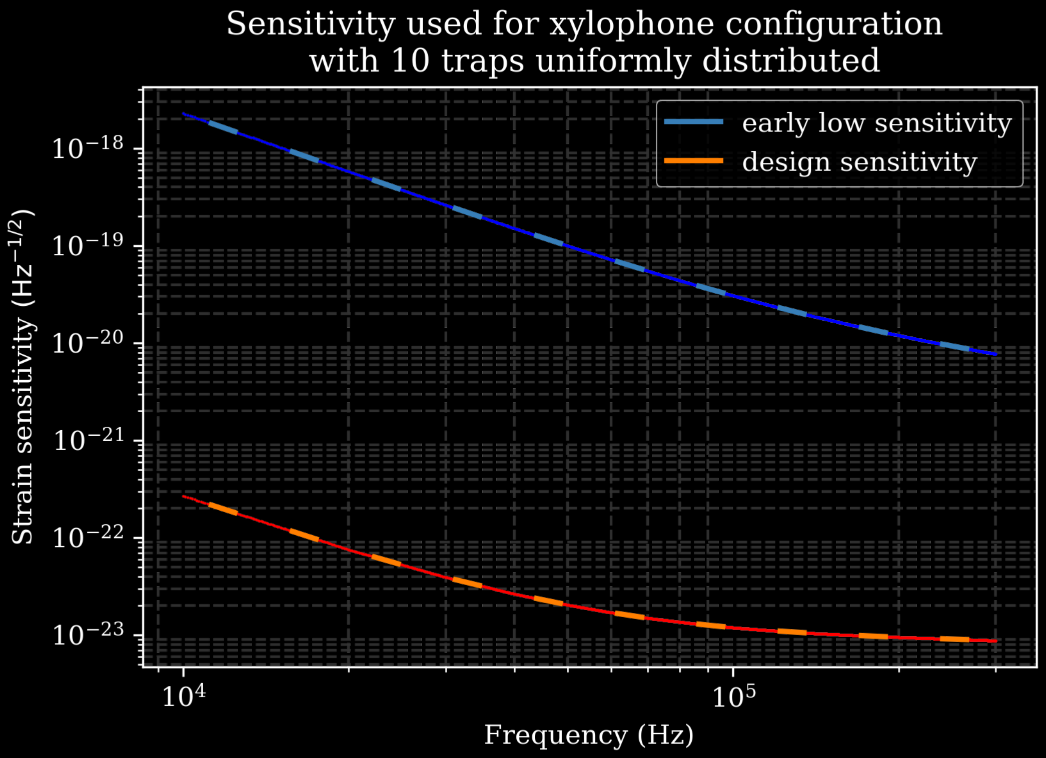
CHANGE NUMBER OF TRAPS

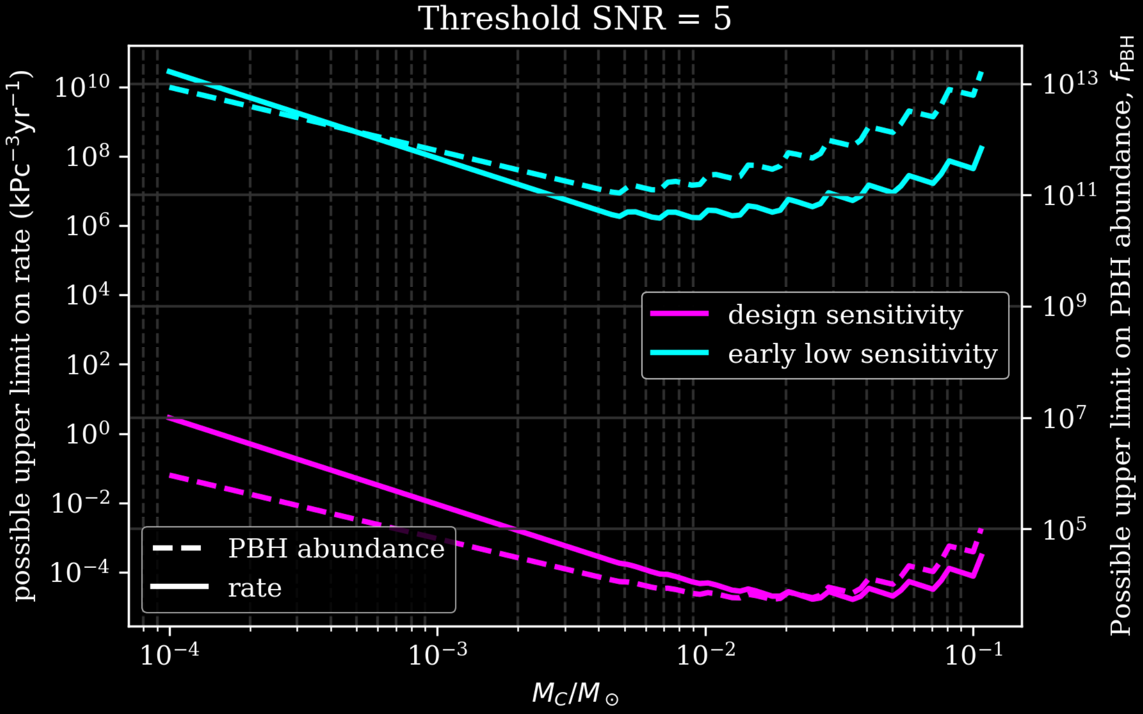




Preliminary: Aggarwal et al.

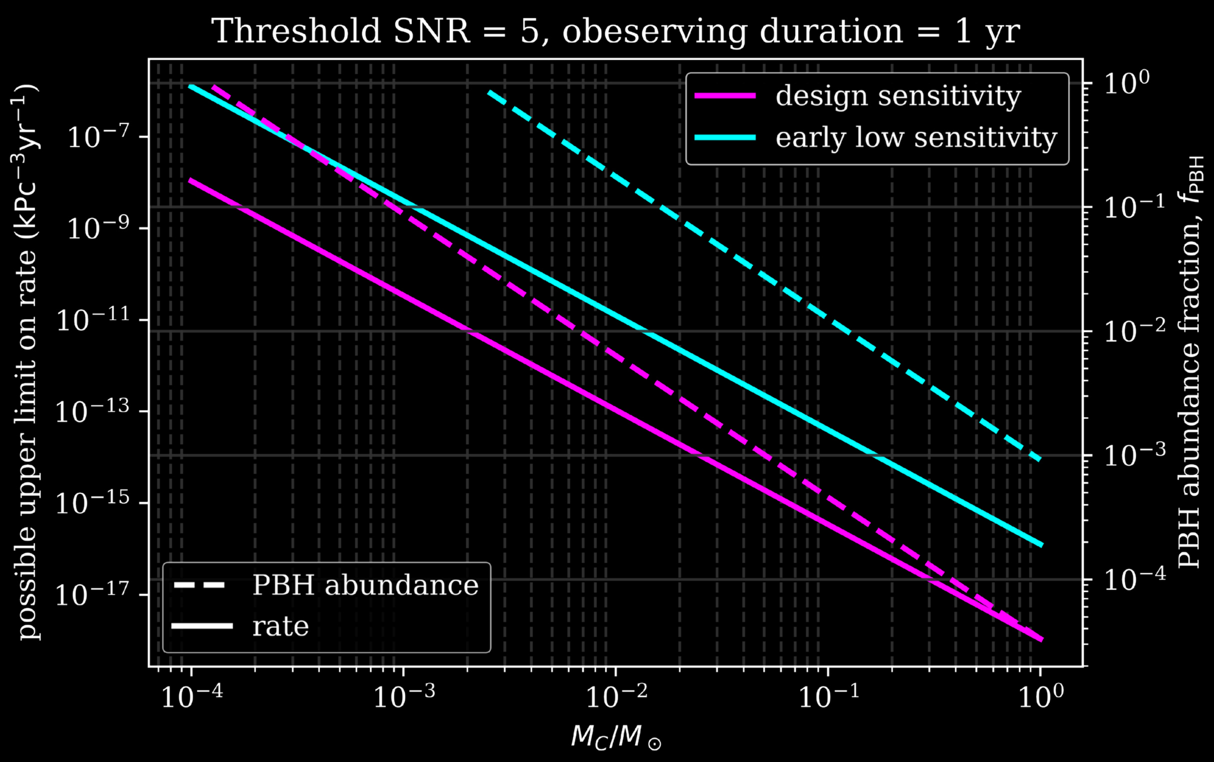
FUTURE DIRECTION 1: XYLOPHONE



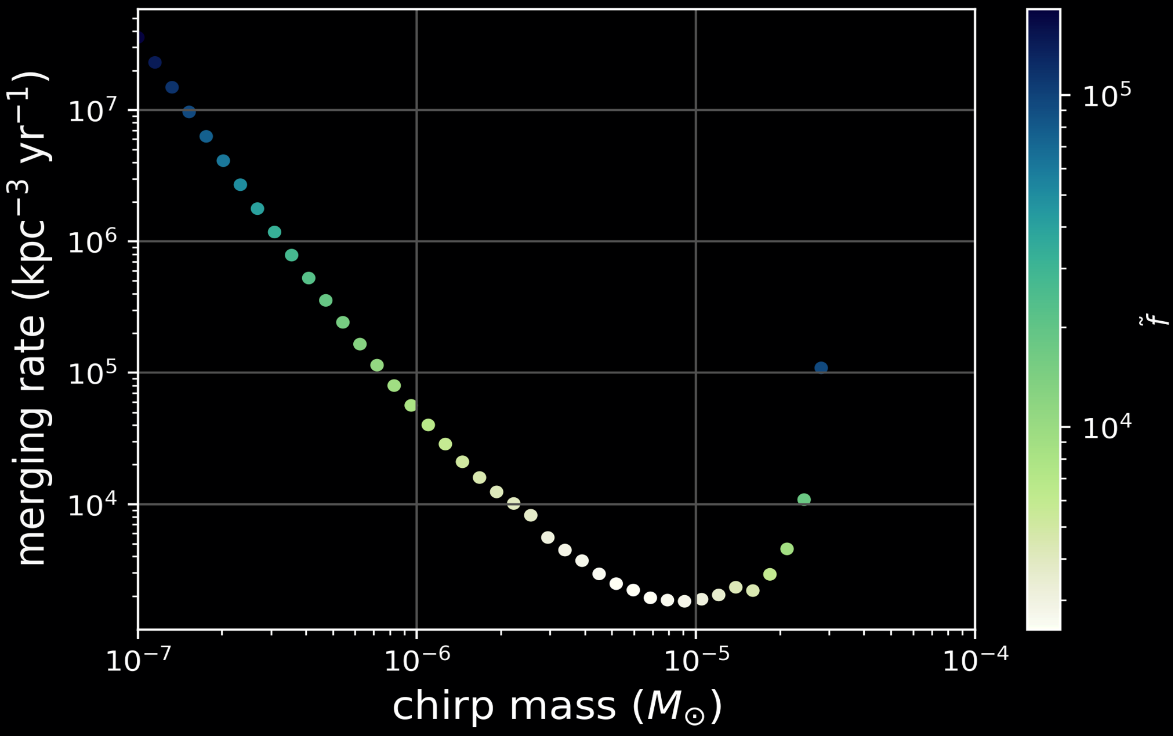


Preliminary: Aggarwal et al.

EXCLUSION W/ LIGO



Preliminary: Aggarwal et al. (see LIGO T2000423)

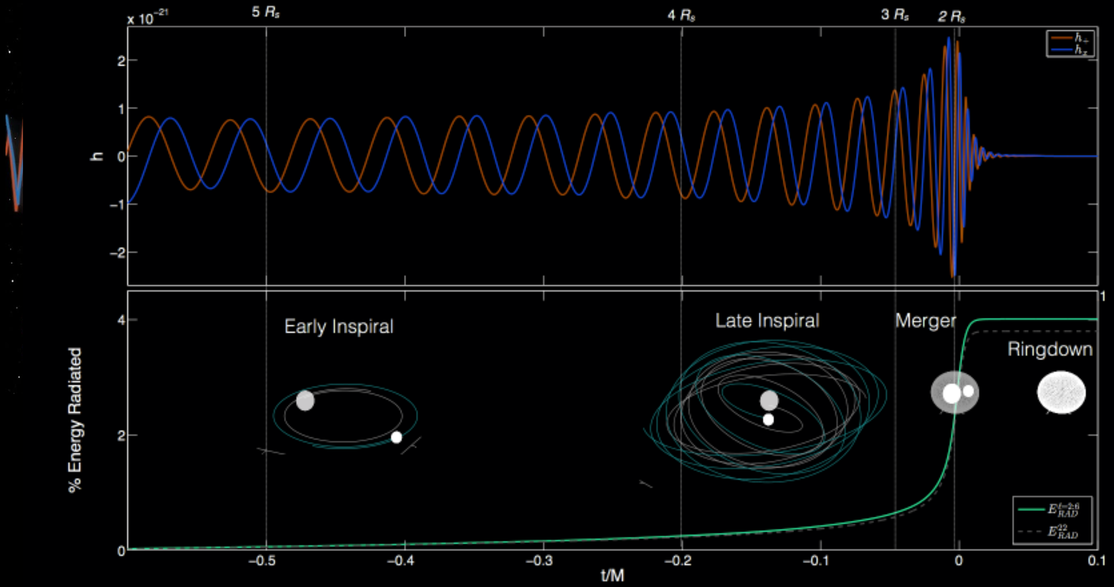


Miller, A., Aggarwal, N., A. *et al*. Constraints on planetary and asteroid-mass primordial black holes from continuous gravitational wave searches. PRD, 2022

CBC VS CW SEARCHES


LIGO, NSF, Illustration: A. Simonnet (SSU)

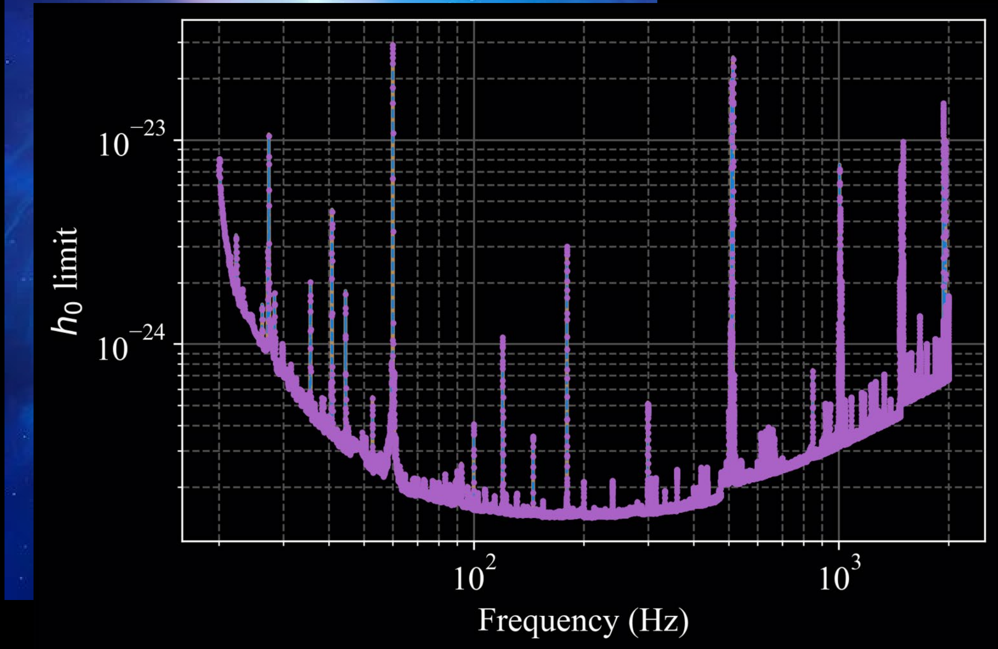
"Chirping" GW



Monochromatic GW

$$\dot{f} < 10^9\ \mathrm{Hz/s}$$

$$f_{GW}(t) = f_{GW}(t_0) + \dot{f}(t - t_0)$$



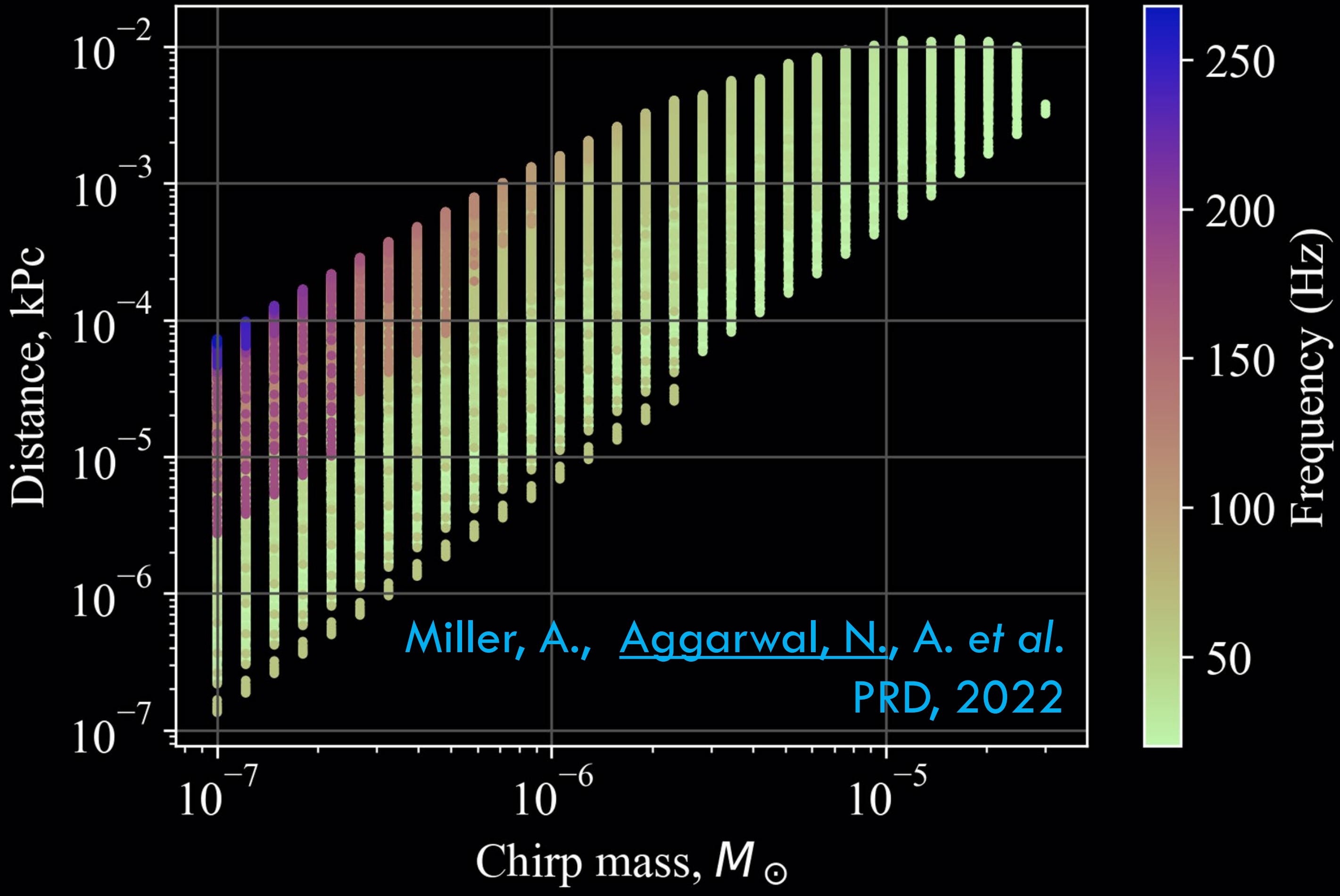
DISTANCE LIMIT FOR EACH M_c AND f_{GW}

$$h_0 = \frac{4}{\enclose{circle}{d}}\left(\frac{G\,\enclose{circle}{\mathcal{M}}}{c^2}\right)^{5/3}\left(\frac{\pi \enclose{circle}{f_{GW}}}{c}\right)^{2/3}$$

CW constraints:

$$\dot{f} < 10^9\ \mathrm{Hz/s}$$

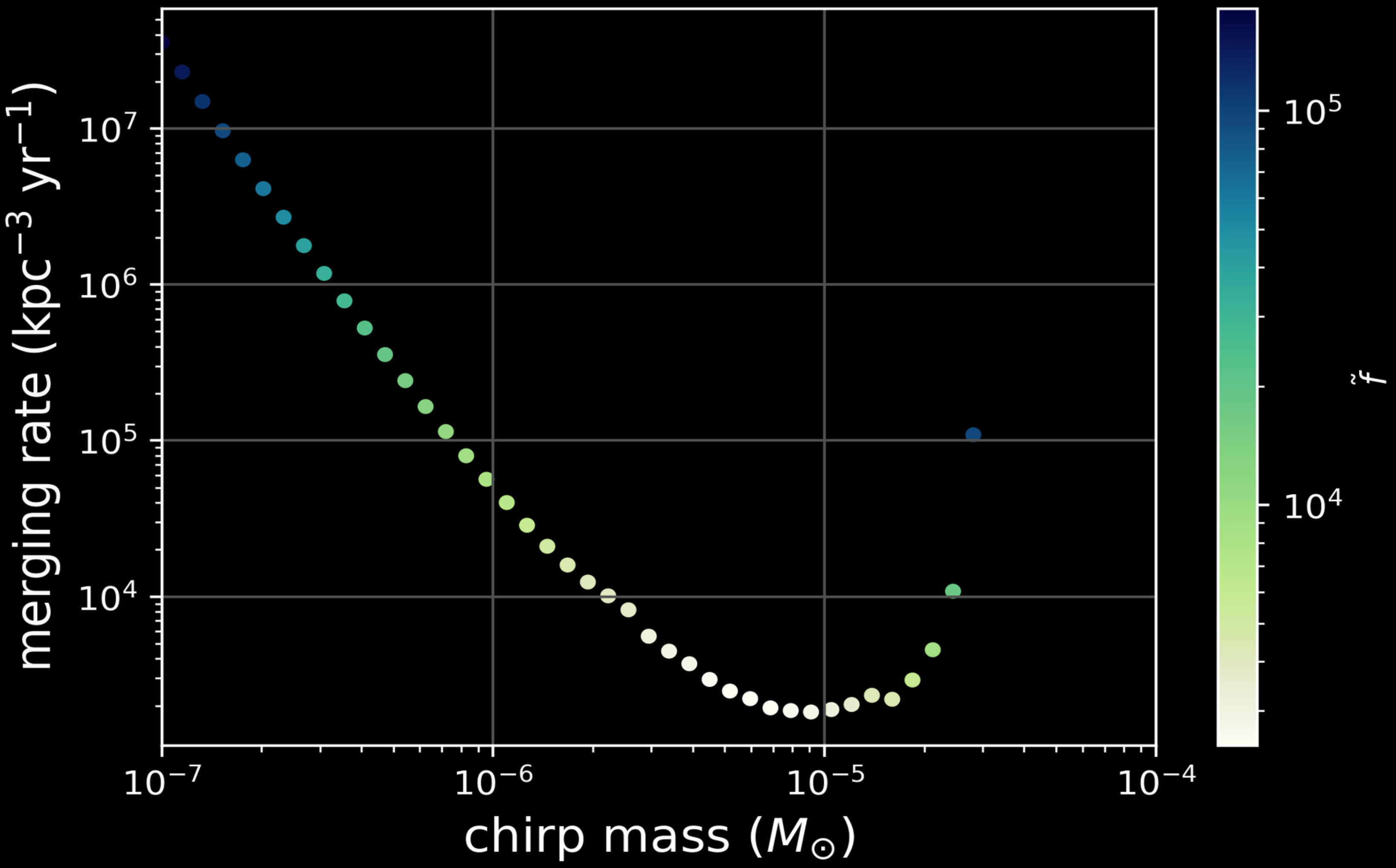
$$f_{GW}(t) = f_{GW}(t_0) + \dot{f}(t - t_0)$$



Miller, A., Aggarwal, N., A. *et al.*
PRD, 2022

EXCLUSION W/ LIGO

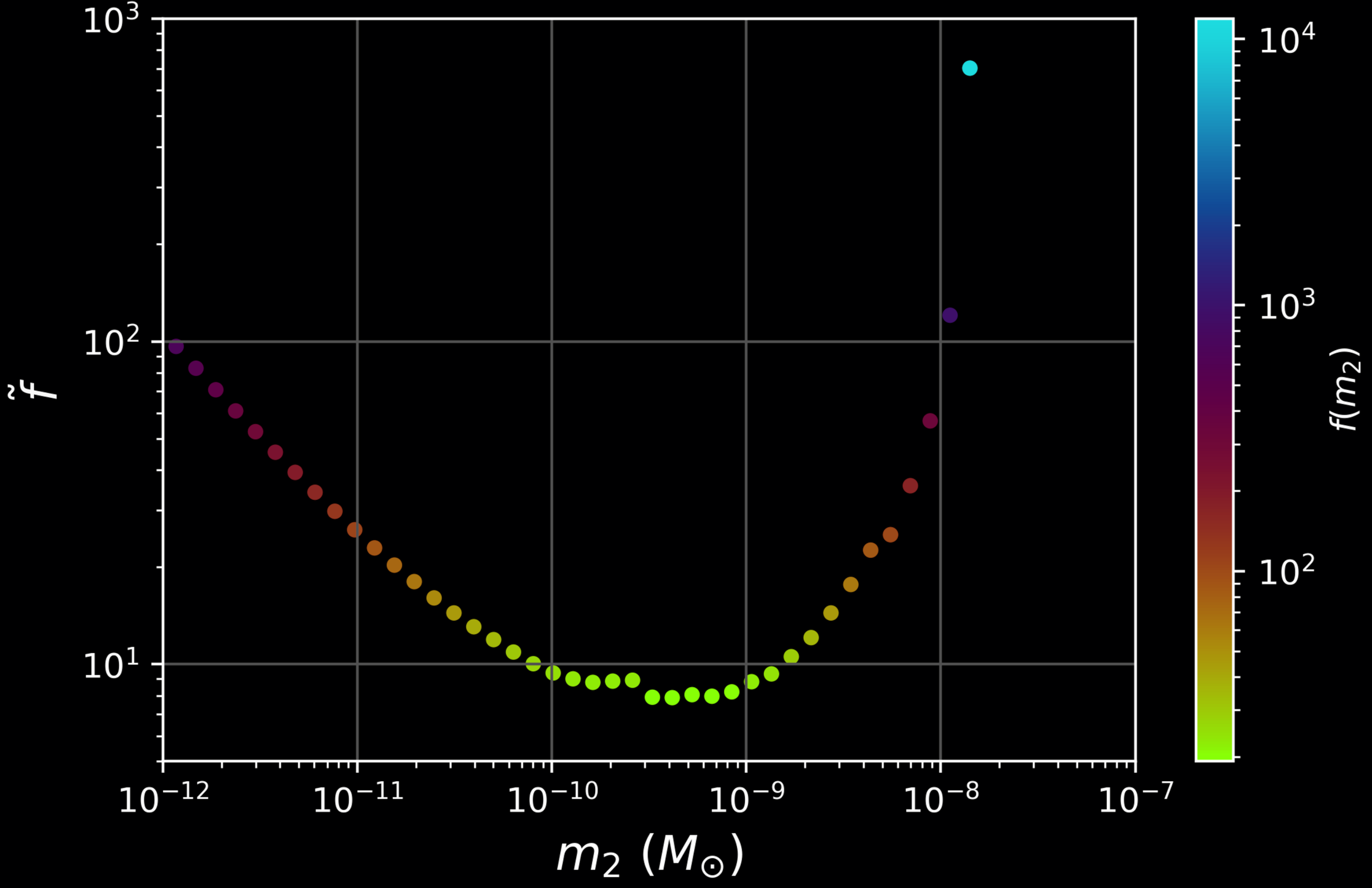
Miller, A., Aggarwal, N., A. *et al*. Constraints on planetary and asteroid-mass primordial black holes from continuous gravitational wave searches. PRD, 2022



CONSTRAINTS WITH ASYMMETRIC MASS RATIO

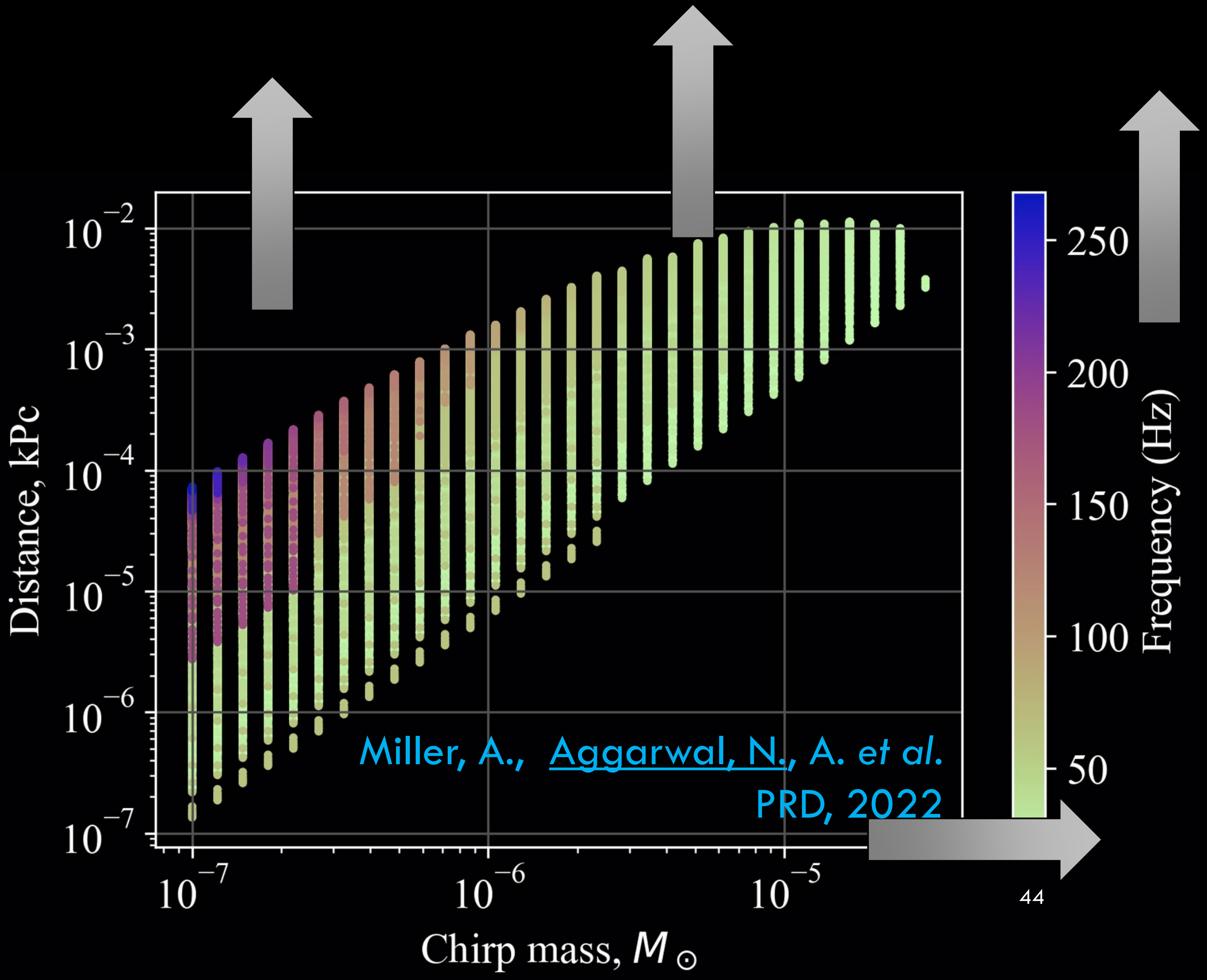
$m_1 = 2.5\ M_\odot$

Miller, A., Aggarwal, N., A. *et al*. Constraints on planetary and asteroid-mass primordial black holes from continuous gravitational wave searches. PRD, 2022



UPPER LIMITS ON PRIMORDIAL BLACK HOLES

1. Extend continuous-wave (CW) searches to faster frequency evolution
2. Combine CBC + CW for higher frequency GWs at a given mass
3. Use 1 & 2 to constrain PBHs of heavier masses
4. Combine constraints from multiple detectors



Miller, A., Aggarwal, N., A. *et al.* PRD, 2022