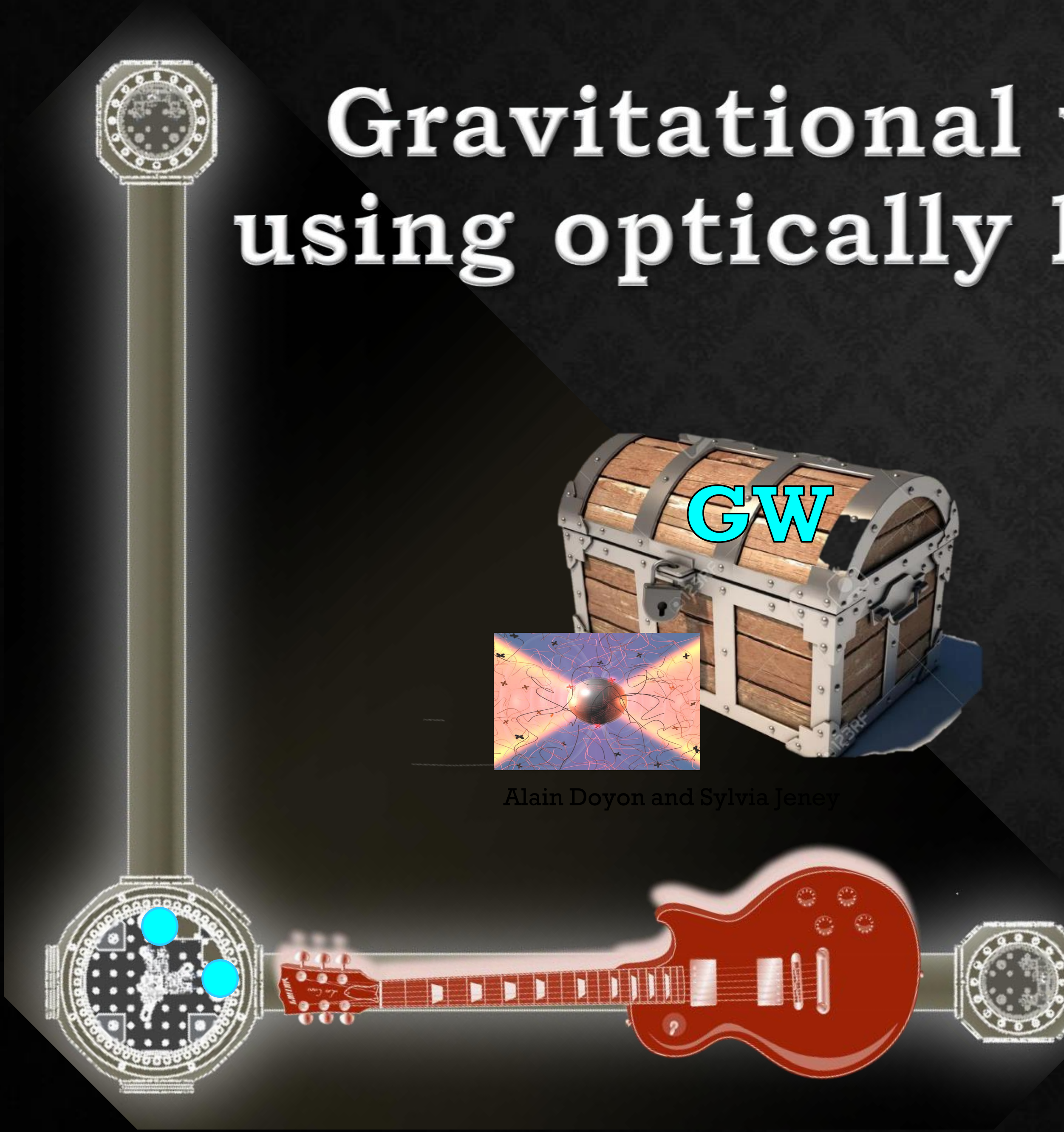
Gravitational wave detection using optically levitated sensors



Alain Doyon and Sylvia Jeney

MMCW Workshop

Jul 12, 2023

Nancy Aggarwal
Northwestern University
UC Davis

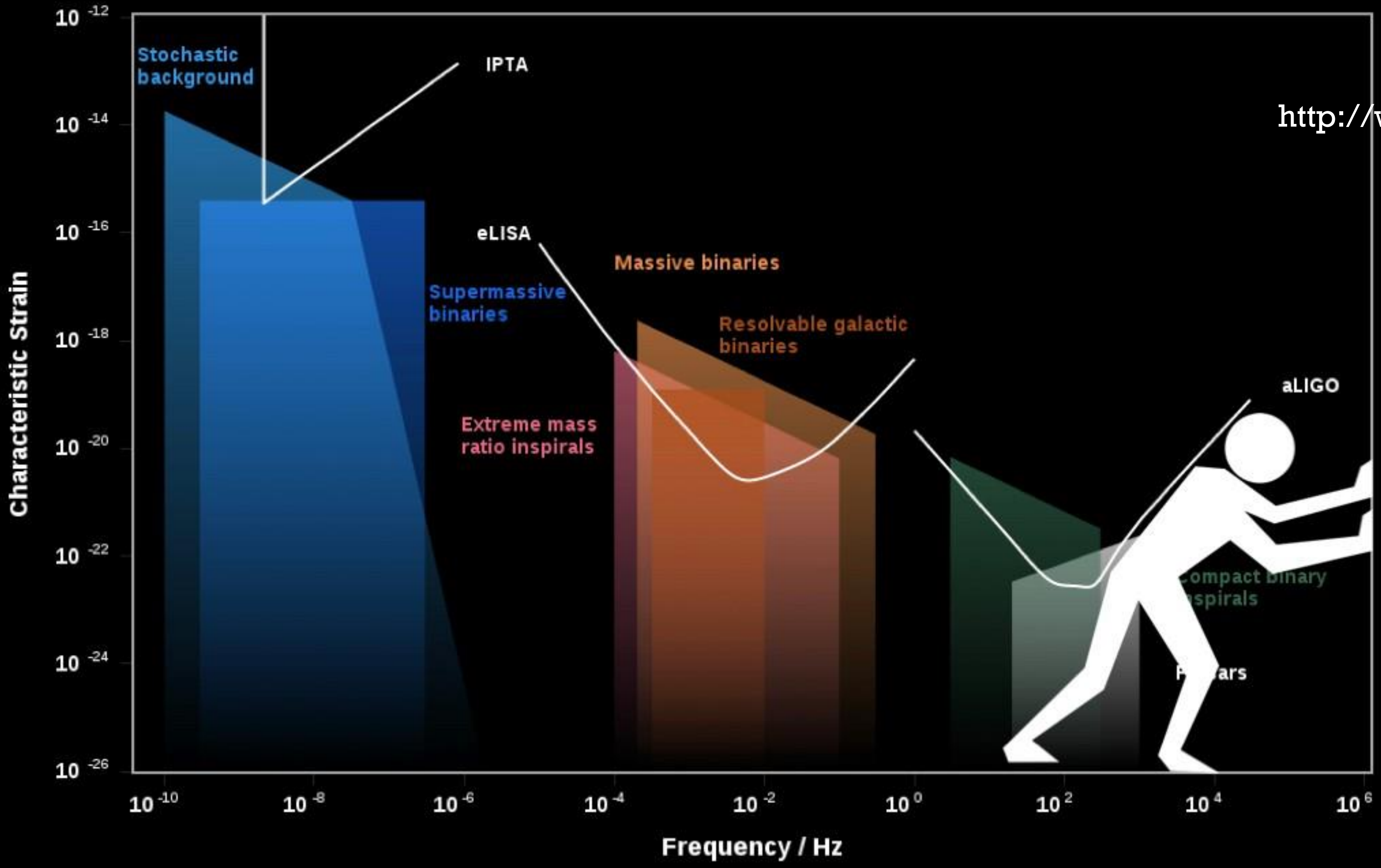
PHYSICS ∩ ME SUMMARY

Project	Summary	Activity

Quantum optomechanics for GW detection and quantum behavior of macroscopic objects	- Quantum behavior of optomechanical cavities in LIGO-like regime (unresolved sideband)
	- Optical trapping of heavy objects at high frequencies with low photon recoil
	  - GW detection
	  - Study quantum behavior of macroscopic objects
	  - Tests of quantum gravity
		- Room-temperature optomechanical quantum measurements (Nature 2019,568 364-367; Nature Physics 2020, 16, 784-788)
		- Proposal to trap flat composite objects (PRL 2022 128, 111101),
		- Demonstration of trapping of hexagons (PRL 2022 129, 053604)
		- Fabry-Perot Michelson integration with optical trapping

Direct detection of axion	- test for spin-dependent fifth-force mediated by the QCD axion - Characterization experiments & cryostat construction	- Testing for magnetic fields from source (PRR 2022 4, 013090) - Design & build custom non-magnetic low-vibration multi-temperature cryostat
Primordial BH detection	- Range and possible upper limits from levitated sensor detector on light primordial BHs - Probing PBH parameter space previously unexplored with LIGO data	- New method and constraints on ultralight PBHs using LIGO (PRD 2022)
Dilaton DM detection using GW detectors	- DM-induced modulation of solid reference cavity in comparison to suspended cavities - DM-induced modulation of beam splitter thickness in Michelson interferometers	- New method to constrain dilaton DM using LIGO (arxiv 2210.17487)
ultra-high-frequency GW and axion detection	- Design new detectors for UHF GWs - Calculate GW strain from sources in UHF band - Build prototypes	- Review (*Living Rev Relativ* **24,** 4 (2021)) - Organized workshops to discuss new concepts and methods

GWS ABOVE THE AUDIO BAND?

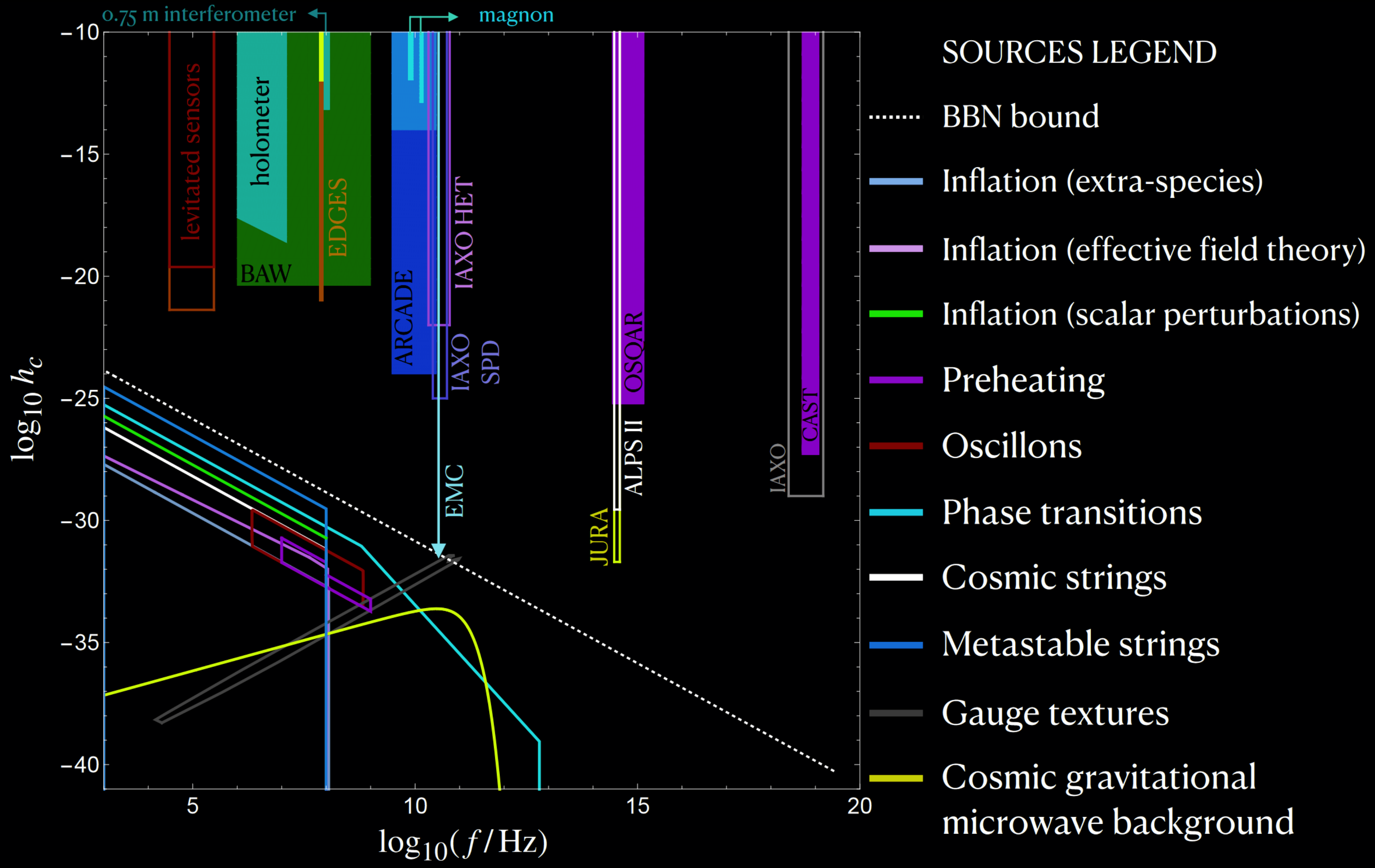


http://www.ctc.cam.ac.uk/activities/UHF-GW.php

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

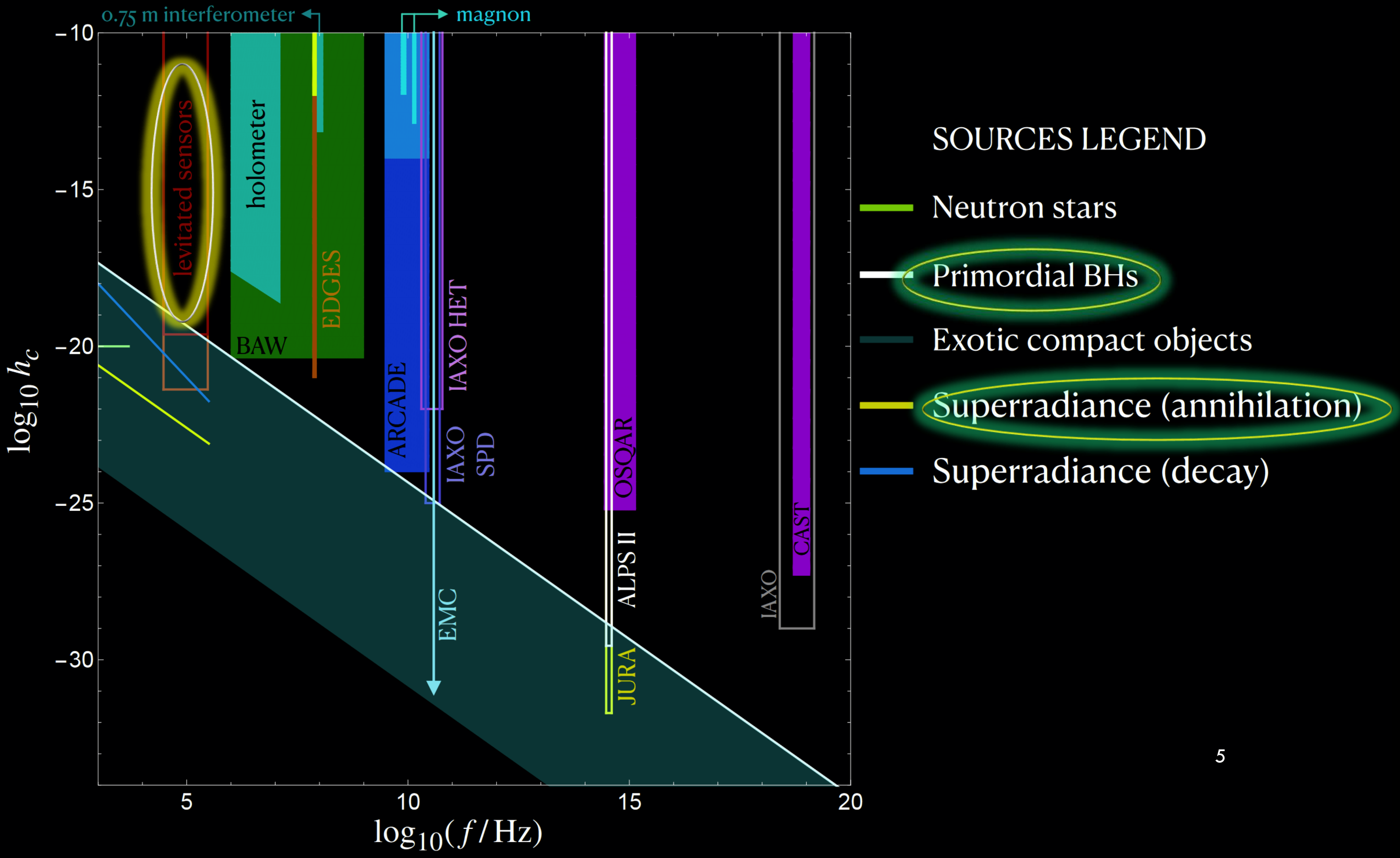
RECENT REVIEW ARTICLE

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).

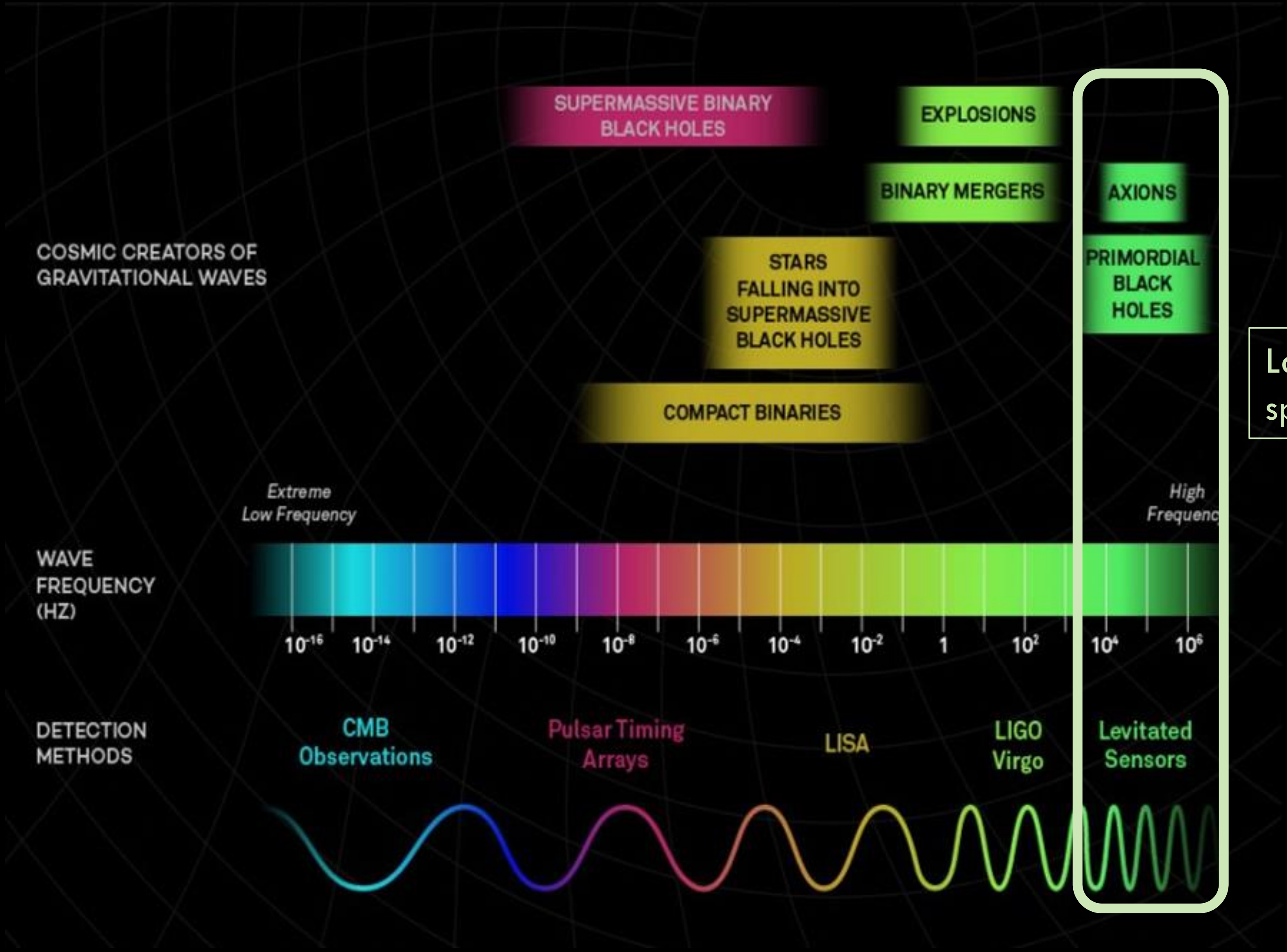


NUMEROUS INTERESTING SOURCES & PROMISING TECHS!!!

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).



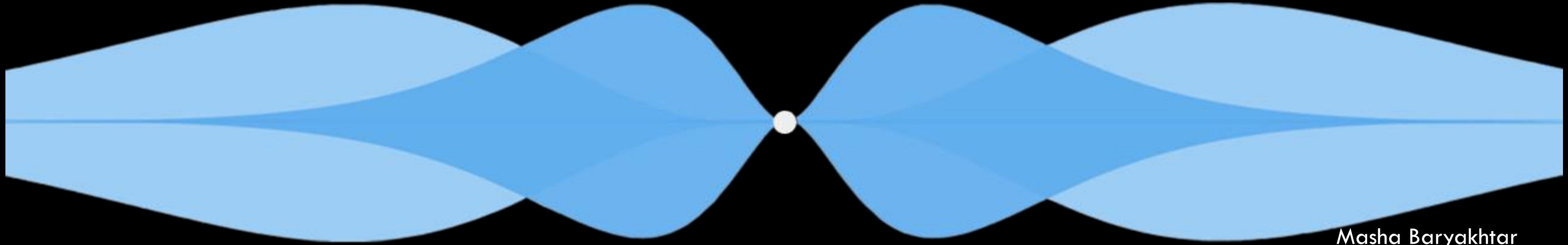
GW DETECTOR AT 10-300 KHZ



Latest addition to the spectrum!

SCIENCE CASE

BH Superradiance

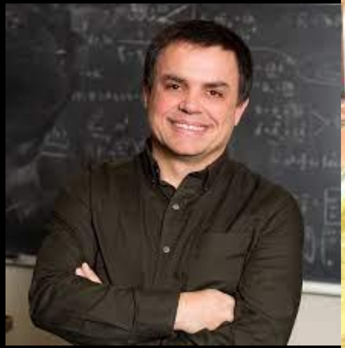


Masha Baryakhtar

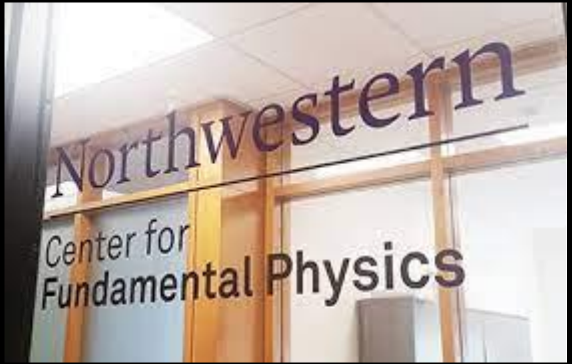
Primordial black holes

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

The unknown unknowns???



Office of Naval Research
ONR
Science & Technology

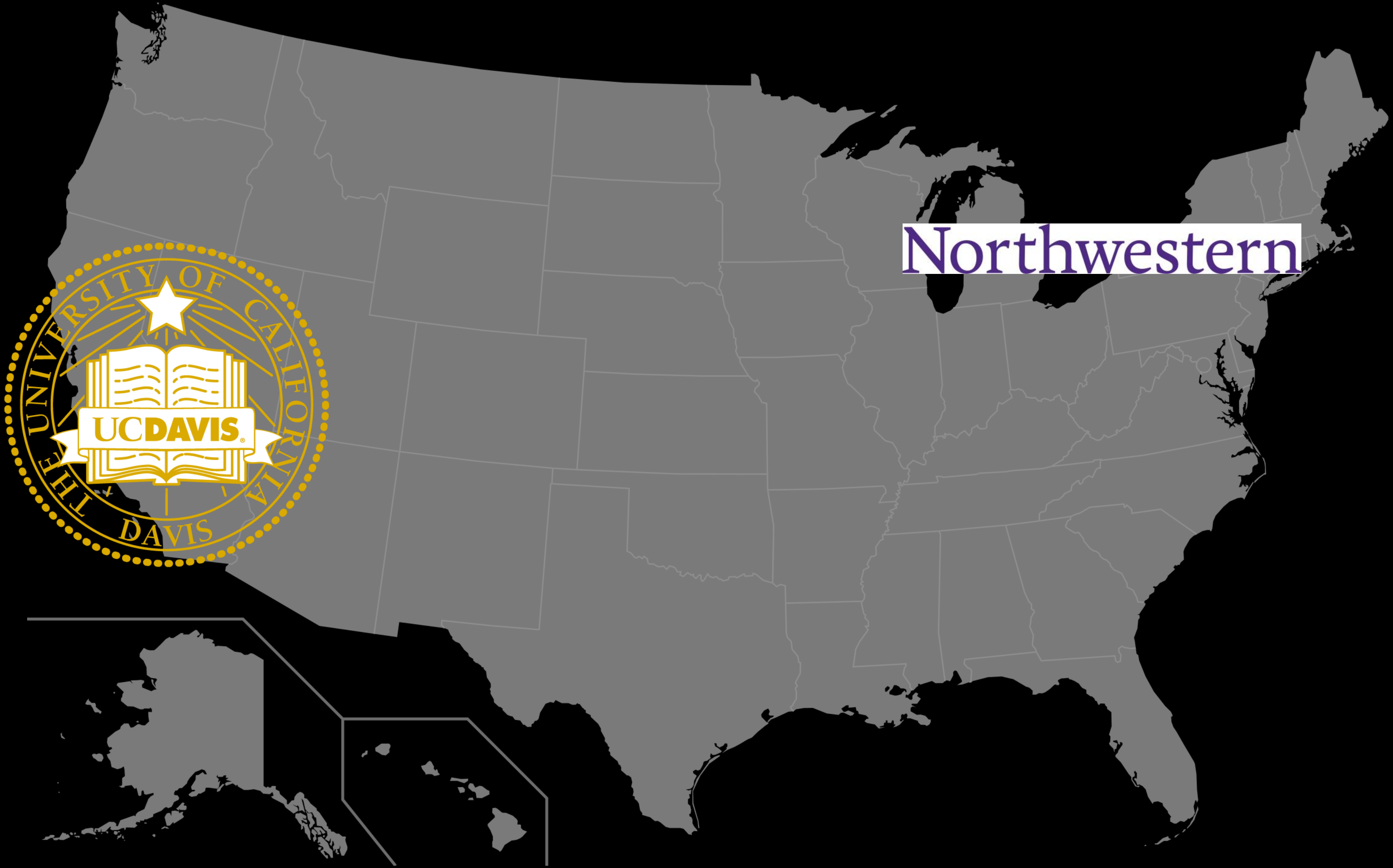


W.M. KECK
FOUNDATION

CIERA
CENTER FOR INTERDISCIPLINARY EXPLORATION
AND RESEARCH IN ASTROPHYSICS

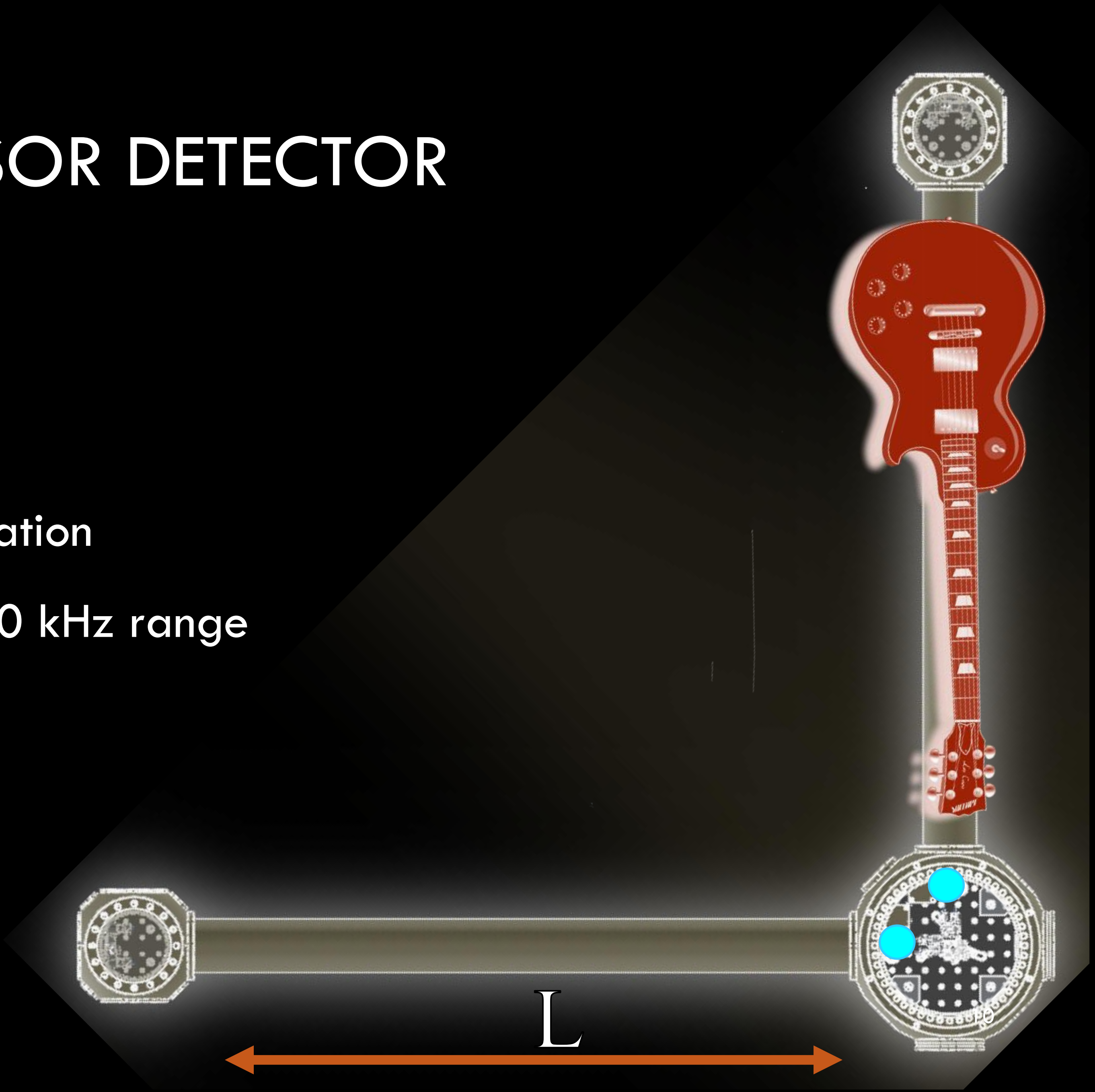
NSF

Northwestern

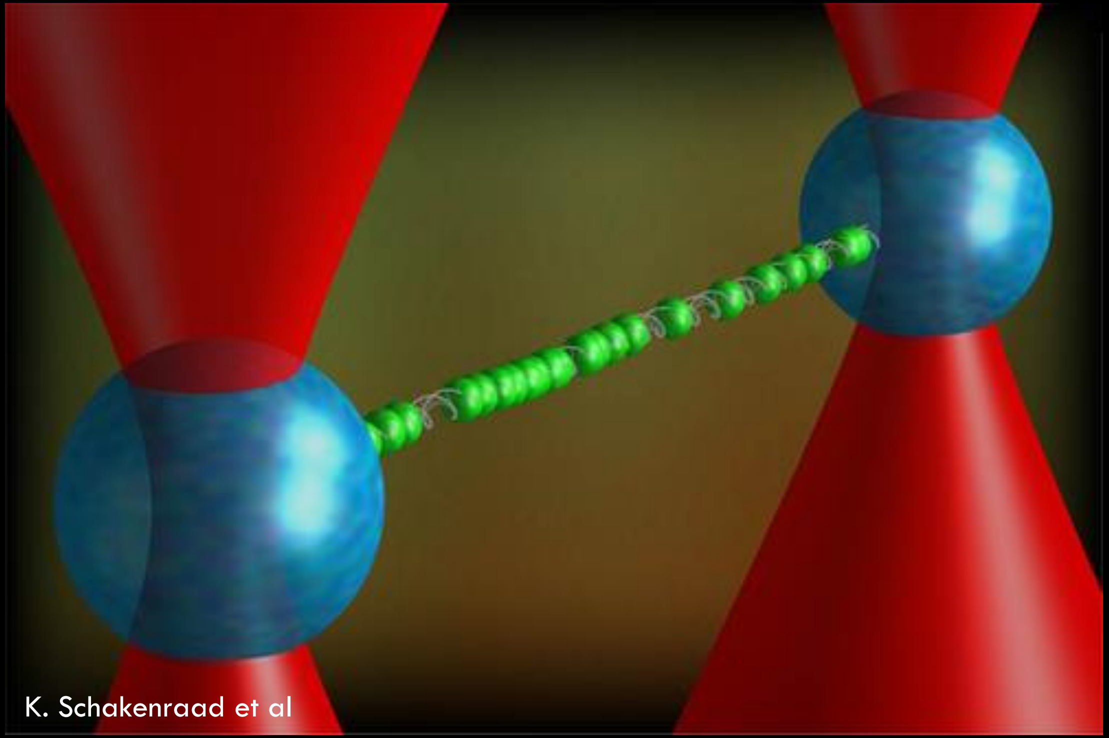

THE UNIVERSITY OF CALIFORNIA
UC DAVIS
DAVIS
Northwestern

LSD: LEVITATED SENSOR DETECTOR

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

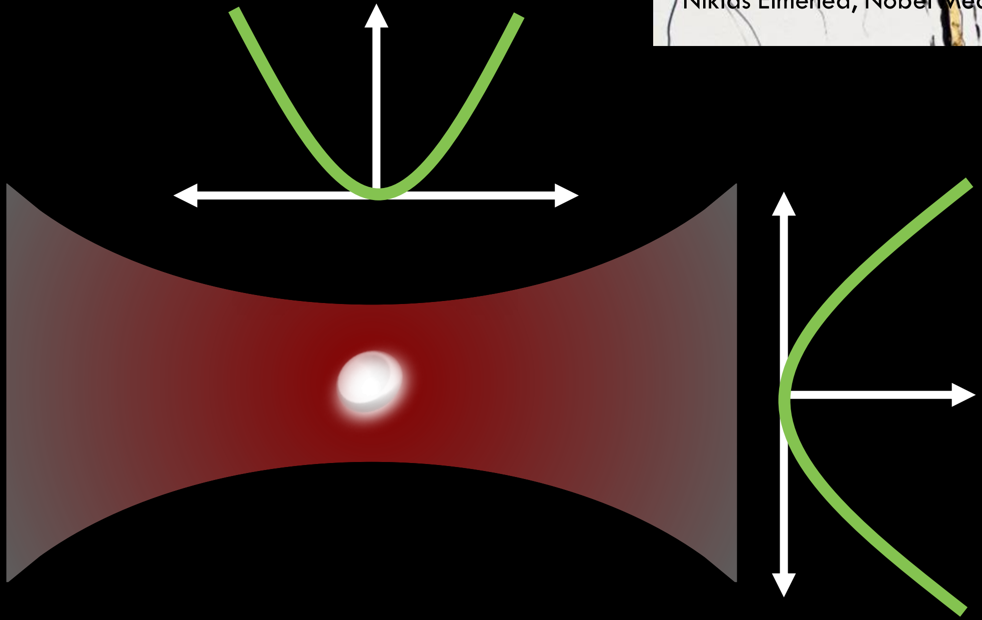


OPTICAL TRAPPING

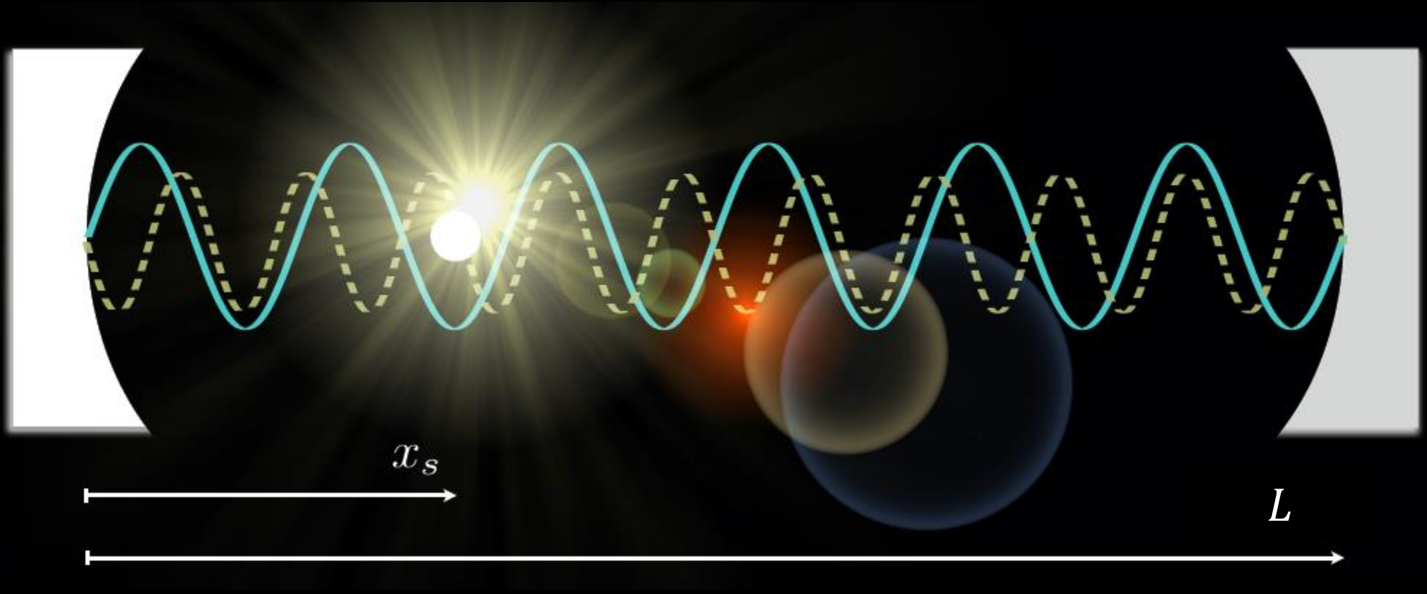

K. Schakenraad et al

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


Niklas Elmehed, Nobel Media



GW DETECTOR: STANDING WAVE OPTICAL TRAP



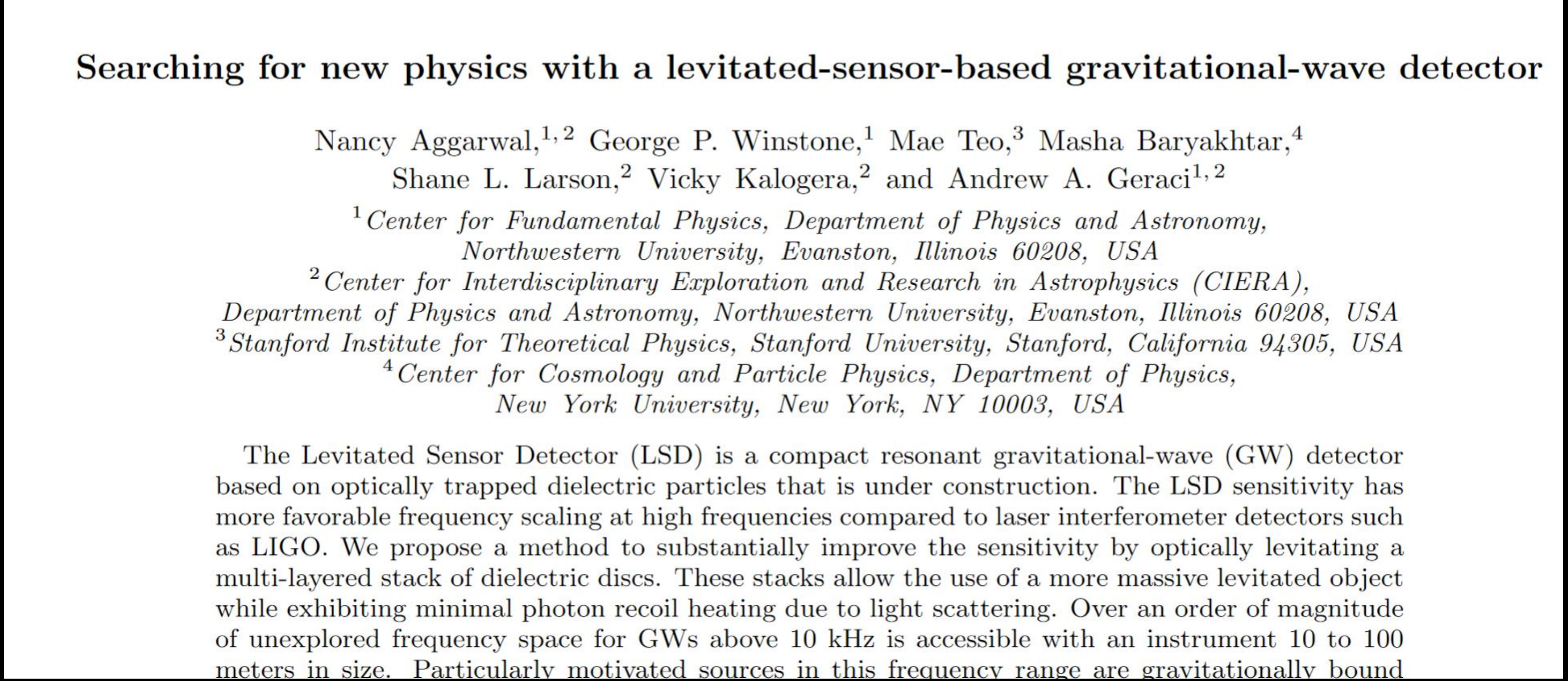
Arvanitaki and Geraci,
PRL 110, 071105 (2013)

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

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

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

HONING THE NOISE AND REFINING SOURCE ESTIMATE

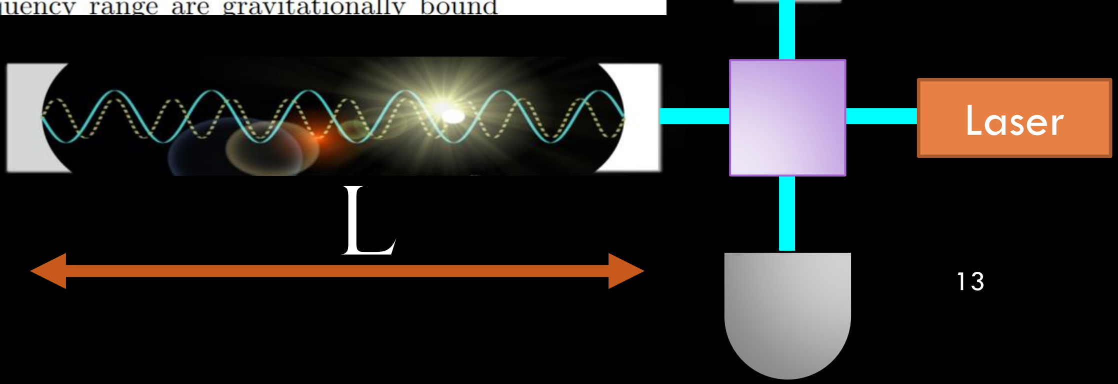


Searching for new physics with a levitated-sensor-based gravitational-wave detector

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

LIMITING NOISE: GAS DAMPING AND PHOTON RECOIL HEATING

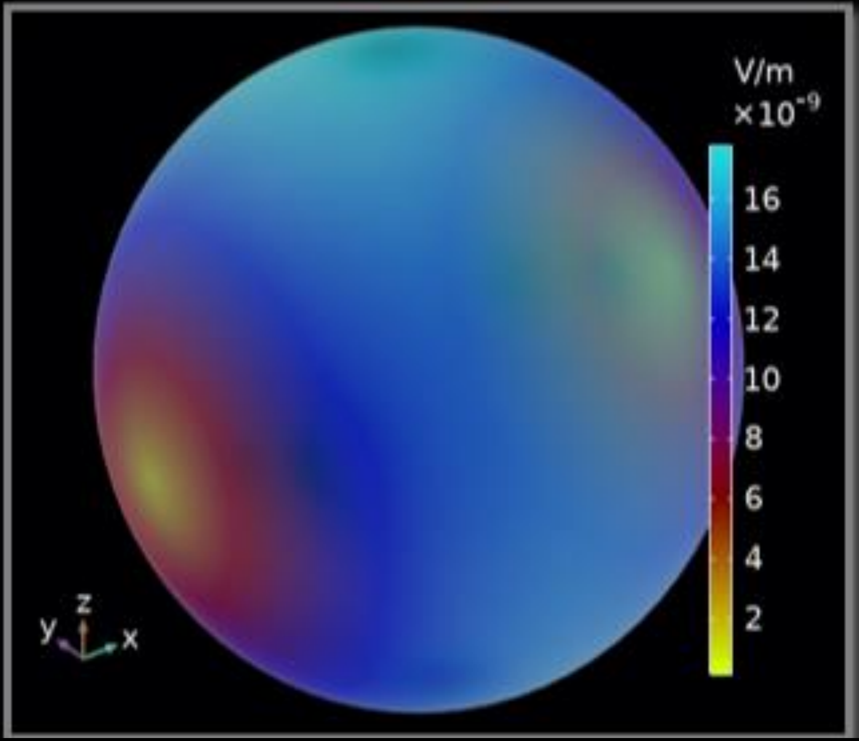
- $S_{FF} = 4\,M(\,k_B T\ \gamma_g + \ \hbar\,\omega\,\gamma_{sc})$
- Limit on resonance $(\Omega \rightarrow \Omega_T)$, $S_{hh} \sim 16\,\frac{1}{\Omega_T^2}\frac{1}{M}\frac{1}{L^2}(\hbar\,\omega\,\gamma_{sc} + k_B T\,\gamma_g)$

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

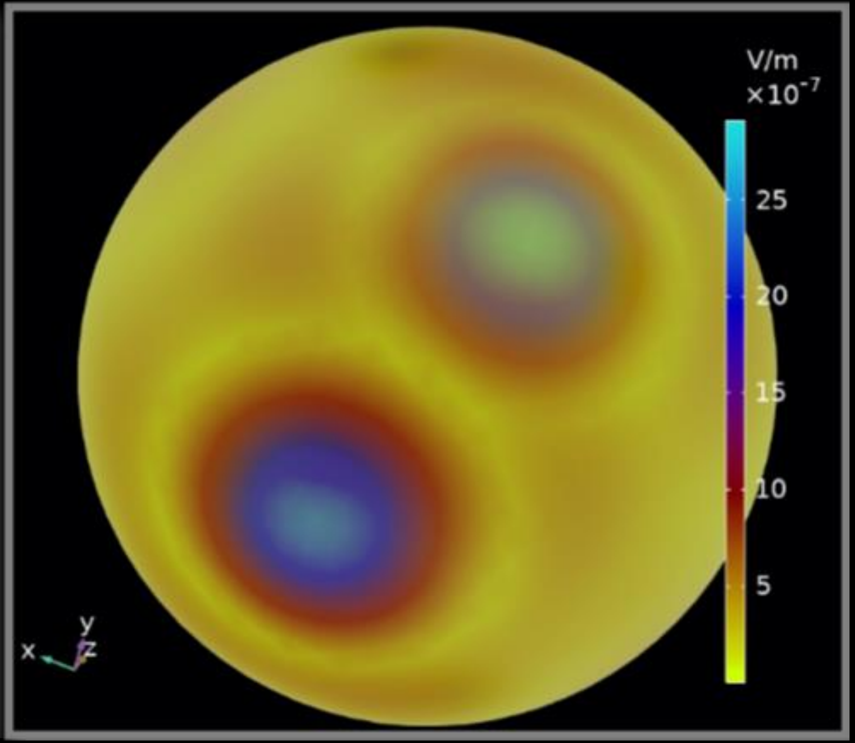
PARTICLE GEOMETRY AFFECTS SCATTER

- 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)

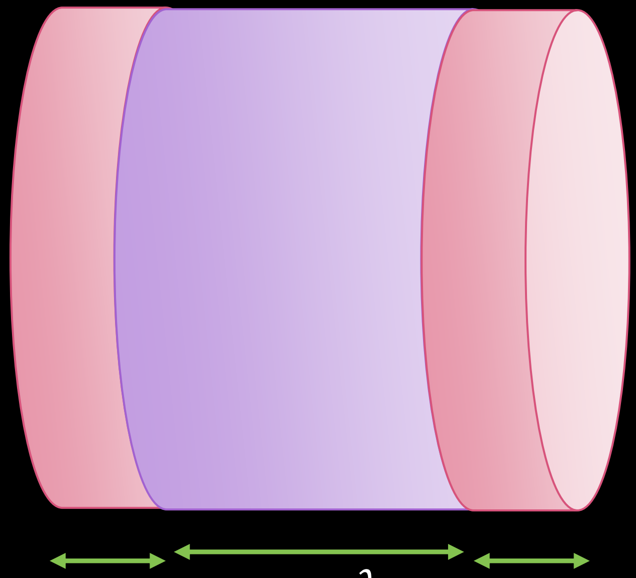


NaYF Hexagon (d=4 um, τ =200 nm), 300 times more mass

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)

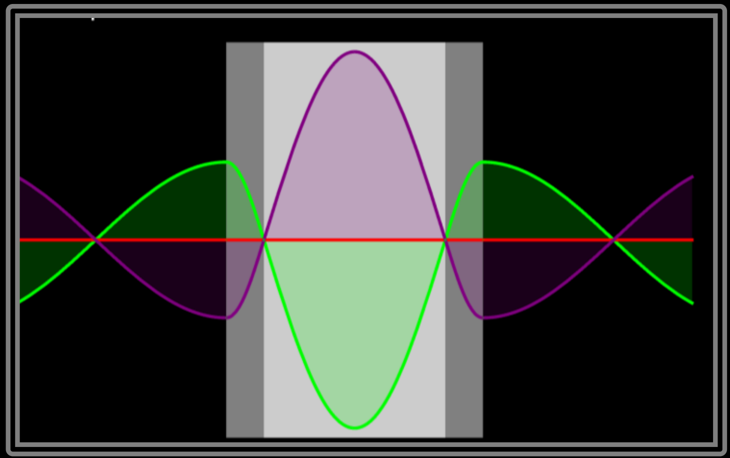


$t_1 = \frac{\lambda_1}{4}$ $t_2 = \frac{\lambda_2}{2}$ t_1

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?

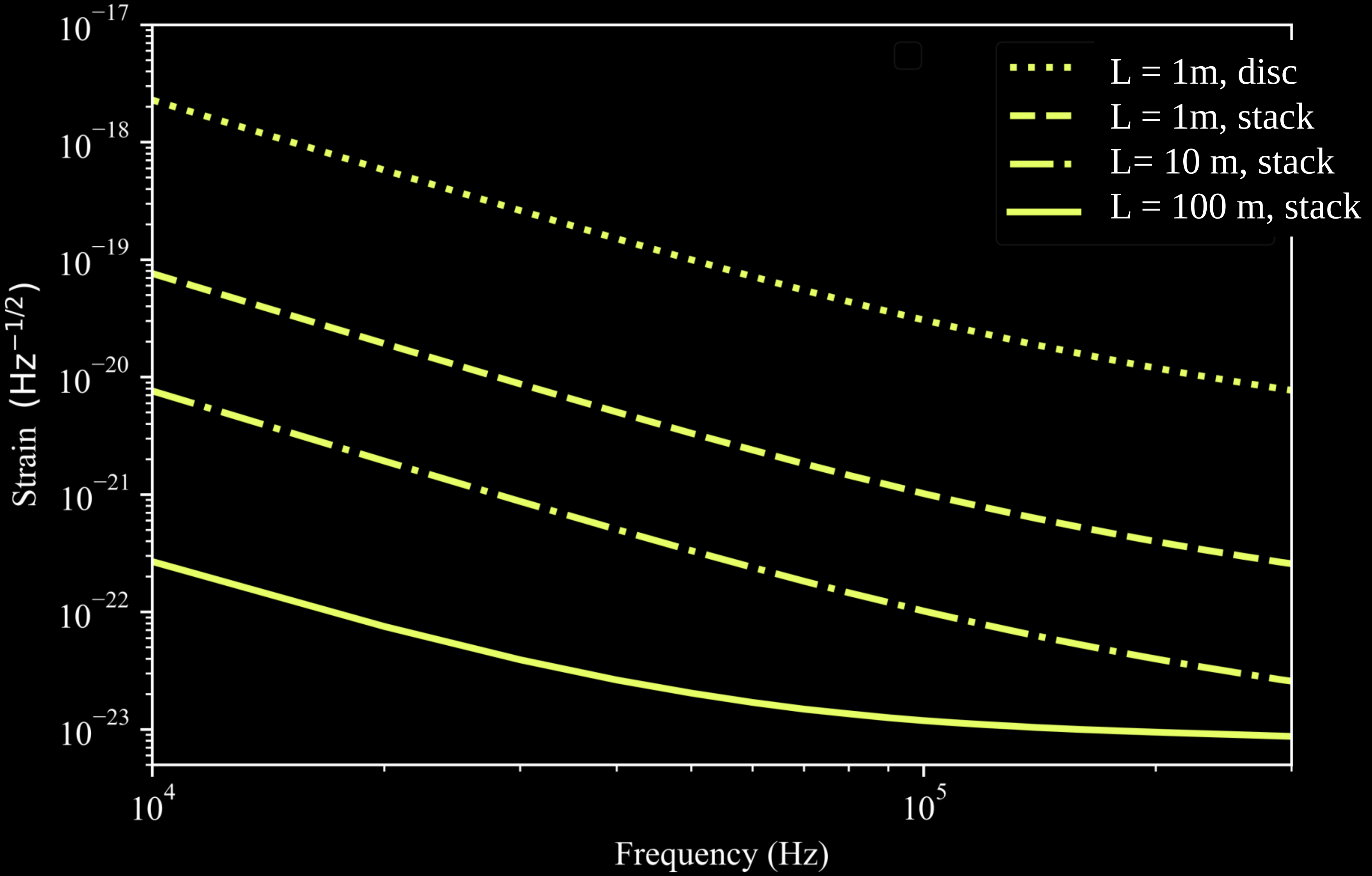


Aggarwal et al arxiv:2010.13157
Phys. Rev. Lett. 128, 111101

IMPROVED SENSITIVITY

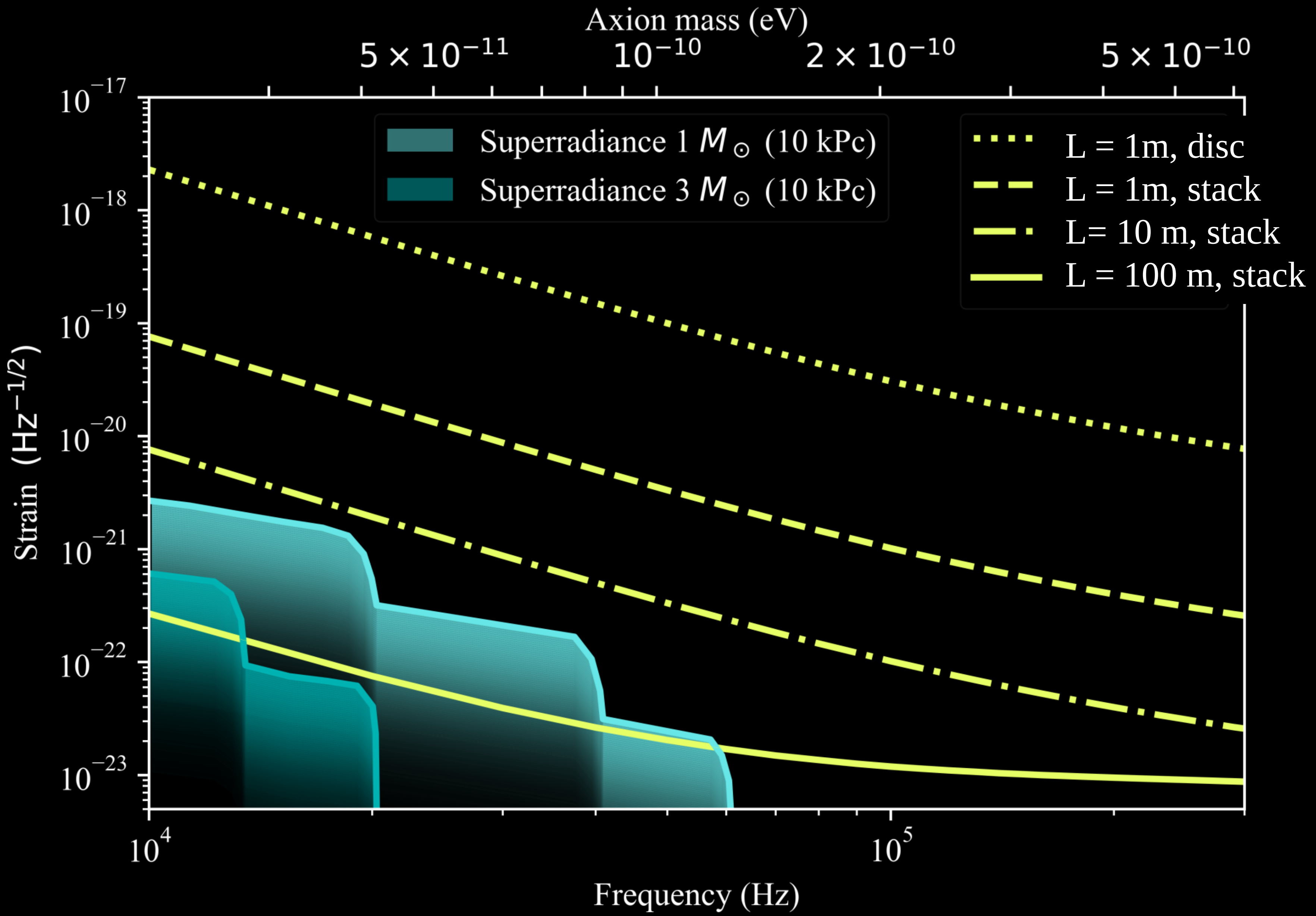
Aggarwal et al arxiv:2010.13157

Phys. Rev. Lett. 128, 111101

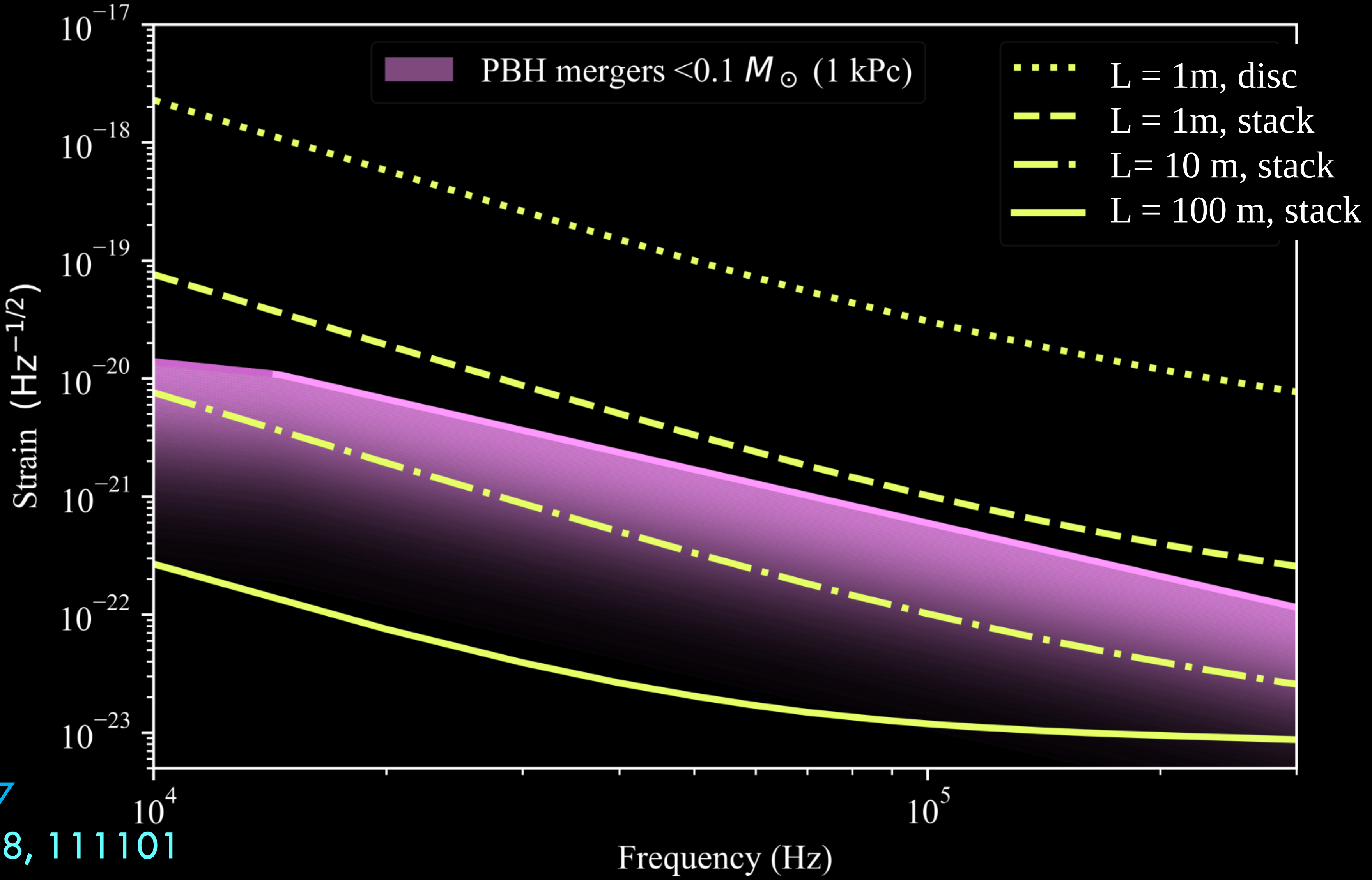


SENSITIVITY TO BH SUPERRADIANCE

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

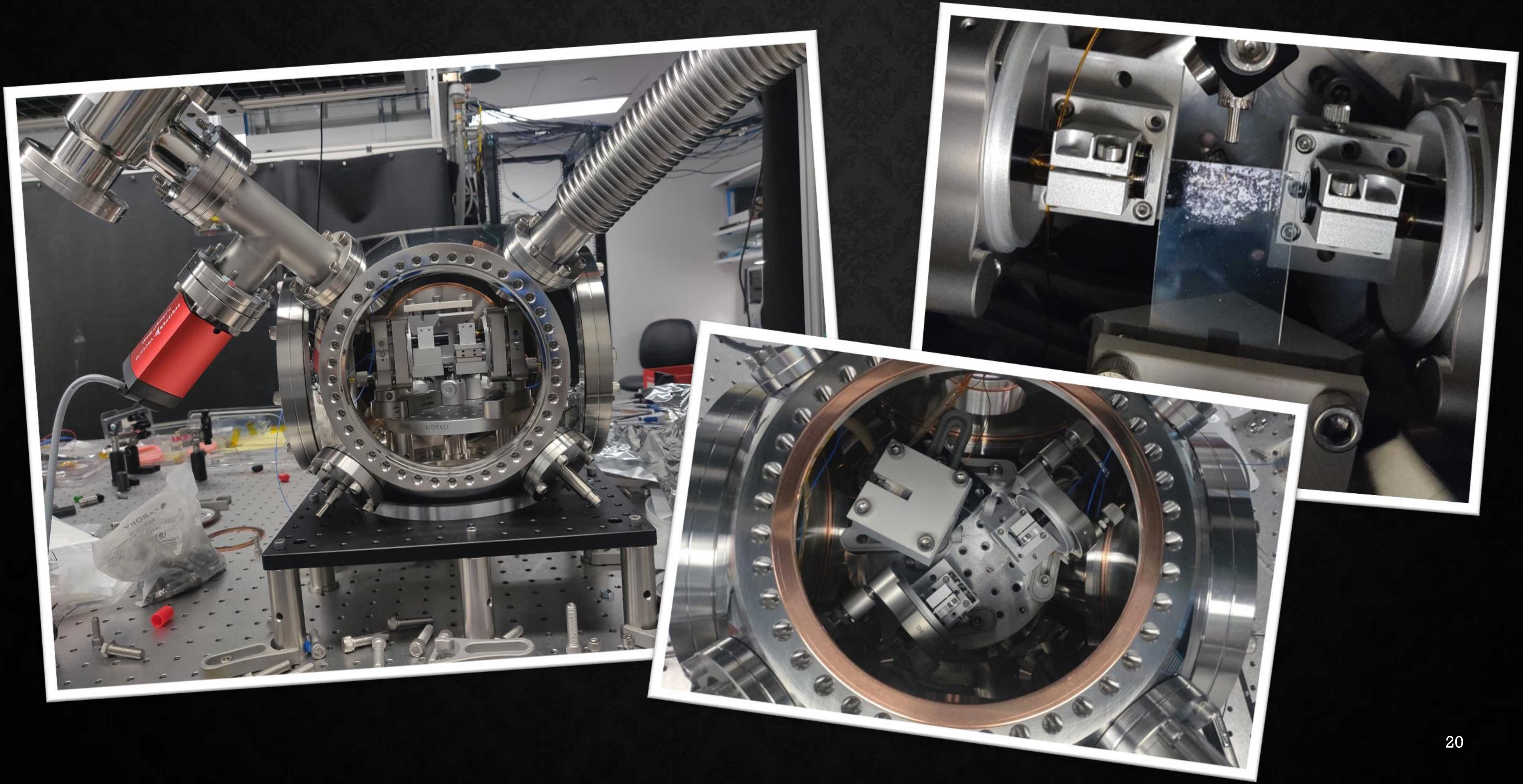


SENSITIVITY TO BLACKHOLE MERGERS

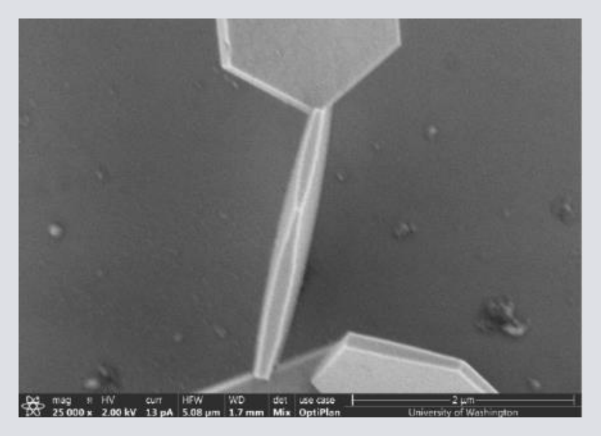


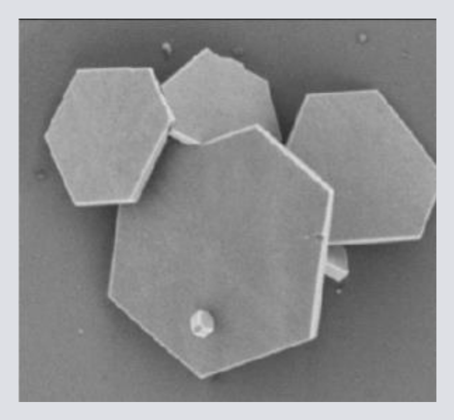
Aggarwal et al
arxiv:2010.13157
Phys. Rev. Lett. 128, 111101

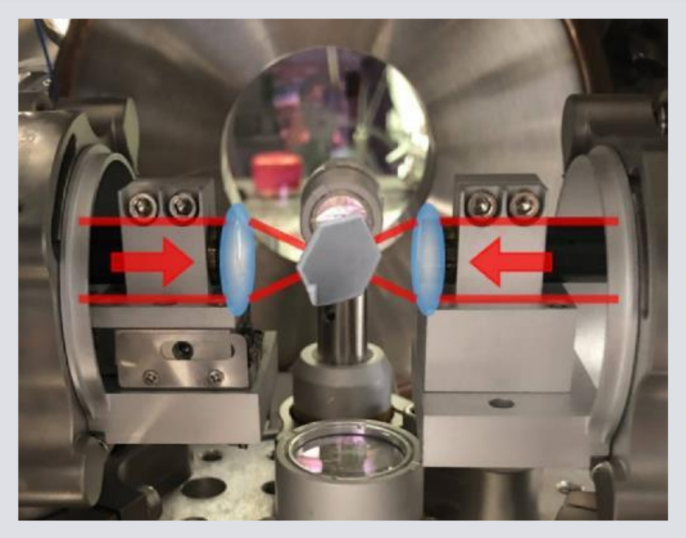
TRAPPING OF FLAT OBJECTS IN THE LAB…

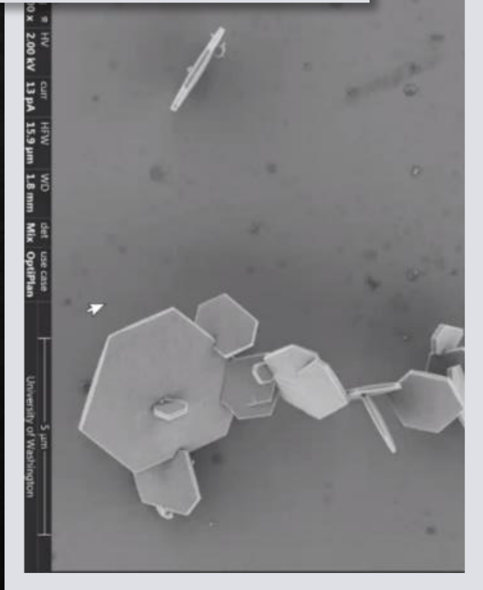


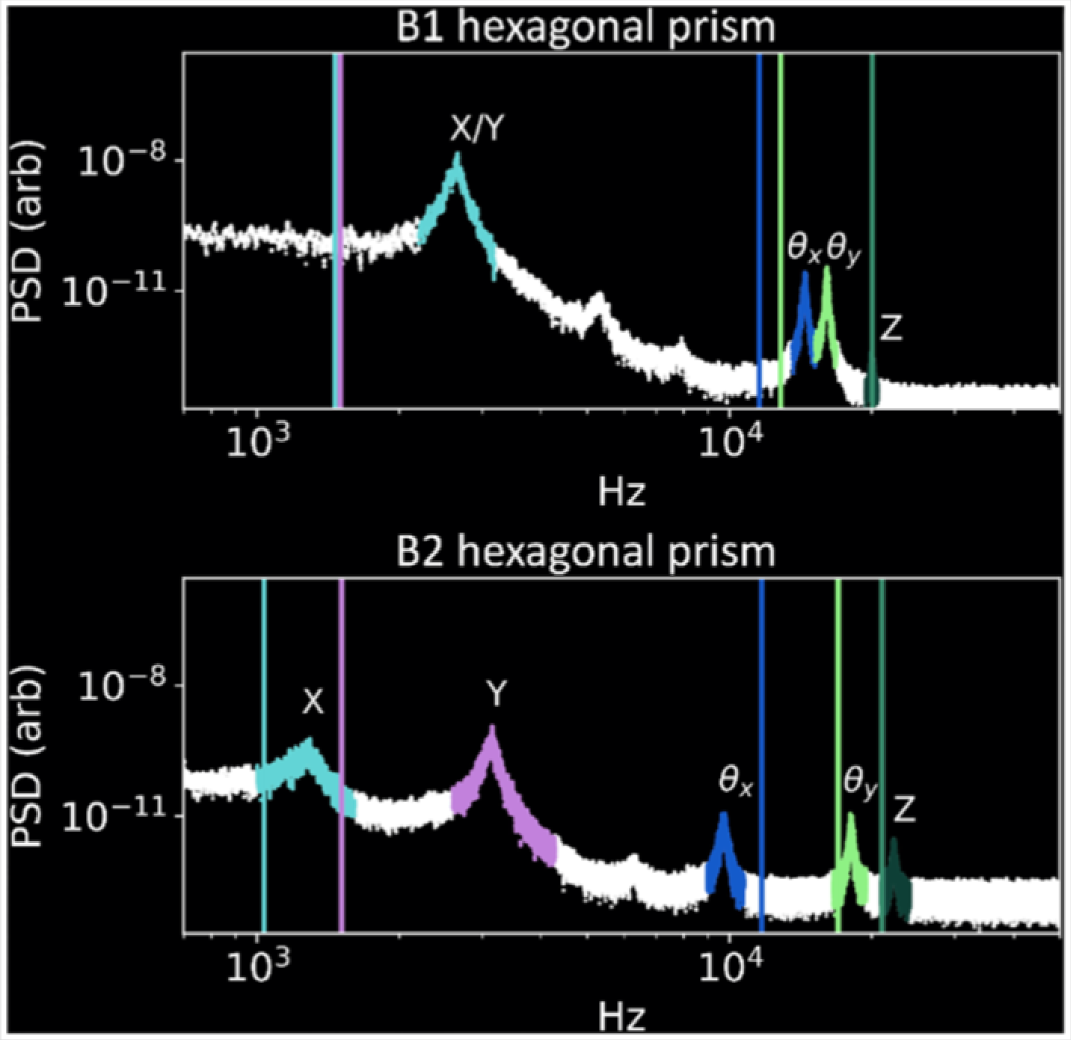
TRAPPING OF NAYF HEXAGON PLATES



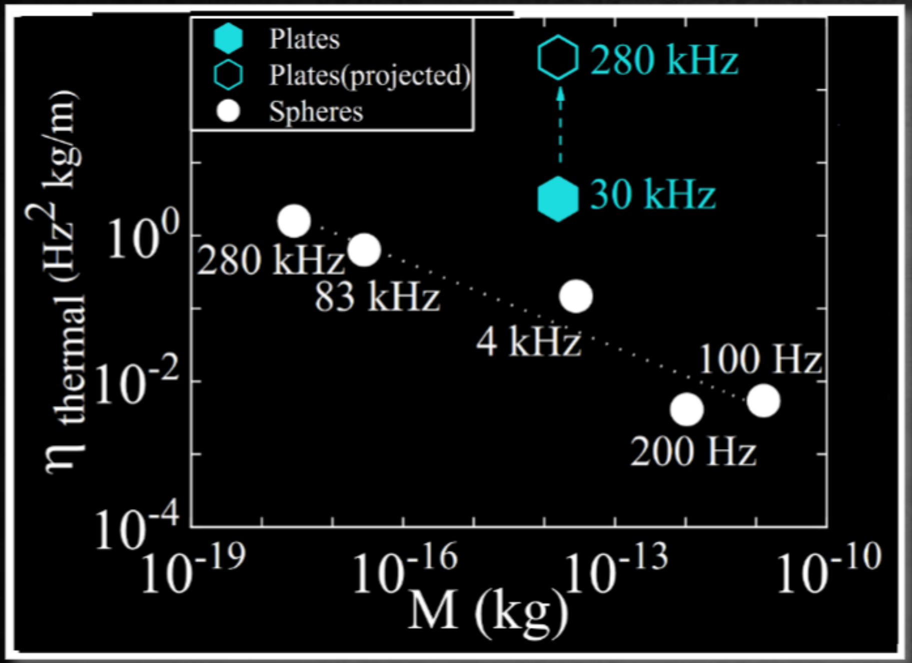


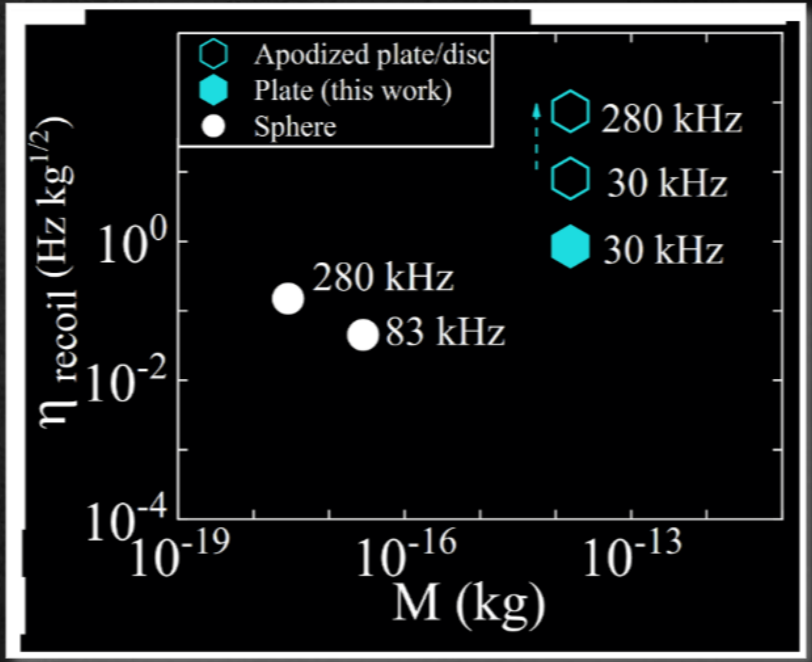






STATE OF THE ART IN OPTICAL TRAPPING



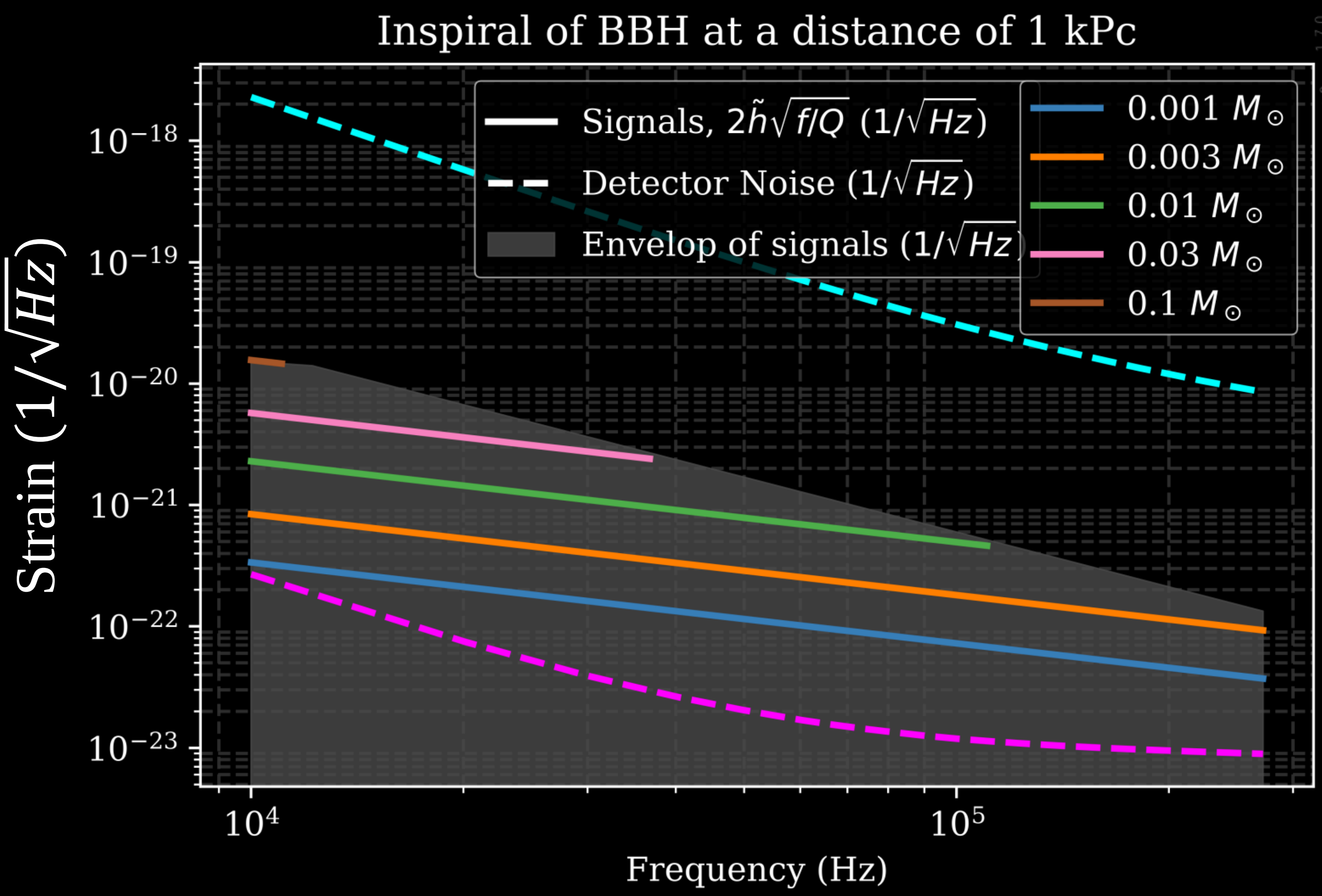


$$\eta_{\text{thermal}} = \left(\frac{\Omega_z}{2\pi}\right)^2 \sqrt{M\rho\tau}$$

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

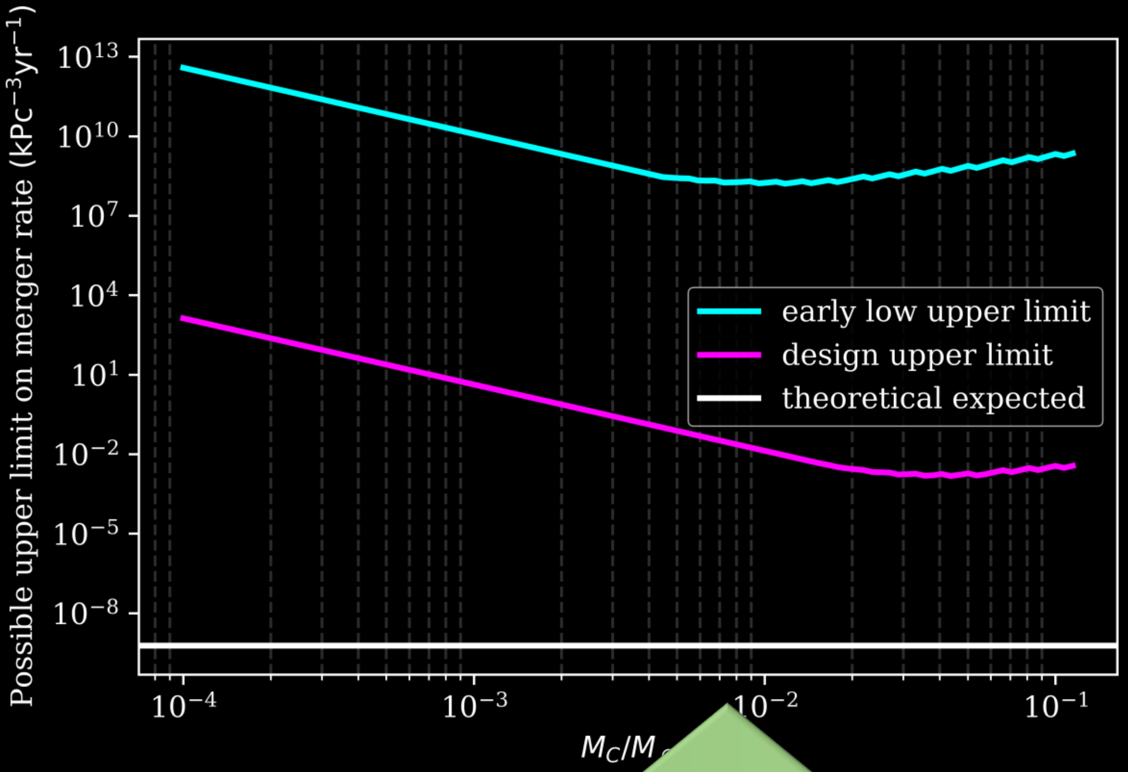
$$\eta_{\text{recoil}} = \left(\frac{\Omega_z}{2\pi}\right)^{3/2} \sqrt{\frac{M}{\gamma_{sc}}}$$

GALACTIC PBH MERGER STRAIN AND LSD SENSITIVITY



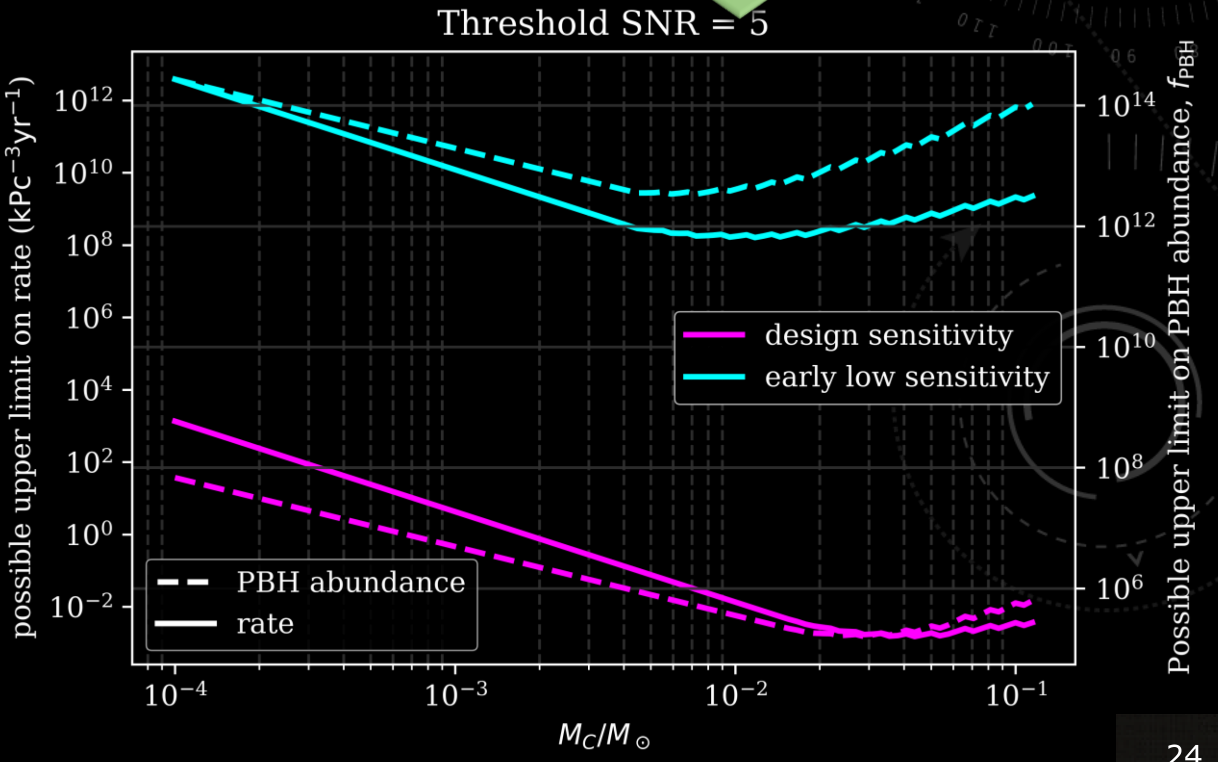
Preliminary: Aggarwal et al.

ESTIMATED PBH RATE UPPER LIMIT



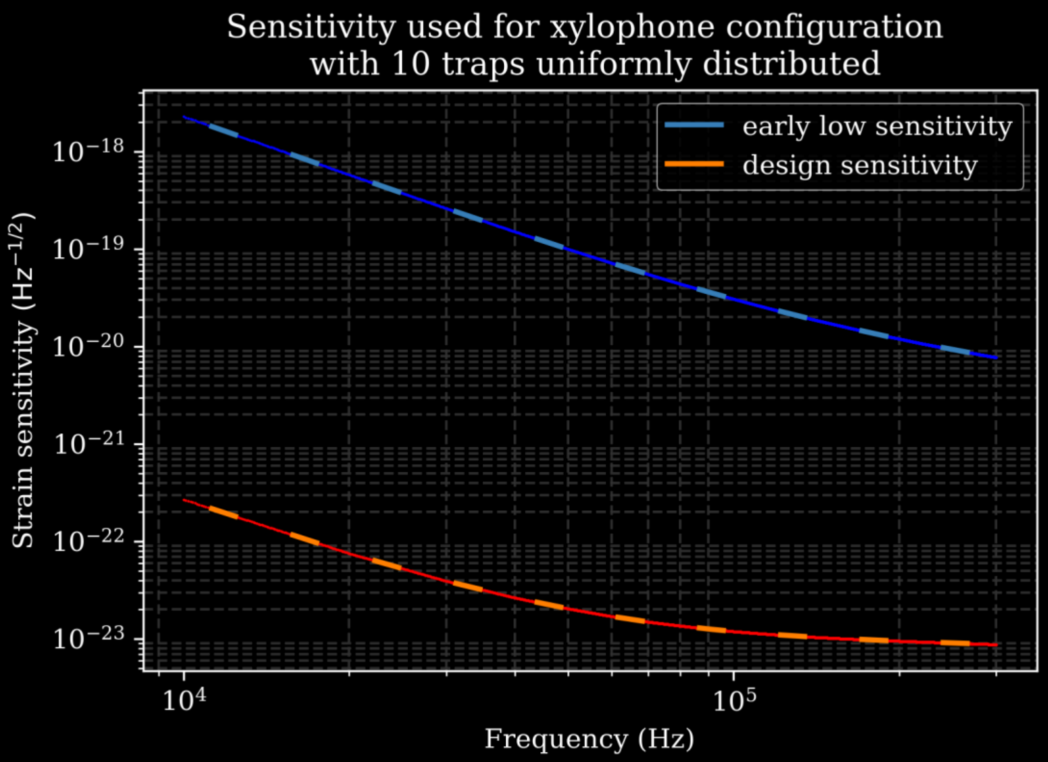
PBH binary formation+merger models

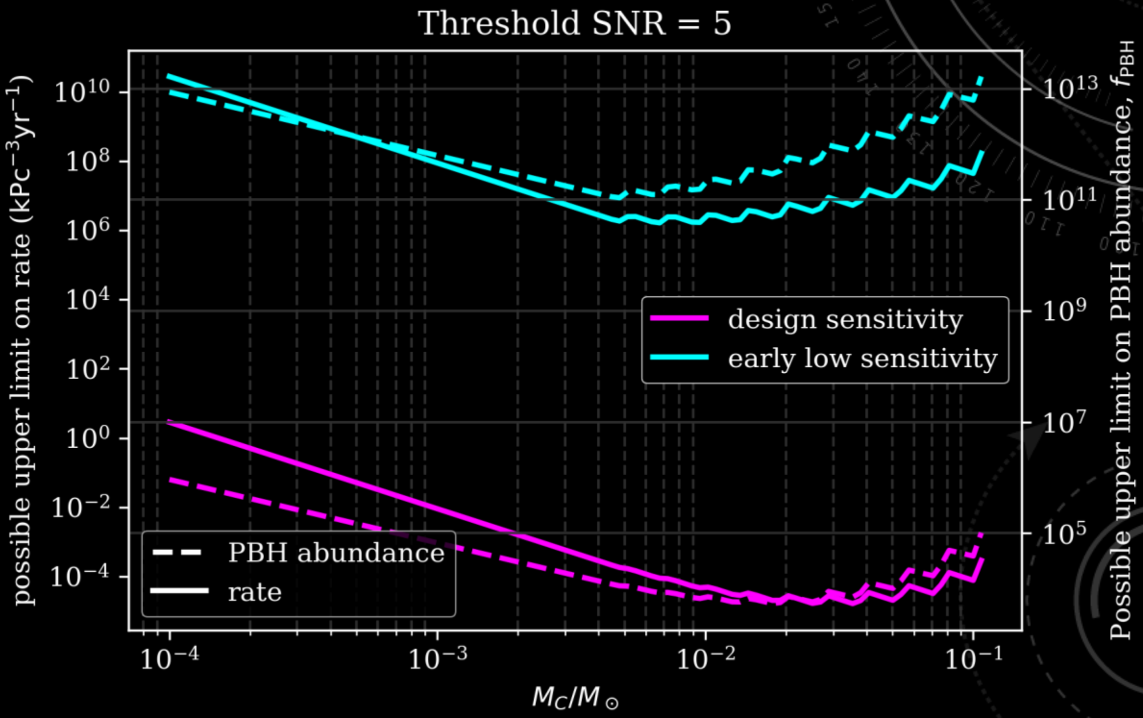
Assume 1 year run



Preliminary: Aggarwal et al.

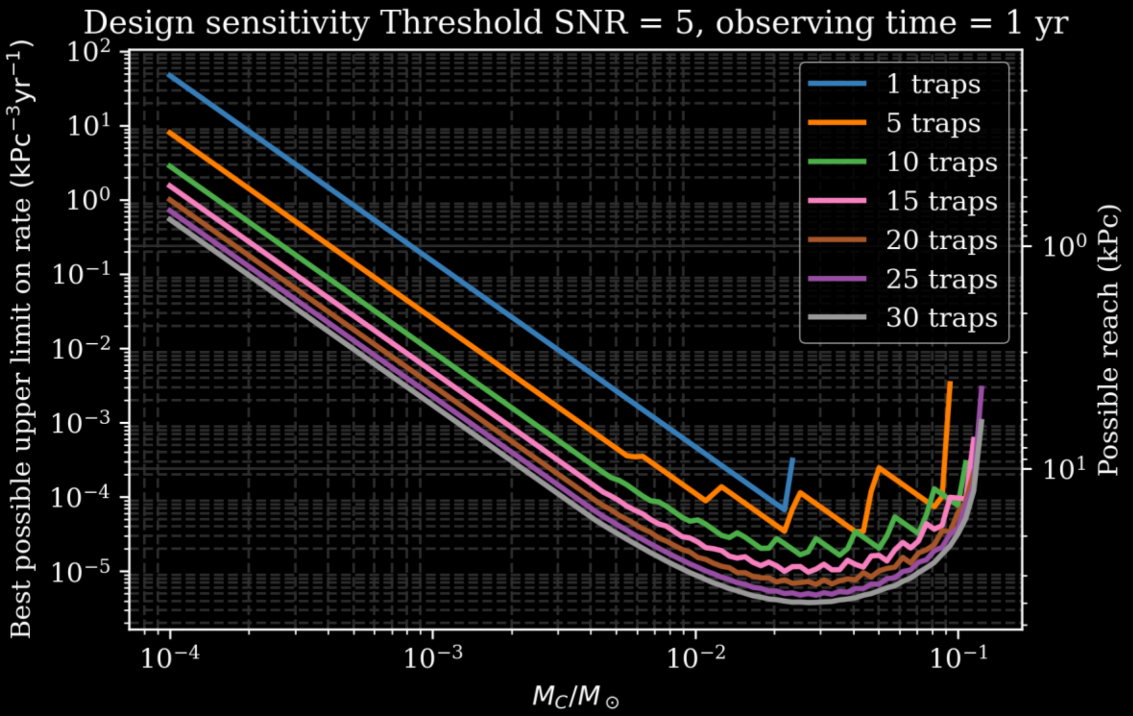
FUTURE DIRECTION 1: XYLOPHONE

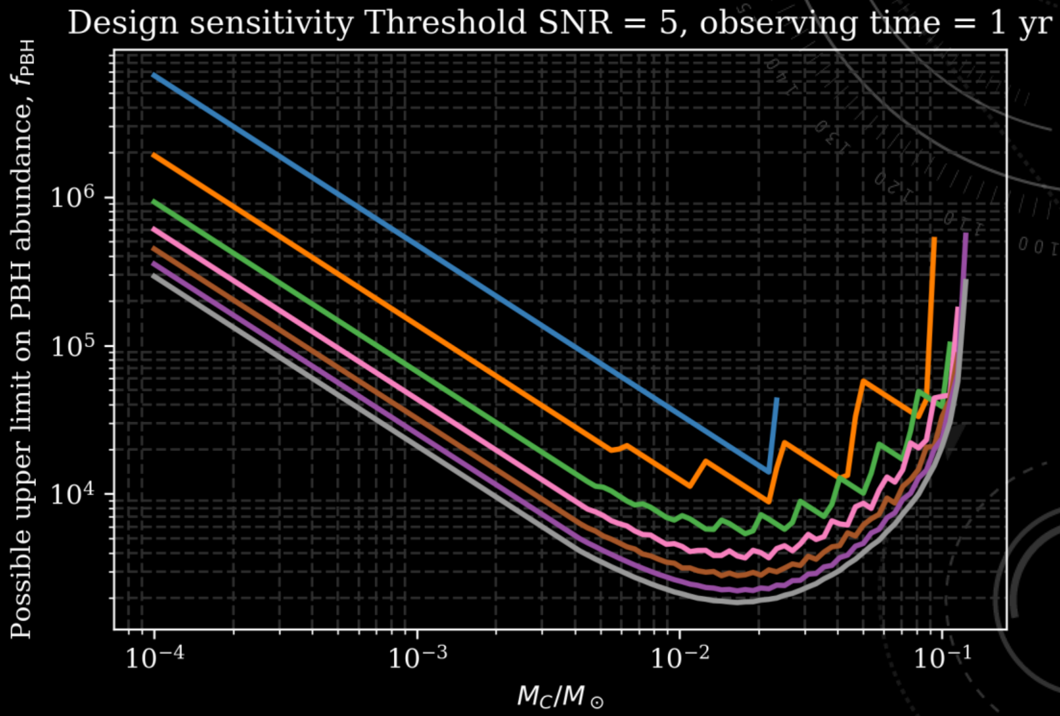




Preliminary: Aggarwal et al.

CHANGE NUMBER OF TRAPS

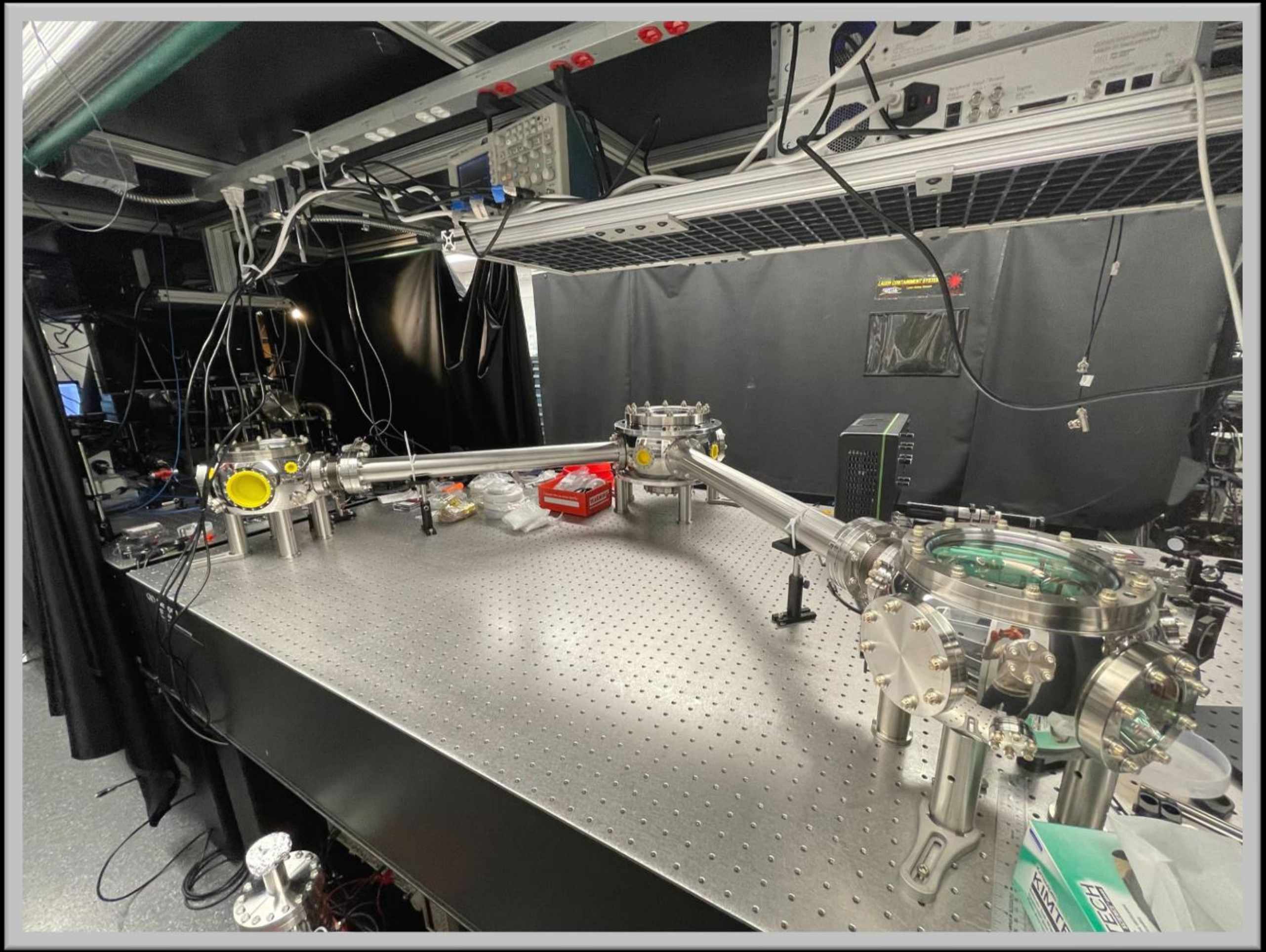




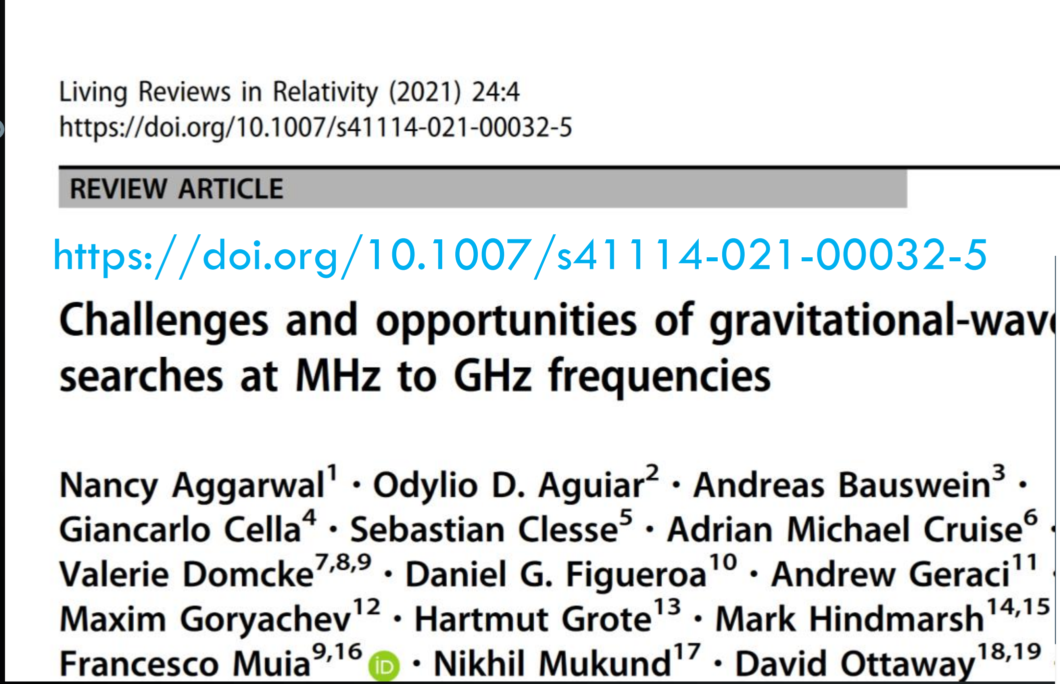
Preliminary: Aggarwal et al.

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
- Further improvements can be achieved by xylophone configuration and/or increasing the mass



GRAVITATIONAL WAVES IN OTHER ‘COLORS’



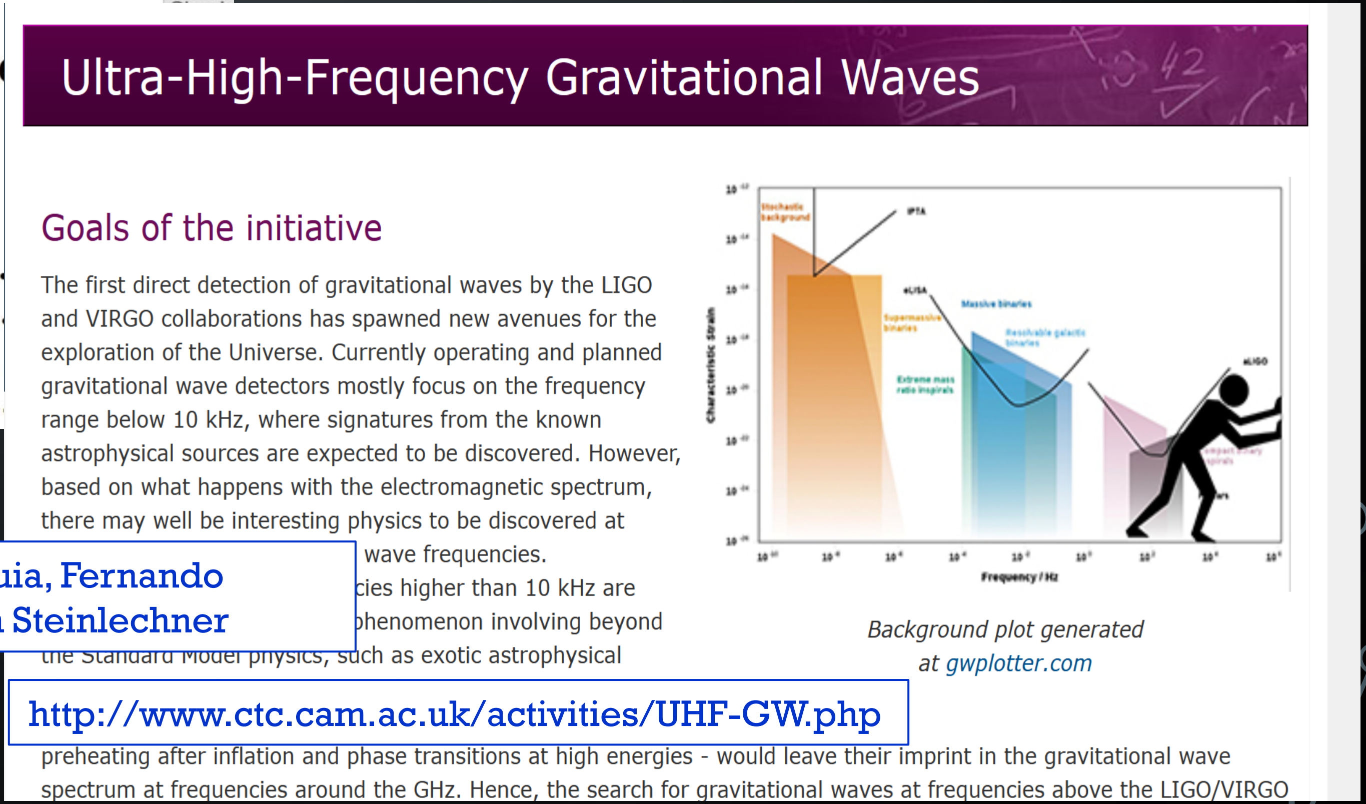
Living Reviews in Relativity (2021) 24:4
https://doi.org/10.1007/s41114-021-00032-5

REVIEW ARTICLE

https://doi.org/10.1007/s41114-021-00032-5

Challenges and opportunities of gravitational-wav
searches at MHz to GHz frequencies

Nancy Aggarwal[1] · Odylio D. Aguiar[2] · Andreas Bauswein[3] ·
Giancarlo Cella[4] · Sebastian Clesse[5] · Adrian Michael Cruise[6]
Valerie Domcke[7,8,9] · Daniel G. Figueroa[10] · Andrew Geraci[11]
Maxim Goryachev[12] · Hartmut Grote[13] · Mark Hindmarsh[14,15]
Francesco Muia[9,16] · Nikhil Mukund[17] · David Ottaway[18,19]



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

wave frequencies.
cies higher than 10 kHz are
phenomenon involving beyond
the Standard Model physics, such as exotic astrophysical

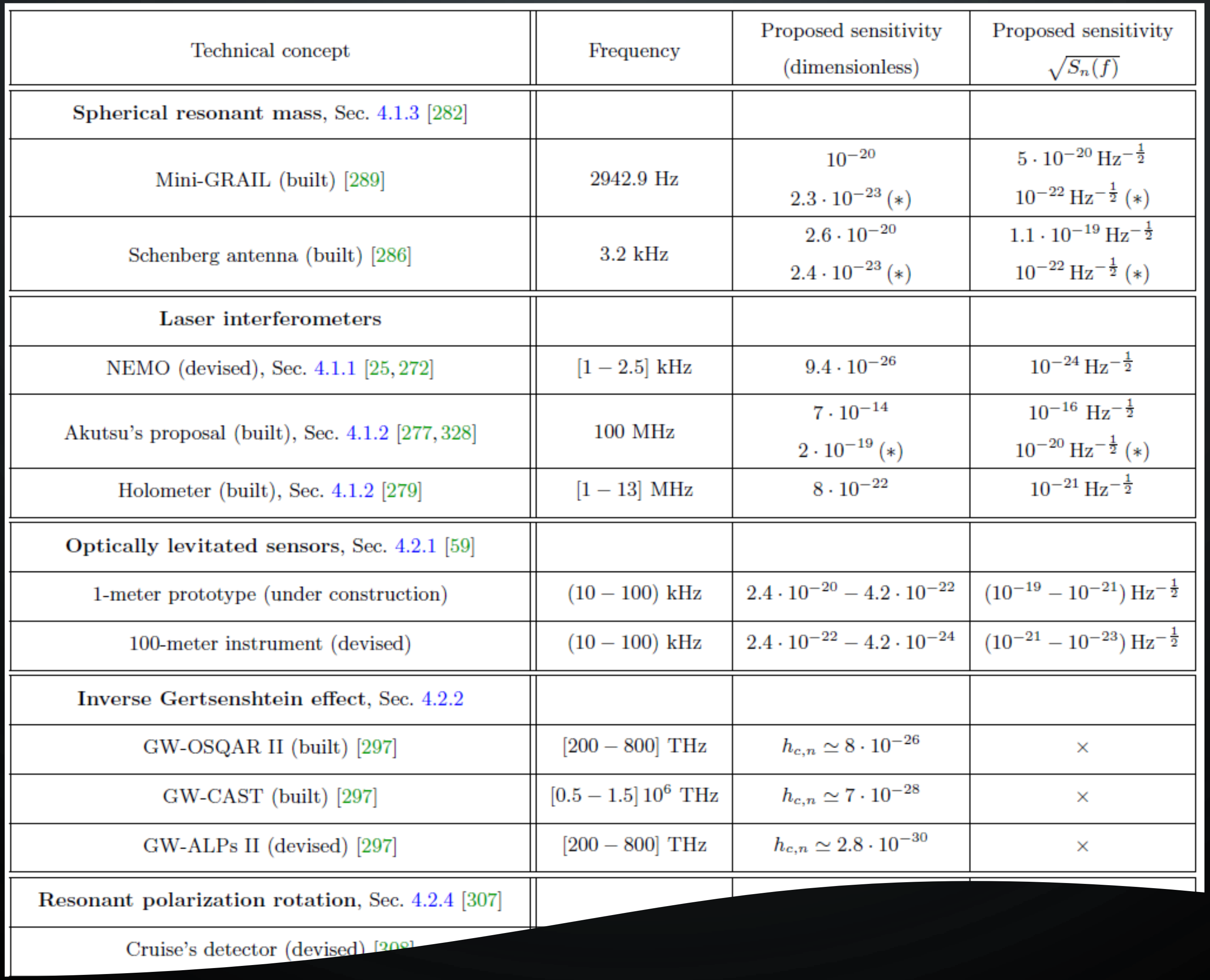
Background plot generated at gwplotter.com

preheating after inflation and phase transitions at high energies - would leave their imprint in the gravitational wave spectrum at frequencies around the GHz. Hence, the search for gravitational waves at frequencies above the LIGO/VIRGO

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

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

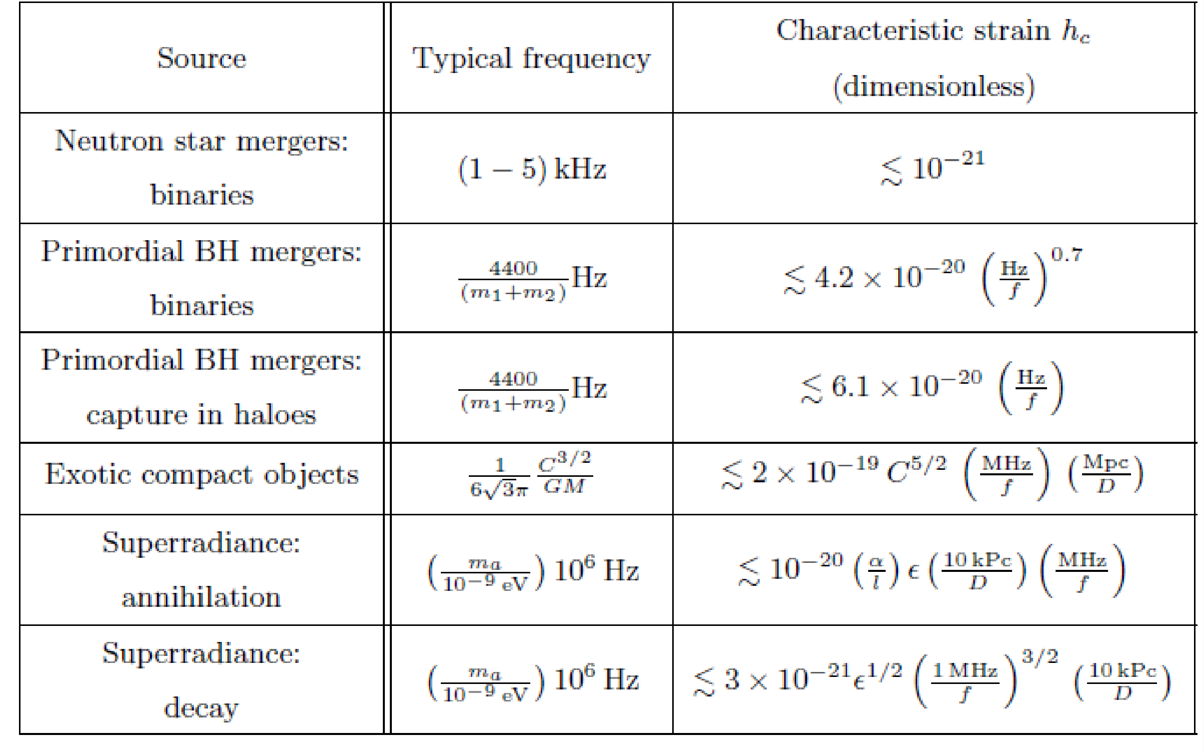
HIGH FREQUENCY GRAVITATIONAL WAVE DETECTORS



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} $2.3 \cdot 10^{-23}$ $(*)$	$5 \cdot 10^{-20}$ Hz$^{-\frac{1}{2}}$ 10^{-22} Hz$^{-\frac{1}{2}}$ $(*)$
Schenberg antenna (built) [286]	3.2 kHz	$2.6 \cdot 10^{-20}$ $2.4 \cdot 10^{-23}$ $(*)$	$1.1 \cdot 10^{-19}$ Hz$^{-\frac{1}{2}}$ 10^{-22} 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} 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} Hz$^{-\frac{1}{2}}$ 10^{-20} Hz$^{-\frac{1}{2}}$ $(*)$
Holometer (built), Sec. 4.1.2 [279]	[1 – 13] MHz	$8 \cdot 10^{-22}$	10^{-21} Hz$^{-\frac{1}{2}}$
Optically levitated sensors, Sec. 4.2.1 [59]			
1-meter prototype (under construction)	(10 – 100) kHz	$2.4 \cdot 10^{-20} - 4.2 \cdot 10^{-22}$	$(10^{-19} - 10^{-21})$ Hz$^{-\frac{1}{2}}$
100-meter instrument (devised)	(10 – 100) kHz	$2.4 \cdot 10^{-22} - 4.2 \cdot 10^{-24}$	$(10^{-21} - 10^{-23})$ 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)			

Aggarwal et al
Arxiv:2011.12414

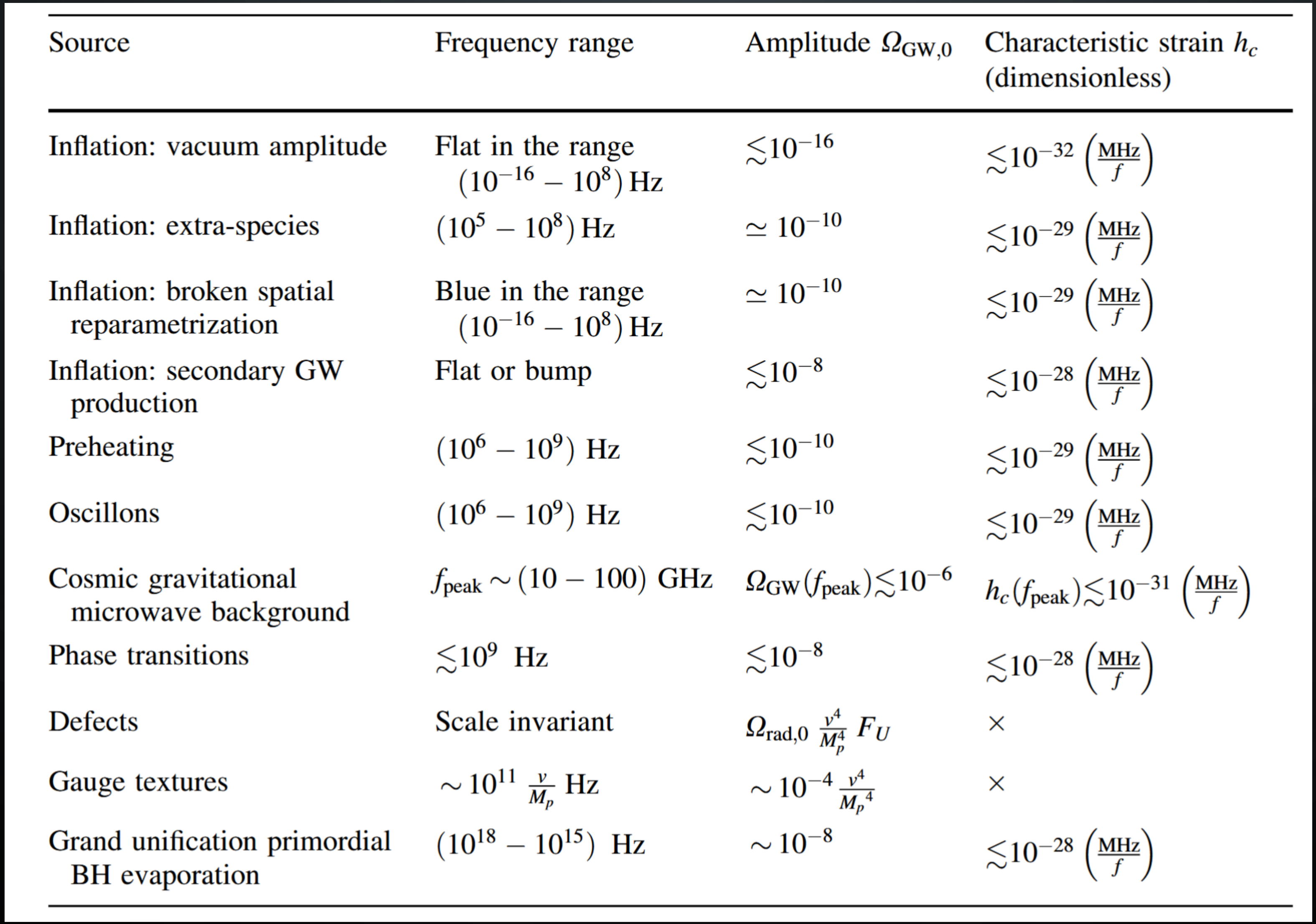
COHERENT SOURCES



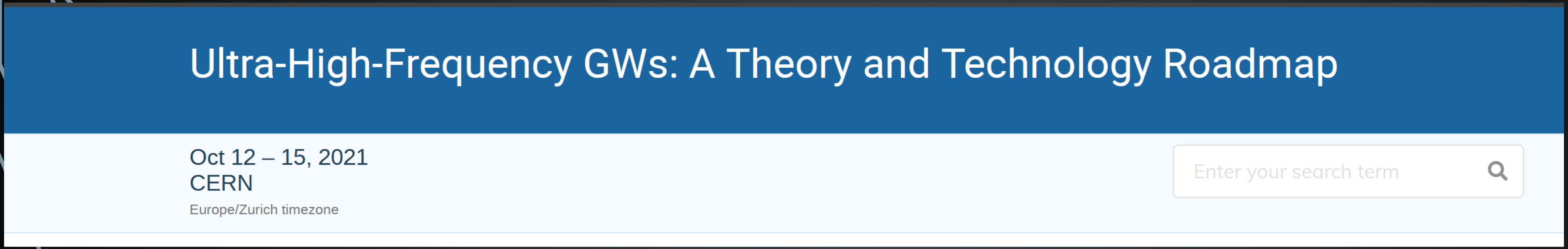
Source	Typical frequency	Characteristic strain h_c (dimensionless)
Neutron star mergers: binaries	$(1-5)\,\mathrm{kHz}$	$\lesssim 10^{-21}$
Primordial BH mergers: binaries	$\frac{4400}{(m_1+m_2)}\mathrm{Hz}$	$\lesssim 4.2\times10^{-20}\left(\frac{\mathrm{Hz}}{f}\right)^{0.7}$
Primordial BH mergers: capture in haloes	$\frac{4400}{(m_1+m_2)}\mathrm{Hz}$	$\lesssim 6.1\times10^{-20}\left(\frac{\mathrm{Hz}}{f}\right)$
Exotic compact objects	$\frac{1}{6\sqrt{3}\pi}\frac{C^{3/2}}{GM}$	$\lesssim 2\times10^{-19}\,C^{5/2}\left(\frac{\mathrm{MHz}}{f}\right)\left(\frac{\mathrm{Mpc}}{D}\right)$
Superradiance: annihilation	$\left(\frac{m_a}{10^{-9}\,\mathrm{eV}}\right)10^6\ \mathrm{Hz}$	$\lesssim 10^{-20}\left(\frac{\alpha}{l}\right)\epsilon\left(\frac{10\,\mathrm{kPc}}{D}\right)\left(\frac{\mathrm{MHz}}{f}\right)$
Superradiance: decay	$\left(\frac{m_a}{10^{-9}\,\mathrm{eV}}\right)10^6\ \mathrm{Hz}$	$\lesssim 3\times10^{-21}\epsilon^{1/2}\left(\frac{1\,\mathrm{MHz}}{f}\right)^{3/2}\left(\frac{10\,\mathrm{kPc}}{D}\right)$

Aggarwal et al
Arxiv:2011.12414

STOCHASTIC SOURCES

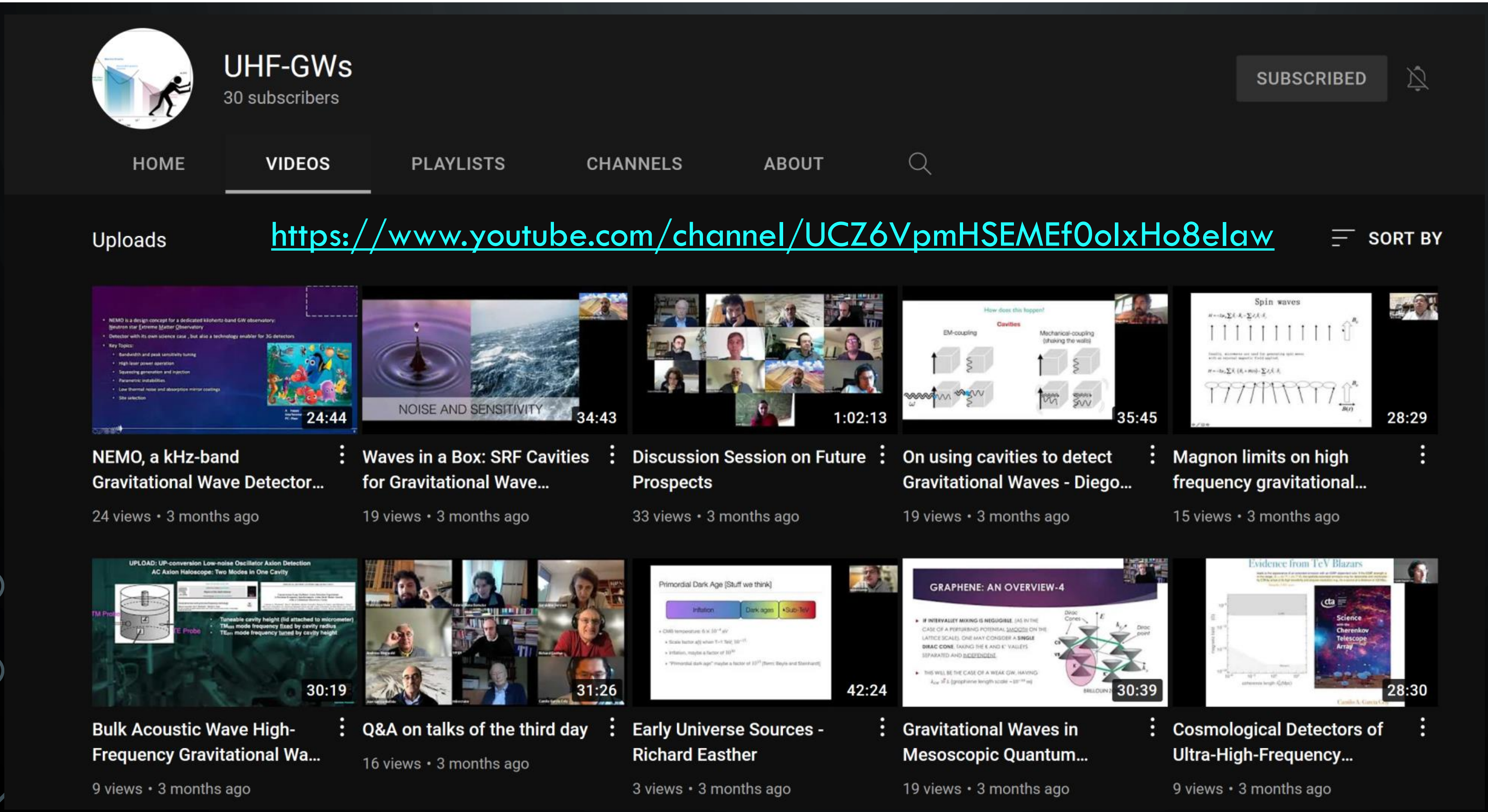


Source	Frequency range	Amplitude $\Omega_{\mathrm{GW},0}$	Characteristic strain h_c (dimensionless)
Inflation: vacuum amplitude	Flat in the range $(10^{-16}-10^{8})\,\mathrm{Hz}$	$\lesssim 10^{-16}$	$\lesssim 10^{-32}\left(\frac{\mathrm{MHz}}{f}\right)$
Inflation: extra-species	$(10^{5}-10^{8})\,\mathrm{Hz}$	$\simeq 10^{-10}$	$\lesssim 10^{-29}\left(\frac{\mathrm{MHz}}{f}\right)$
Inflation: broken spatial reparametrization	Blue in the range $(10^{-16}-10^{8})\,\mathrm{Hz}$	$\simeq 10^{-10}$	$\lesssim 10^{-29}\left(\frac{\mathrm{MHz}}{f}\right)$
Inflation: secondary GW production	Flat or bump	$\lesssim 10^{-8}$	$\lesssim 10^{-28}\left(\frac{\mathrm{MHz}}{f}\right)$
Preheating	$(10^{6}-10^{9})$ Hz	$\lesssim 10^{-10}$	$\lesssim 10^{-29}\left(\frac{\mathrm{MHz}}{f}\right)$
Oscillons	$(10^{6}-10^{9})$ Hz	$\lesssim 10^{-10}$	$\lesssim 10^{-29}\left(\frac{\mathrm{MHz}}{f}\right)$
Cosmic gravitational microwave background	$f_{\mathrm{peak}} \sim (10-100)$ GHz	$\Omega_{\mathrm{GW}}(f_{\mathrm{peak}}) \lesssim 10^{-6}$	$h_c(f_{\mathrm{peak}}) \lesssim 10^{-31}\left(\frac{\mathrm{MHz}}{f}\right)$
Phase transitions	$\lesssim 10^{9}$ Hz	$\lesssim 10^{-8}$	$\lesssim 10^{-28}\left(\frac{\mathrm{MHz}}{f}\right)$
Defects	Scale invariant	$\Omega_{\mathrm{rad},0}\,\frac{v^4}{M_p^4}\,F_U$	×
Gauge textures	$\sim 10^{11}\,\frac{v}{M_p}$ Hz	$\sim 10^{-4}\,\frac{v^4}{{M_p}^4}$	×
Grand unification primordial BH evaporation	$(10^{18}-10^{15})$ Hz	$\sim 10^{-8}$	$\lesssim 10^{-28}\left(\frac{\mathrm{MHz}}{f}\right)$



Ultra-High-Frequency GWs: A Theory and Technology Roadmap

Oct 12 – 15, 2021
CERN
Europe/Zurich timezone



https://www.youtube.com/channel/UCZ6VpmHSEMEf0oIxHo8eIaw

Title	Length	Views
NEMO, a kHz-band Gravitational Wave Detector…	24:44	24 views • 3 months ago
Waves in a Box: SRF Cavities for Gravitational Wave…	34:43	19 views • 3 months ago
Discussion Session on Future Prospects	1:02:13	33 views • 3 months ago
On using cavities to detect Gravitational Waves - Diego…	35:45	19 views • 3 months ago
Magnon limits on high frequency gravitational…	28:29	15 views • 3 months ago
Bulk Acoustic Wave High-Frequency Gravitational Wa…	30:19	9 views • 3 months ago
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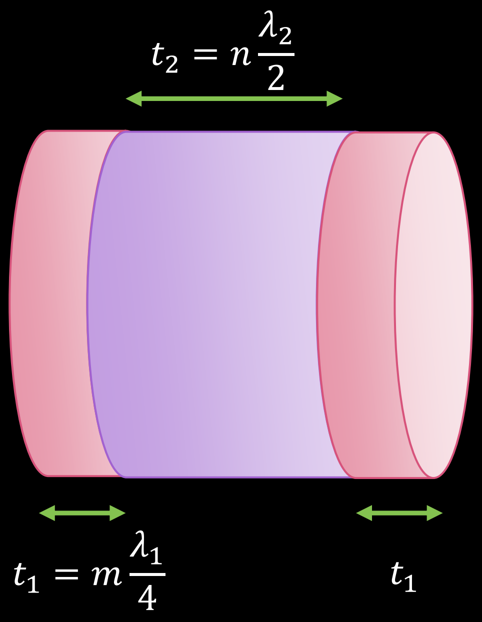
Gravitational Waves in Mesoscopic Quantum…	30:39	19 views • 3 months ago
Cosmological Detectors of Ultra-High-Frequency…	28:30	9 views • 3 months ago

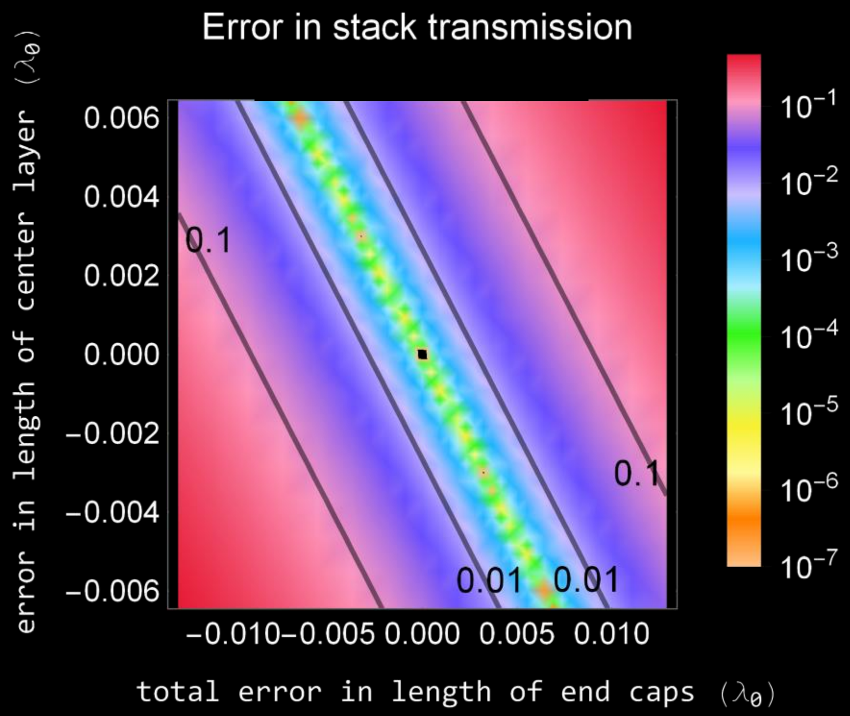
1. EXAMINE TRANSMISSION THROUGH STACKS



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

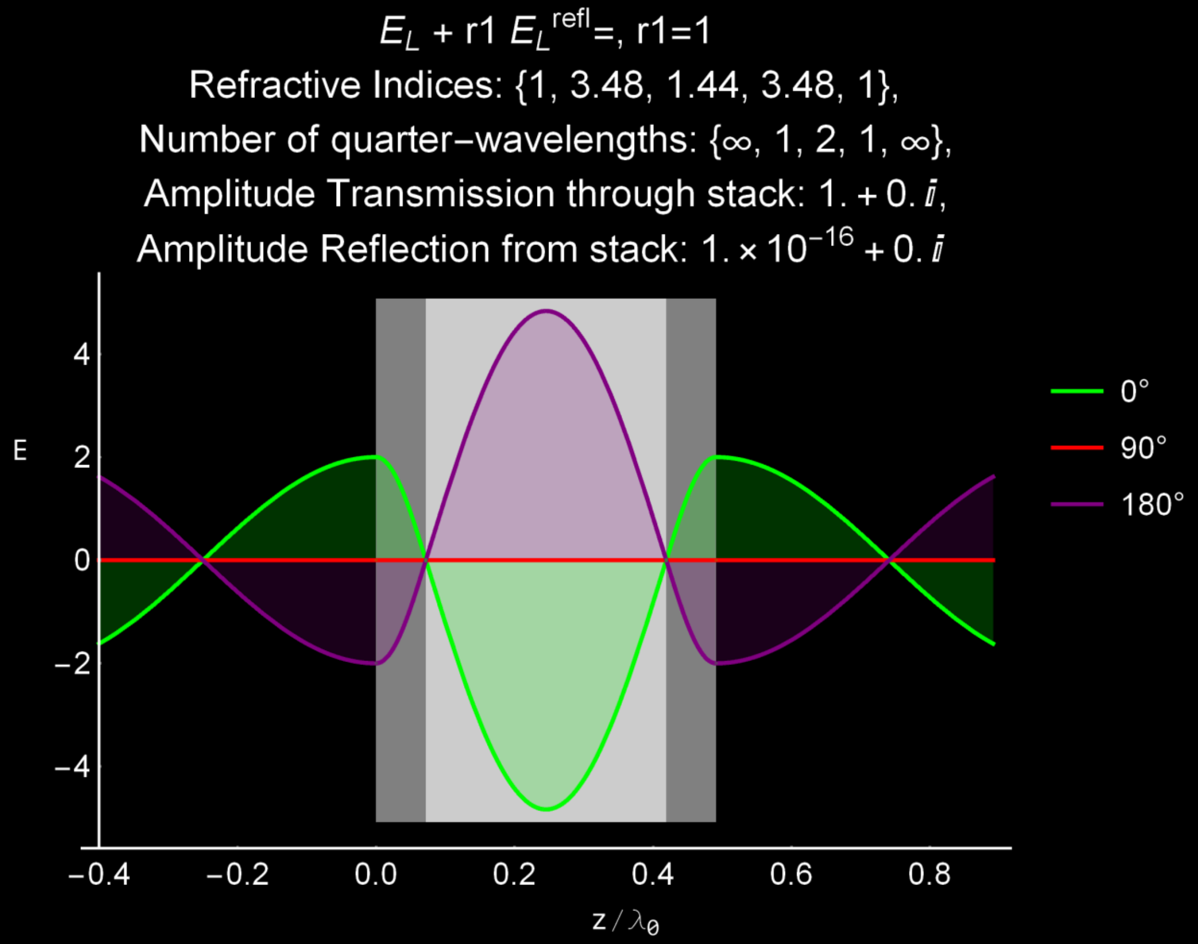


$$\delta T_{OEO} = -1218.31(1.000(\epsilon_1 + \epsilon_3) + 1.075\epsilon_2)^2$$

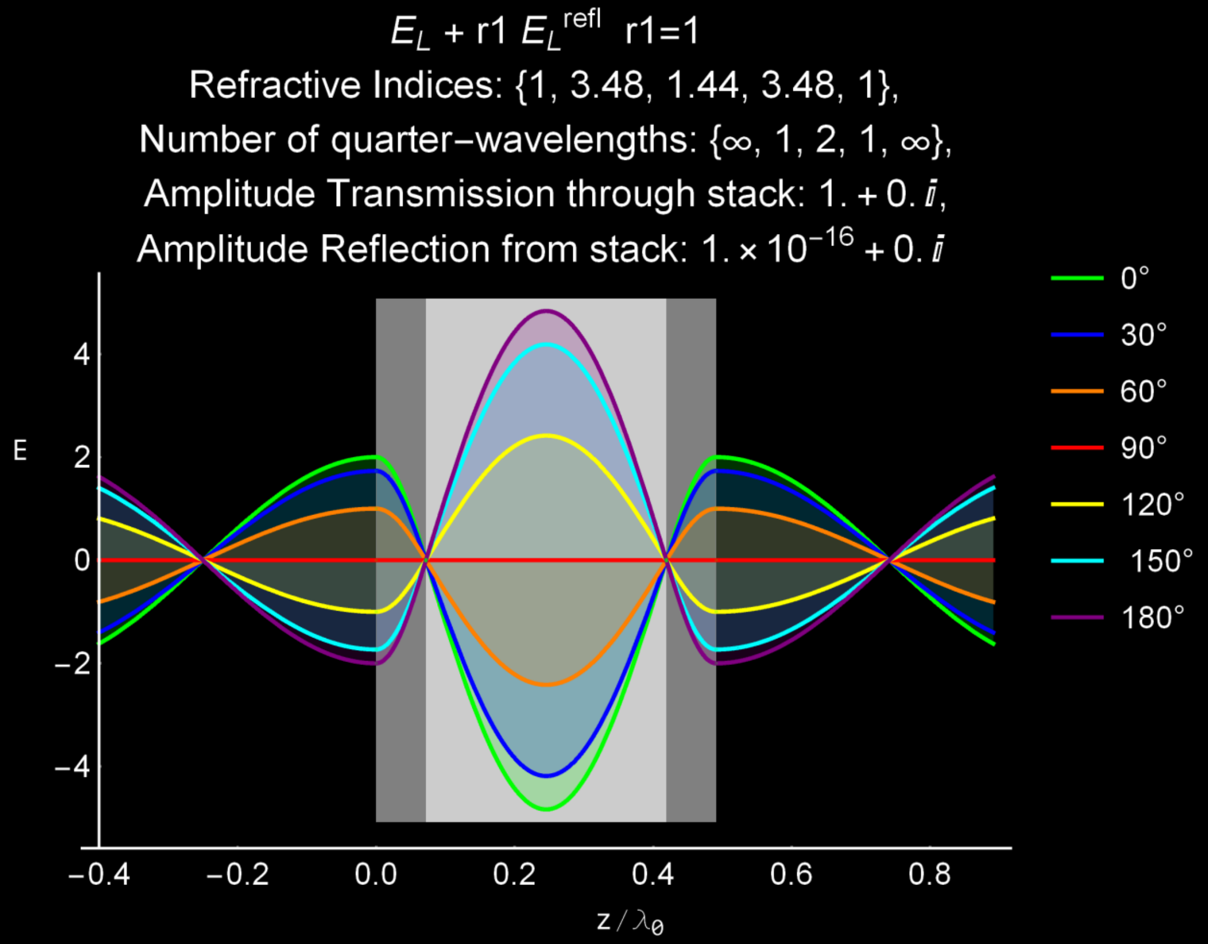
1.5 nm precision for 99%
0.5 nm precision for 99.9%

Preliminary: Aggarwal et al.

2. ELECTRIC FIELD INSIDE STACKS



E_L + r1 $E_L{}^{\text{refl}}$=, 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: $1. \times 10^{-16} + 0.\,i$

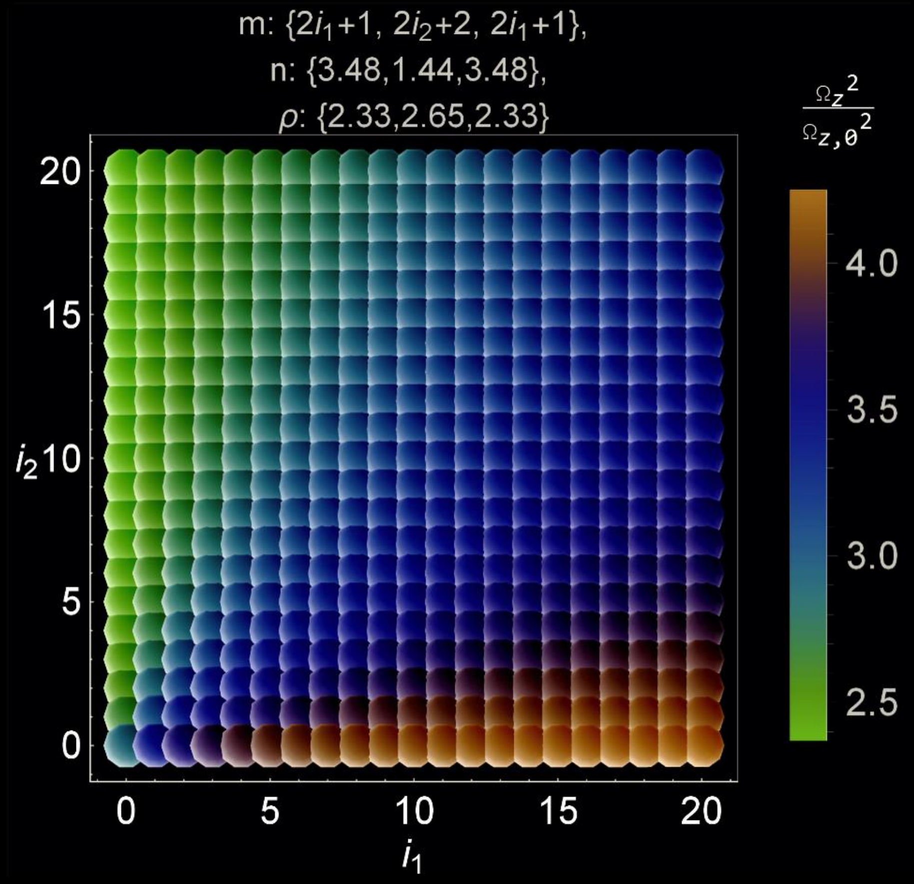


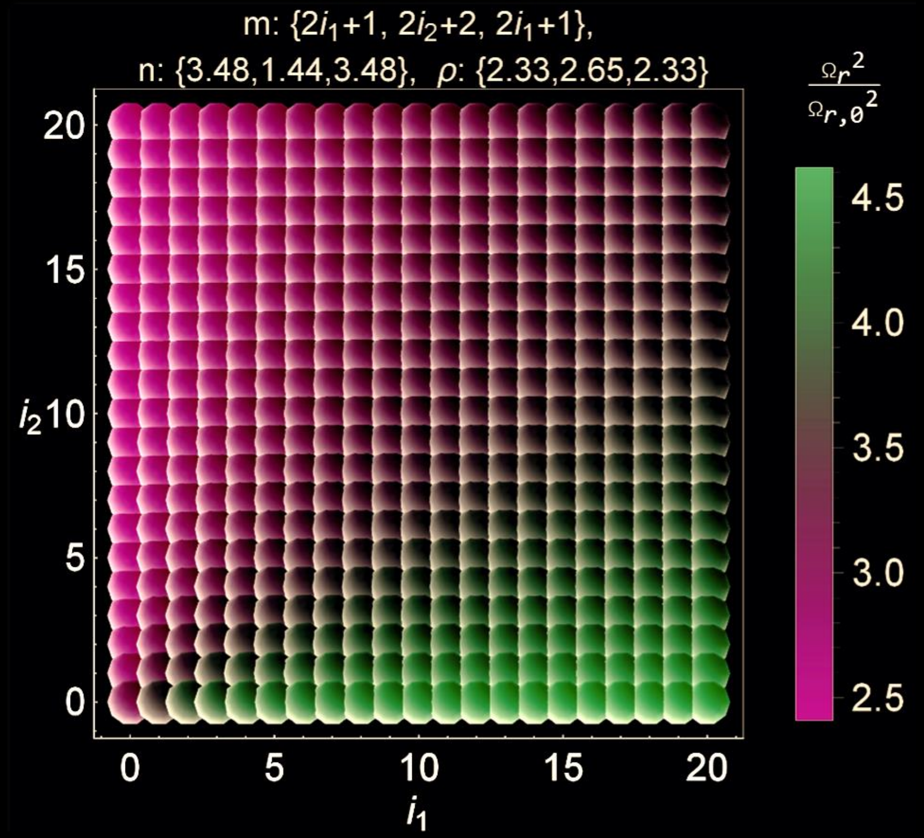
E_L + r1 $E_L{}^{\text{refl}}$ r1=1
Refractive Indices: {1, 3.48, 1.44, 3.48, 1},
Number of quarter−wavelengths: {∞, 1, 2, 1, ∞},
Amplitude Transmission through stack: $1. + 0.\,i$,
Amplitude Reflection from stack: $1. \times 10^{-16} + 0.\,i$

Preliminary: Aggarwal et al.

3. TRAP FREQUENCY

Quantity	Symbol	Value
Beam waist	w	37.5 µm
Stack Radius	R	75 µm
Laser wavelength	λ_0	1550 nm
Intracavity Power	P_0	50 W
Axial frequency scale	$\Omega_{z,0}$	2π 89 kHz
Radial frequency scale	$\Omega_{r,0}$	2π 107 Hz


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

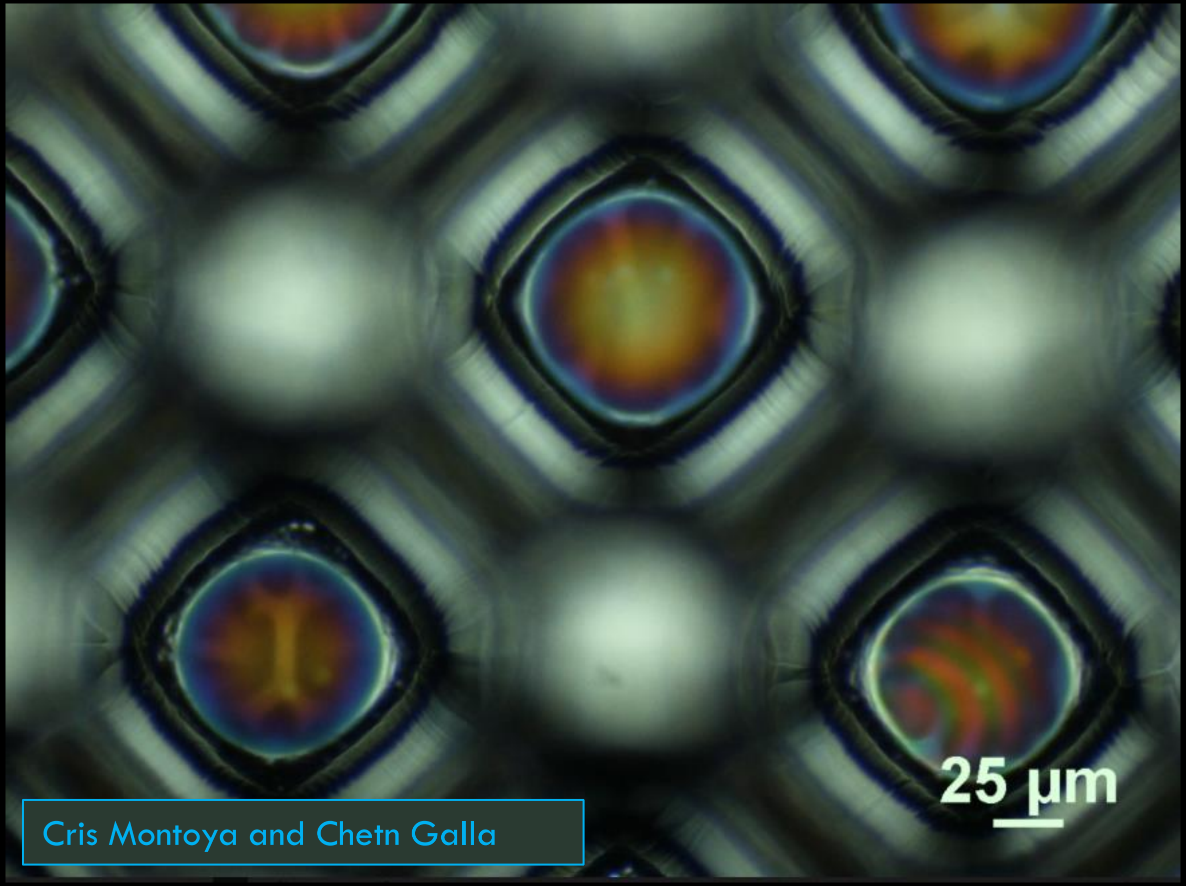

m: $\{2i_1+1, 2i_2+2, 2i_1+1\}$,
n: {3.48,1.44,3.48}, ρ: {2.33,2.65,2.33}

$$\Omega_{z,0}^2 = \frac{8\pi P(1-e^{-2R^2/w^2})}{c\lambda^2\rho_0 R^2}$$

$$\Omega_{r,0}^2 = \frac{8\,P_0\;e^{-2R^2/w^2}}{c\,\pi w^4\rho_0}$$

In prep: Aggarwal et al.

4. FABRICATING THE DISKS

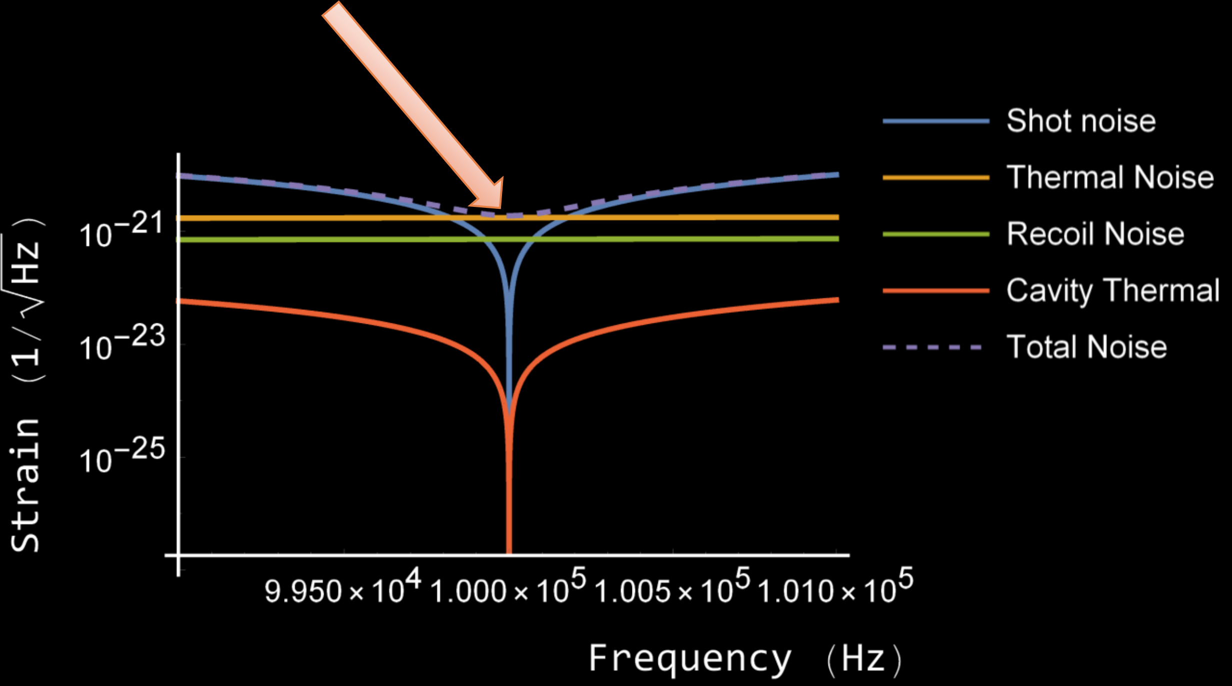


Cris Montoya and Chetn Galla

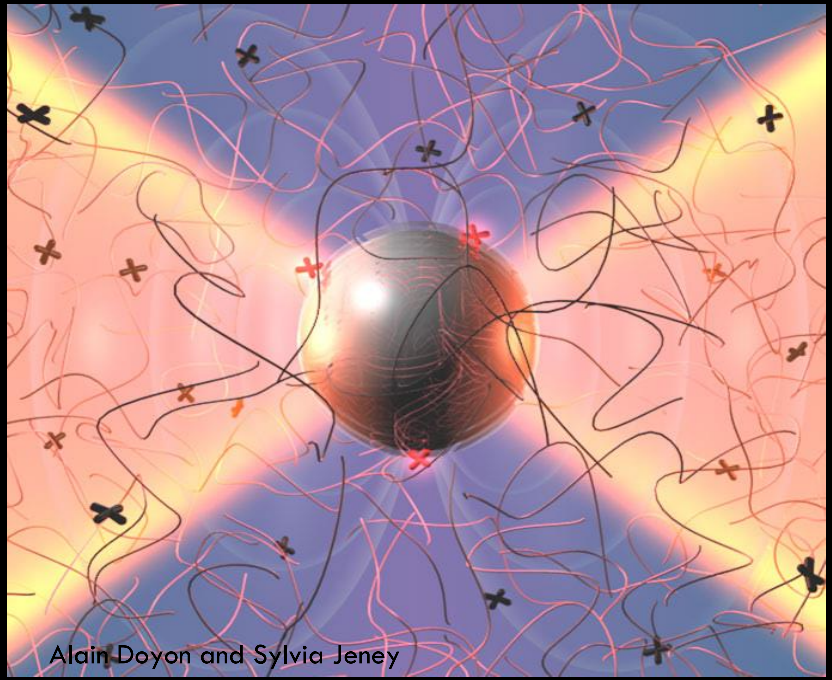
Cris Montoya and Chetn Galla

ANTICIPATED NOISES

Limiting Noise



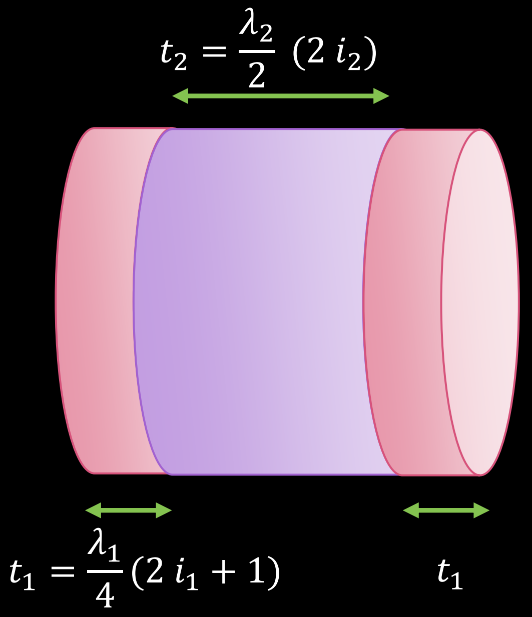
Preliminary Aggarwal et al



Alain Doyon and Sylvia Jeney

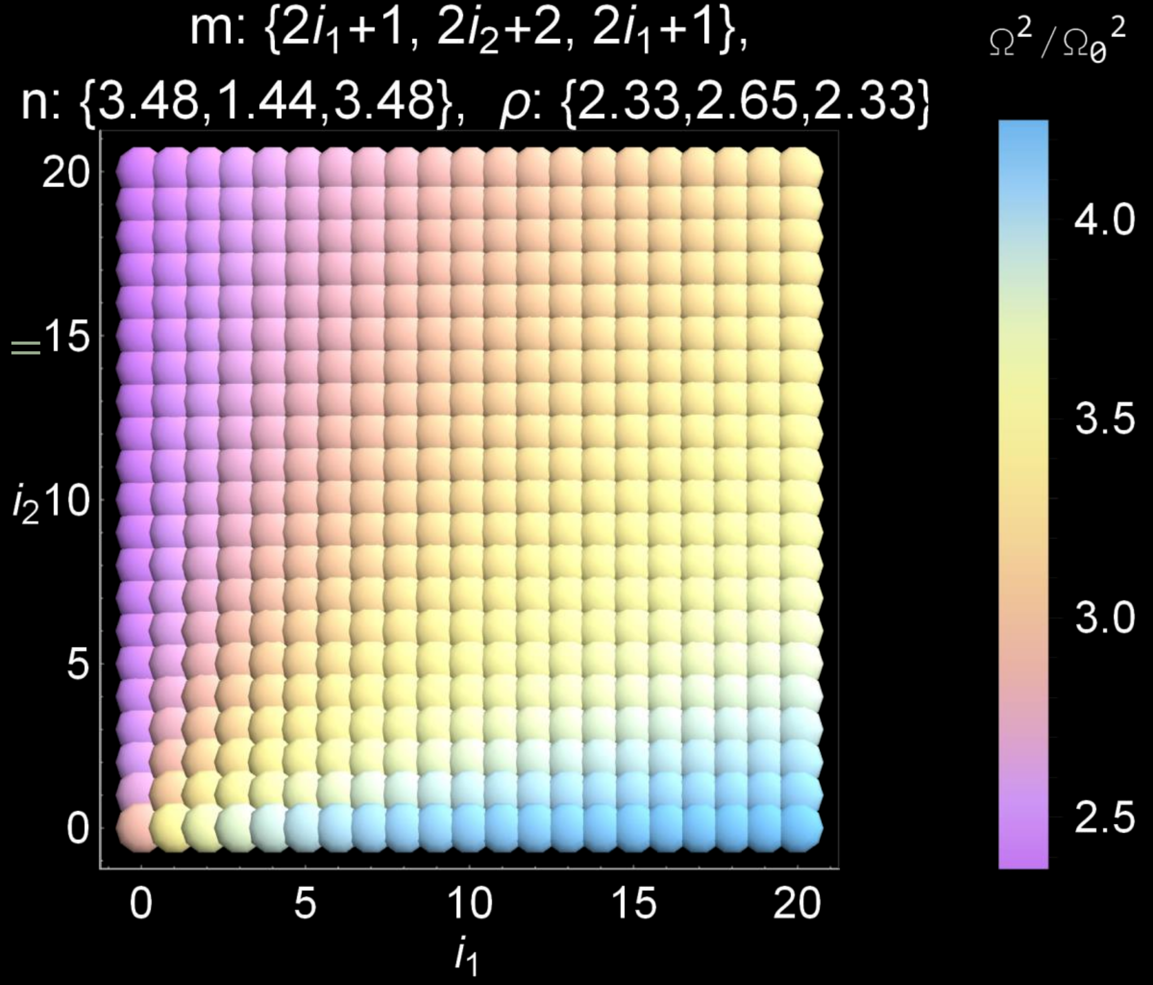
- Thermal noise from gas damping
  - $S_{FF,thermal} = 4\, k_B\, T\, M\, \gamma_g$
- Quantum noise from photon recoil
  - $S_{FF,Recoil} = 4\, \hbar\omega\, M\, \gamma_{sc}$

3. FEASIBLE TRAP FREQUENCY



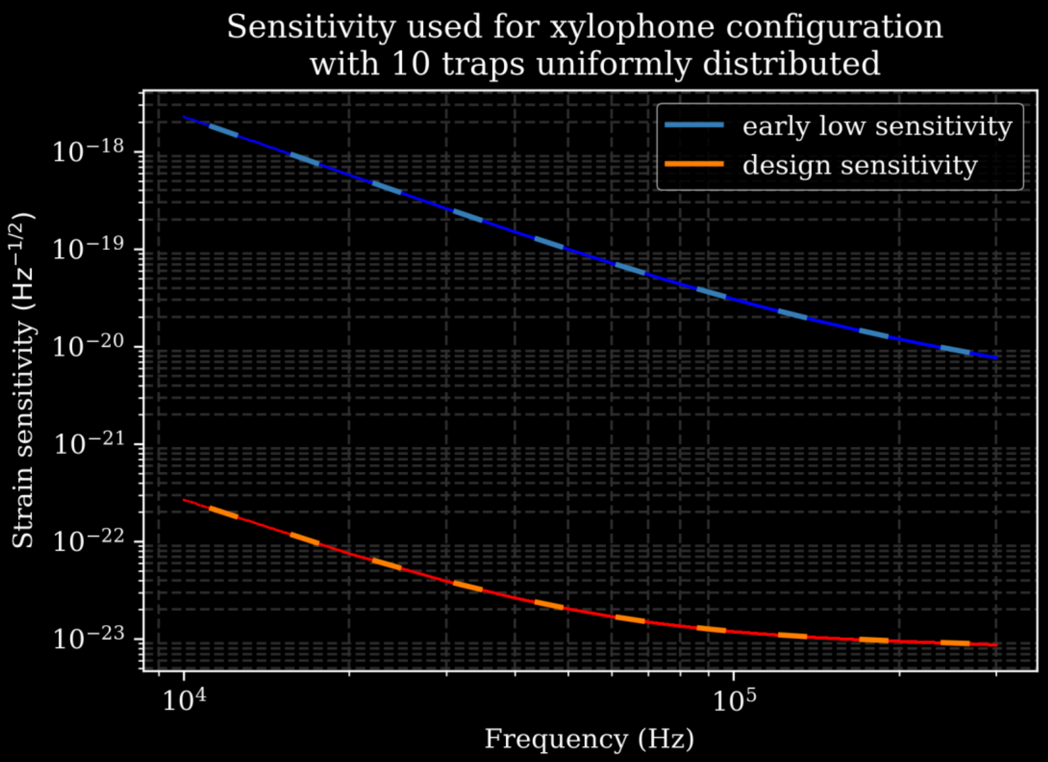
Modified wavelength $\lambda_i = \frac{\lambda_0}{n_i}$

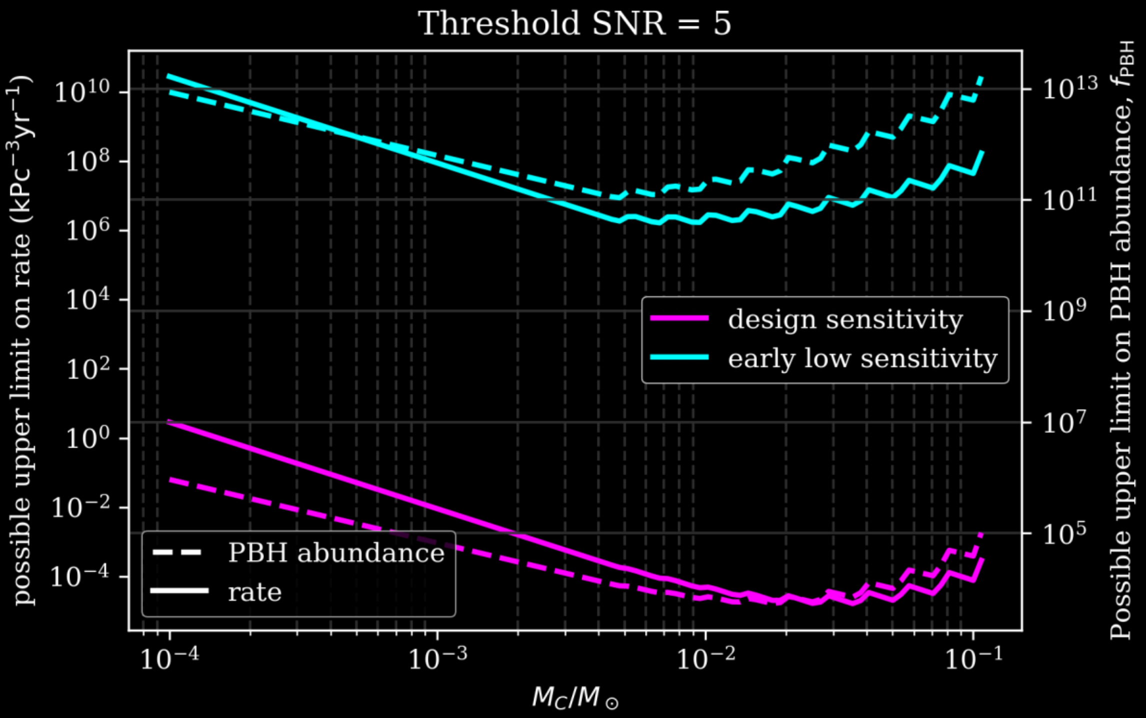
$$\Omega_0^2 = \frac{8\pi P(1 - e^{-2R^2/w^2})}{c\lambda^2\rho_0 R^2}$$



Preliminary: Aggarwal et al.

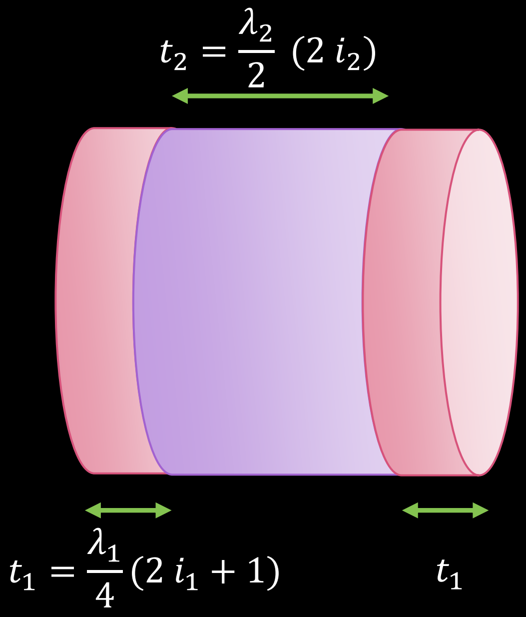
FUTURE DIRECTION 1: XYLOPHONE


Sensitivity used for xylophone configuration with 10 traps uniformly distributed

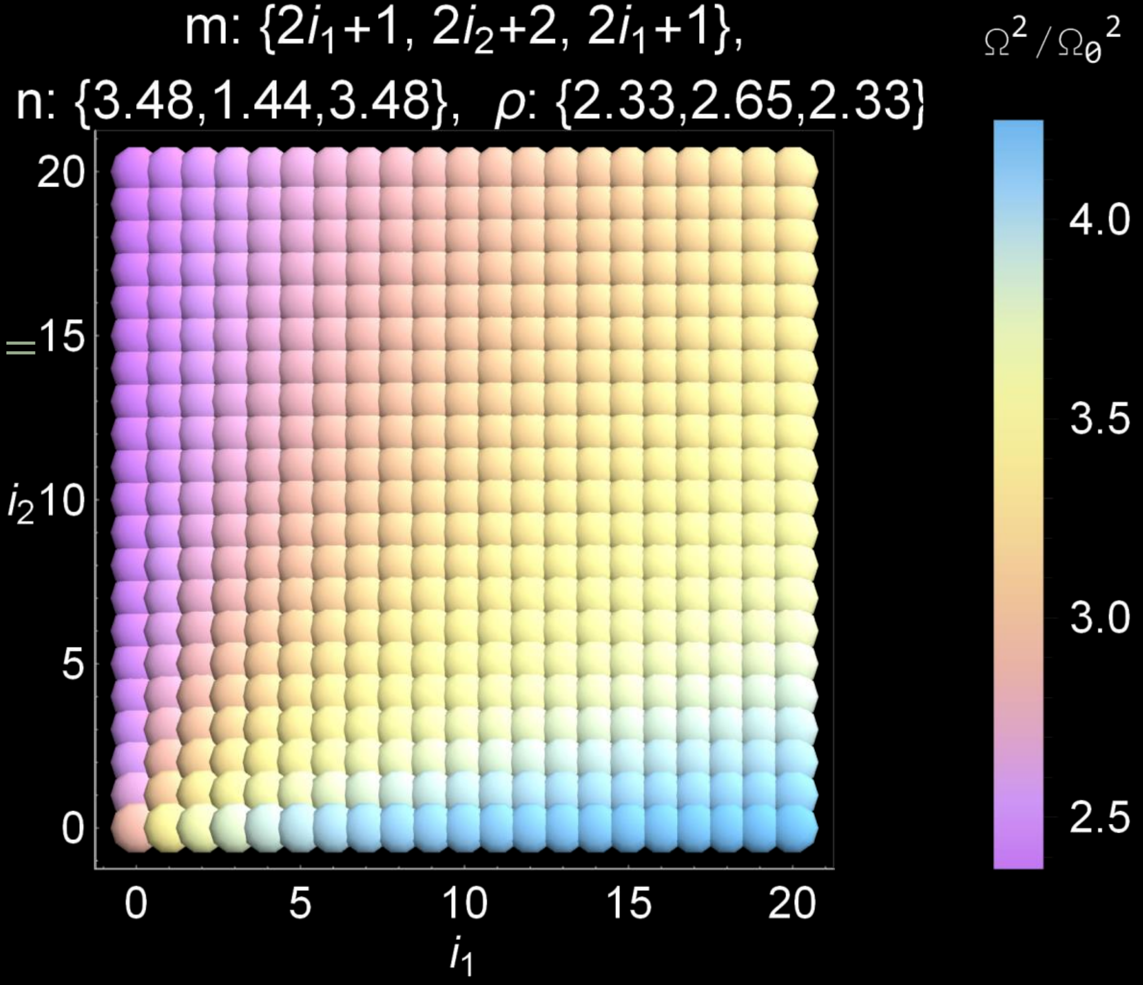

Threshold SNR = 5

Preliminary: Aggarwal et al.

FUTURE DIRECTION2: ADD MORE MASS!!



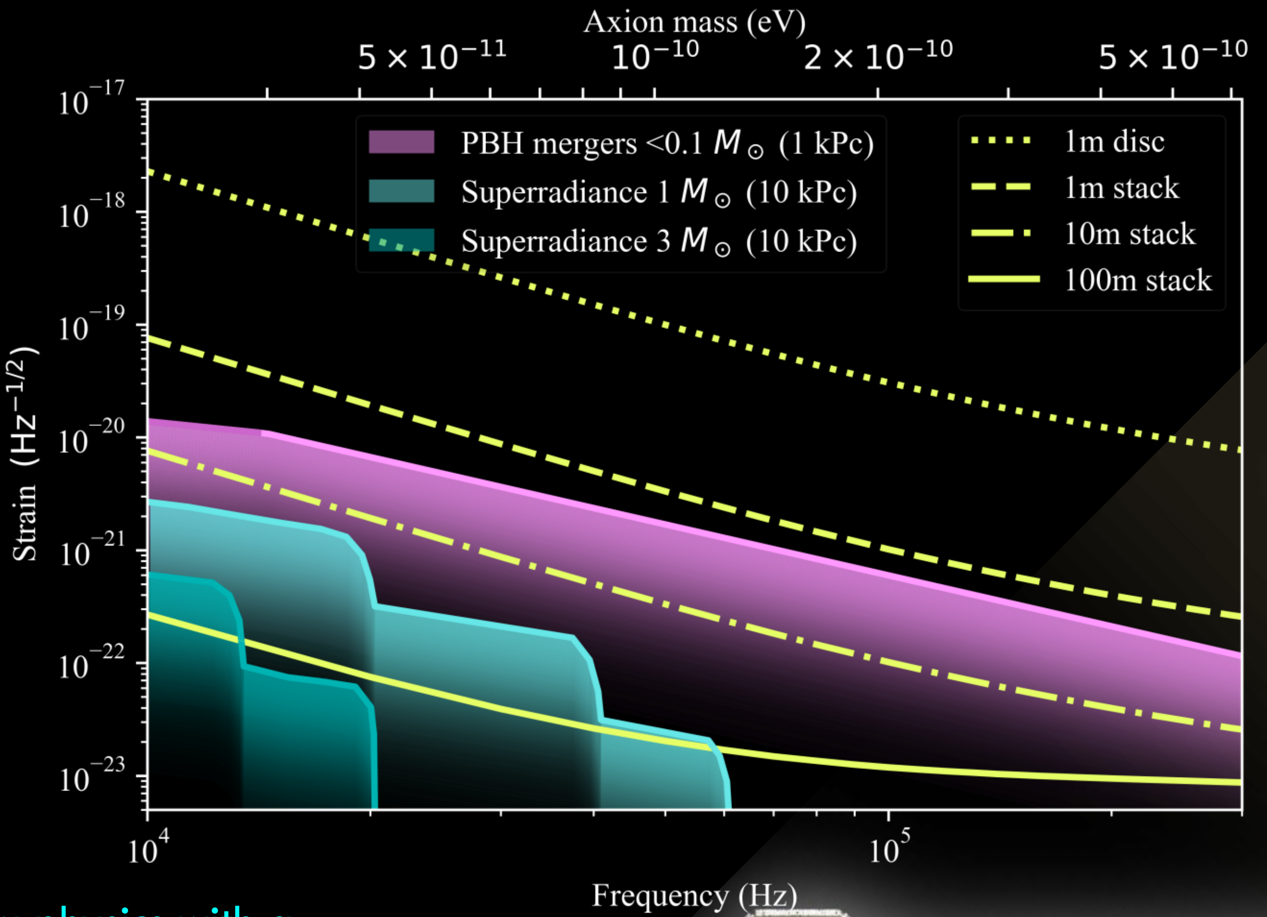
Modified wavelength $\lambda_i = \frac{\lambda_0}{n_i}$



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

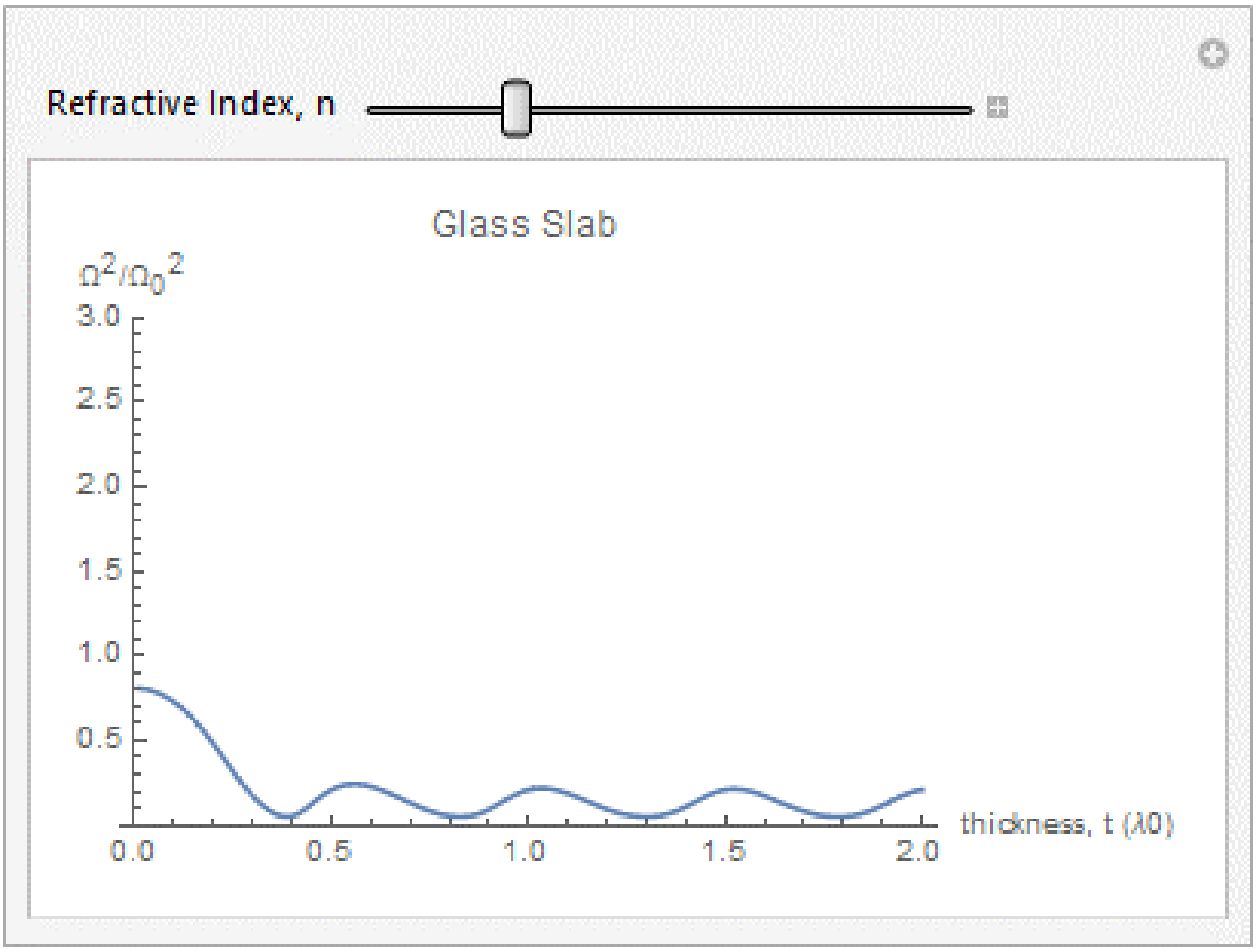
Preliminary: Aggarwal et al.

OPTICAL TRAPPING FOR GW DETECTION

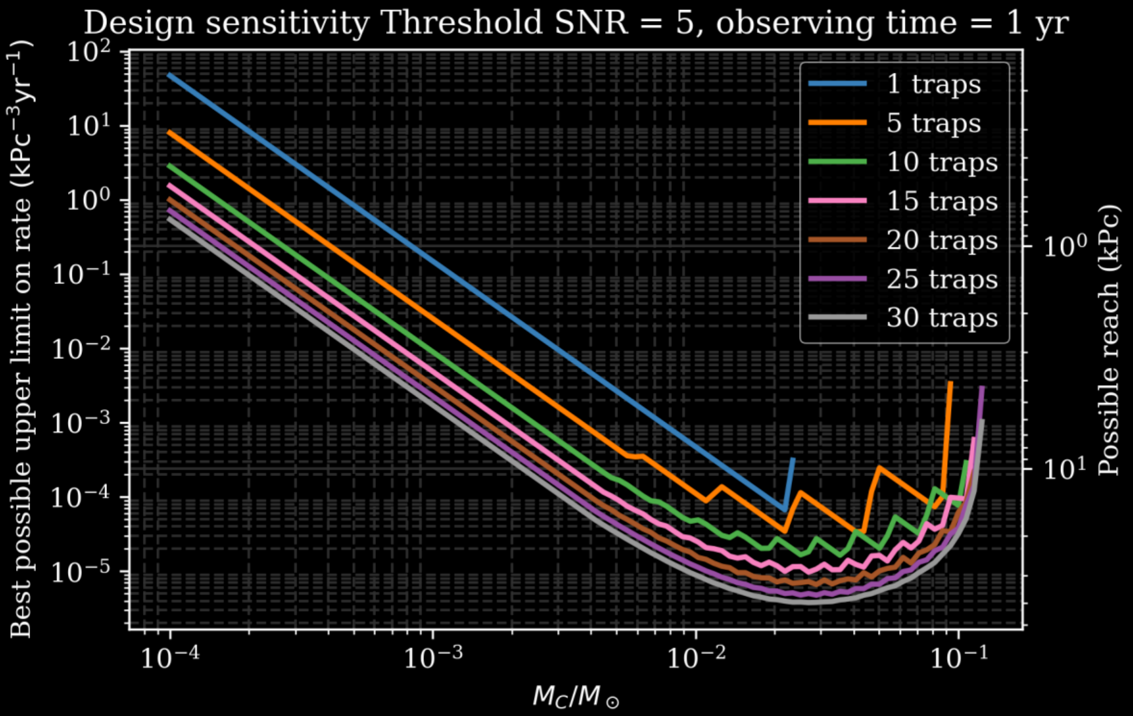


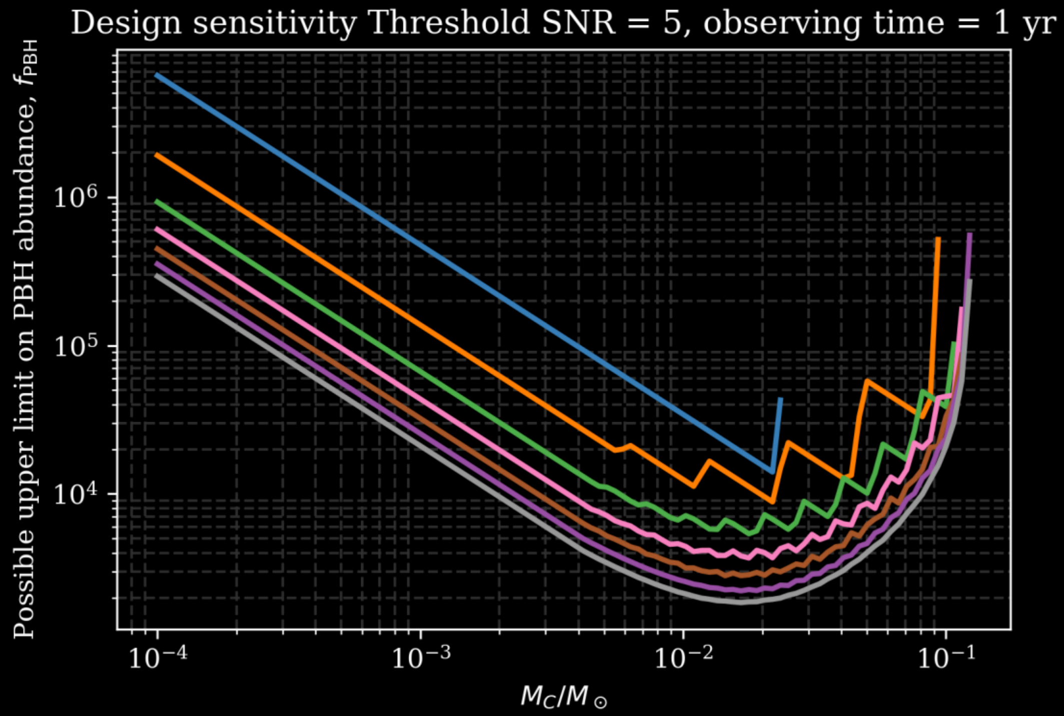
Searching for new physics with a levitated-sensor-based GW detector
NA, G. Winstone, M. Teo et al
arxiv:2010.13157

TRAP FREQUENCY FOR SINGLE CYLINDER



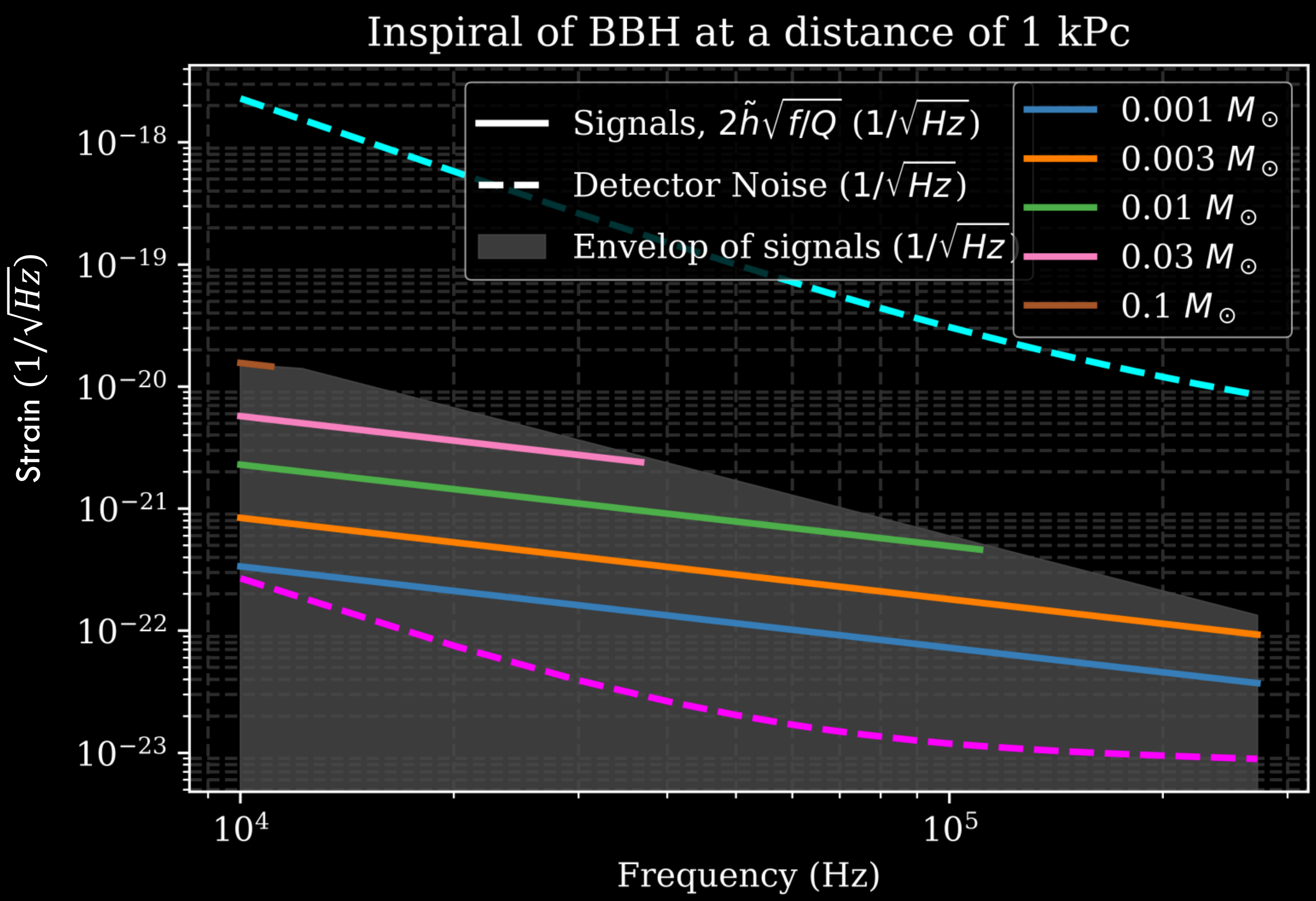
CHANGE NUMBER OF TRAPS





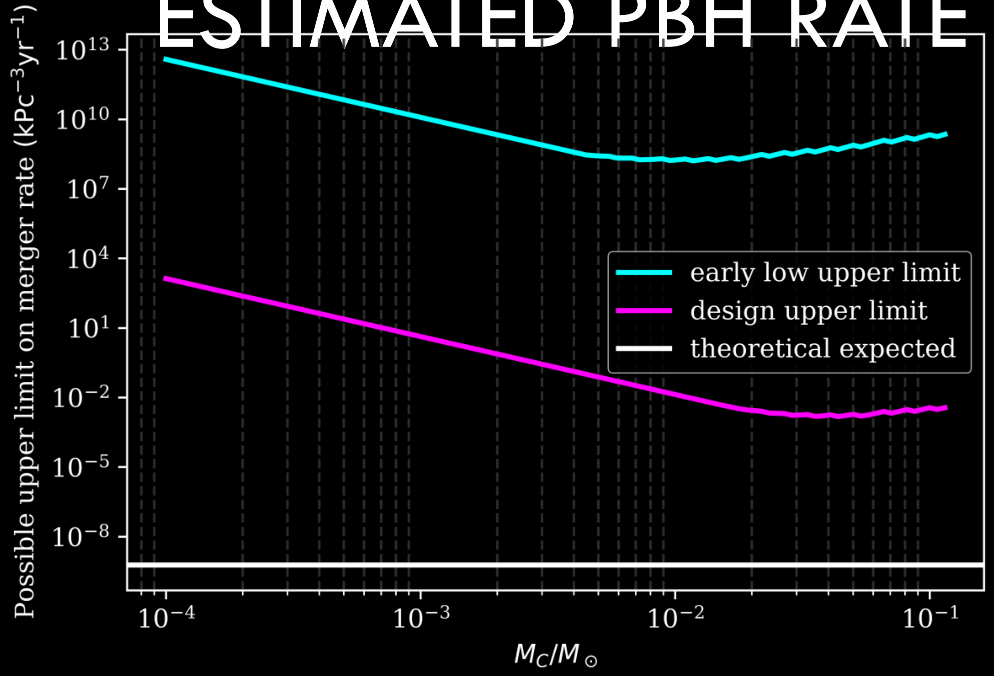
Preliminary: Aggarwal et al.

DETAILED PBH STRAIN

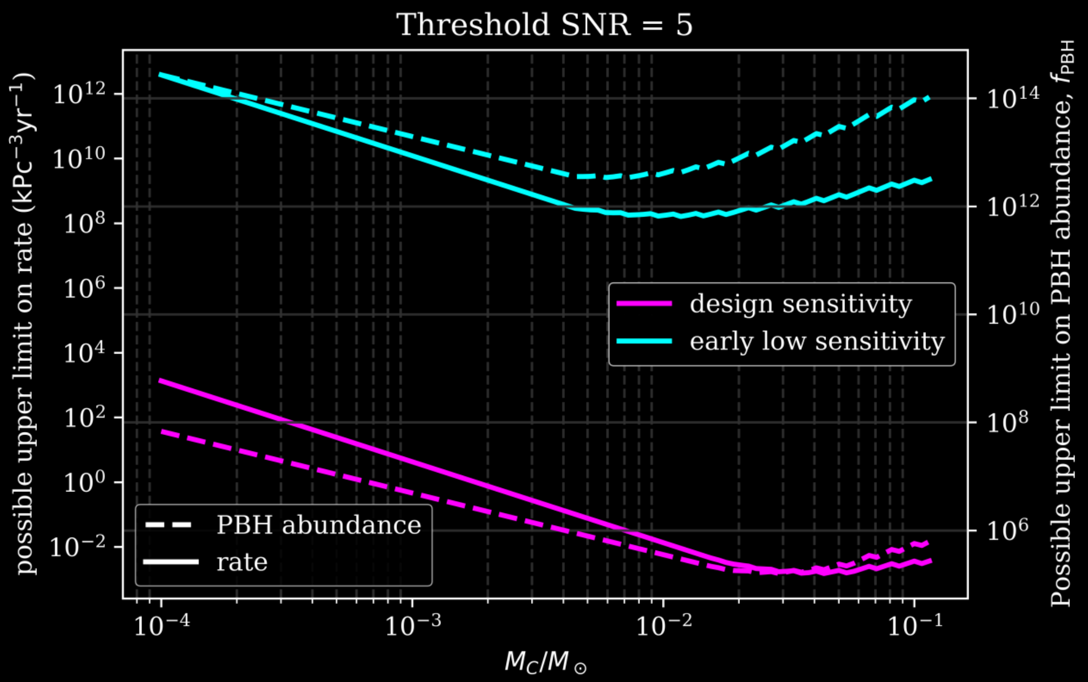


Preliminary: Aggarwal et al.

ESTIMATED PBH RATE UPPER LIMIT

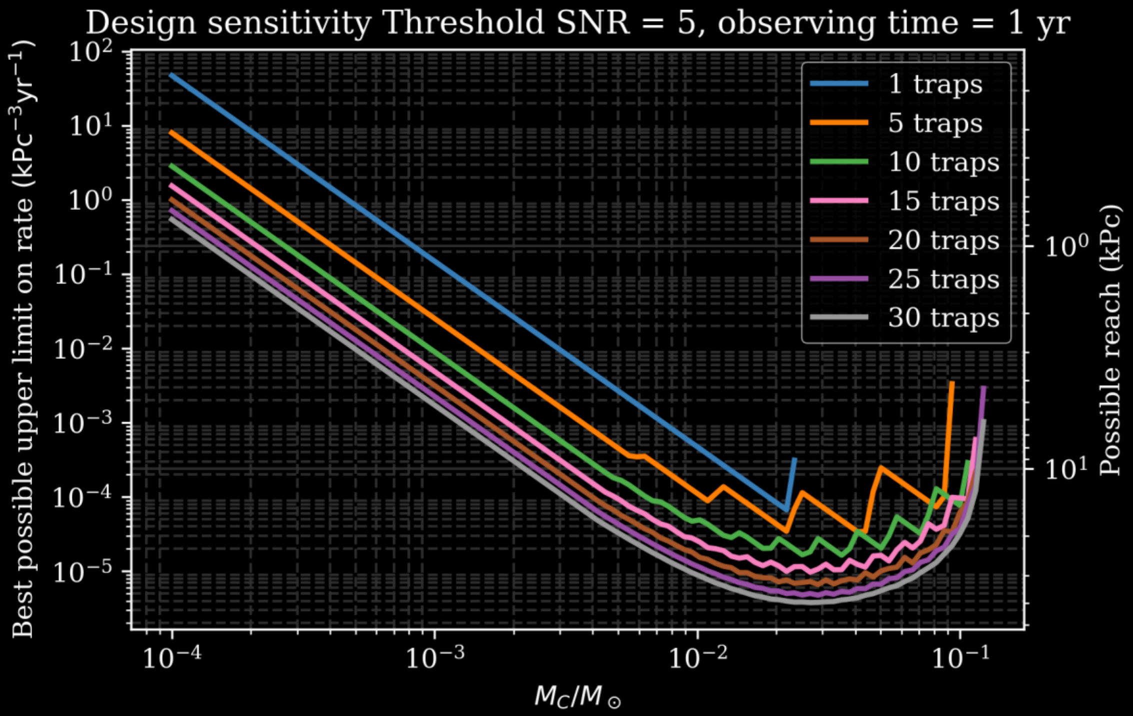


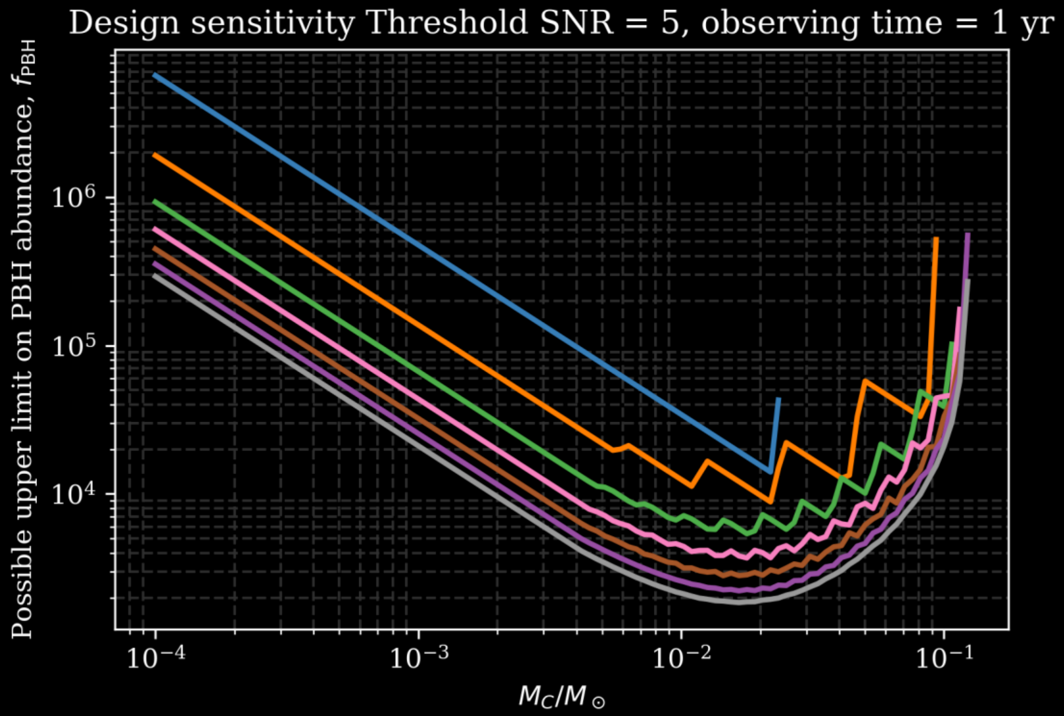
PBH binary formation+merger models



Preliminary: Aggarwal et al.

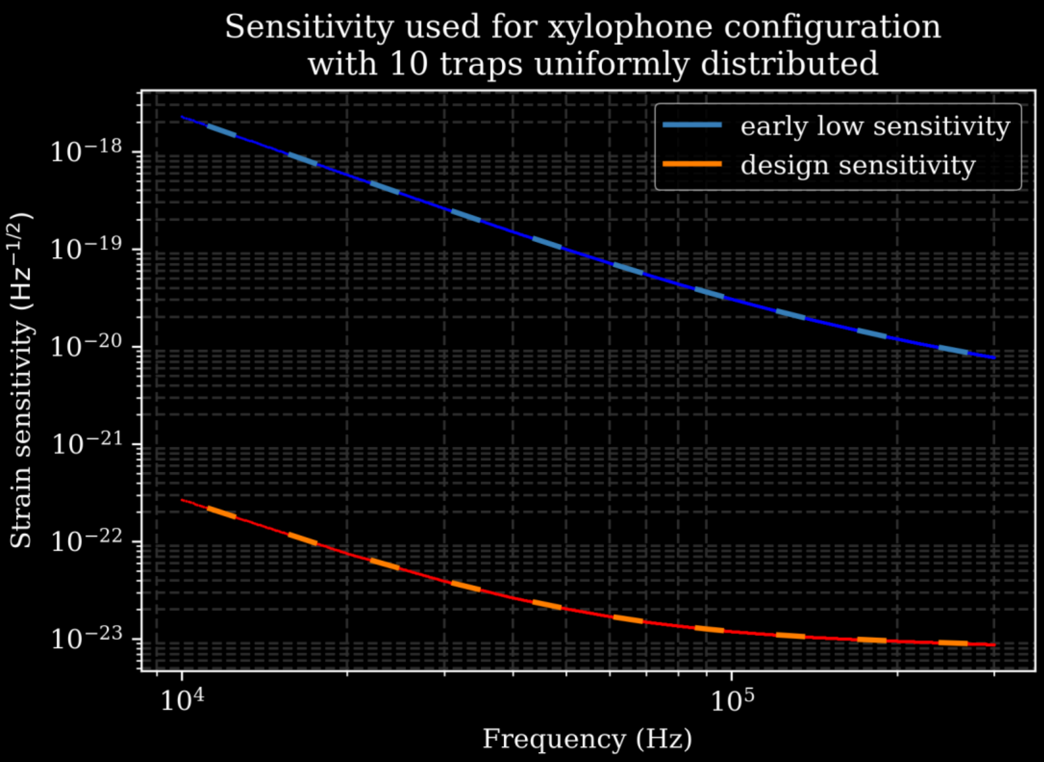
CHANGE NUMBER OF TRAPS

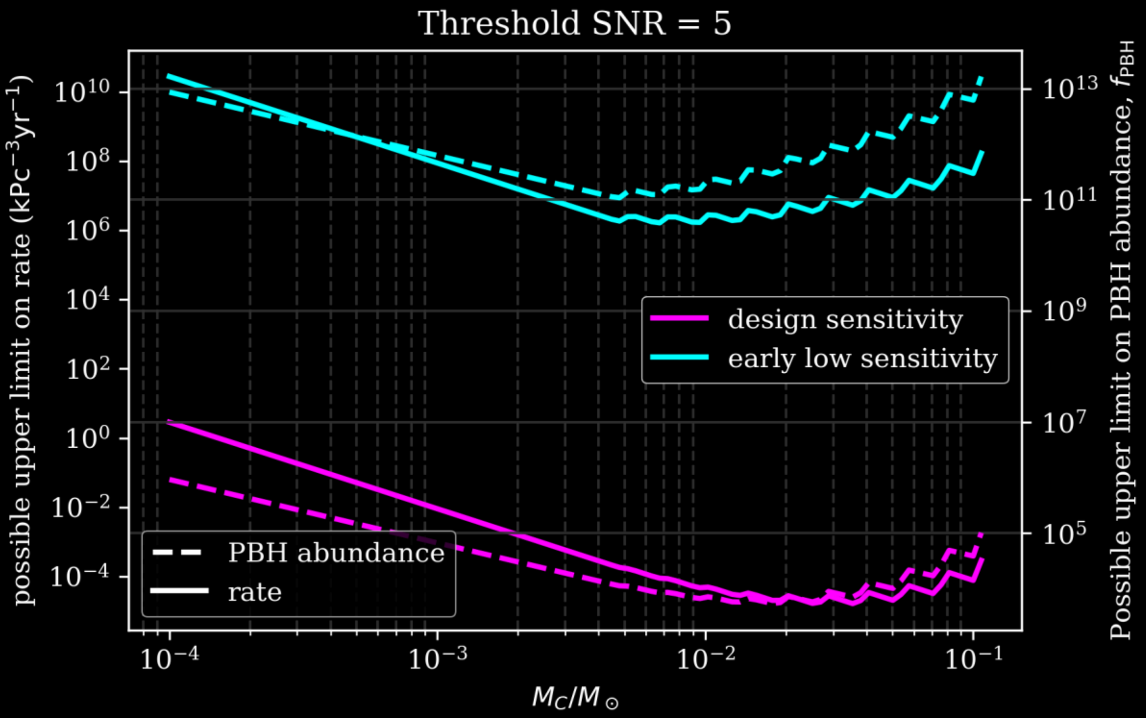




Preliminary: Aggarwal et al.

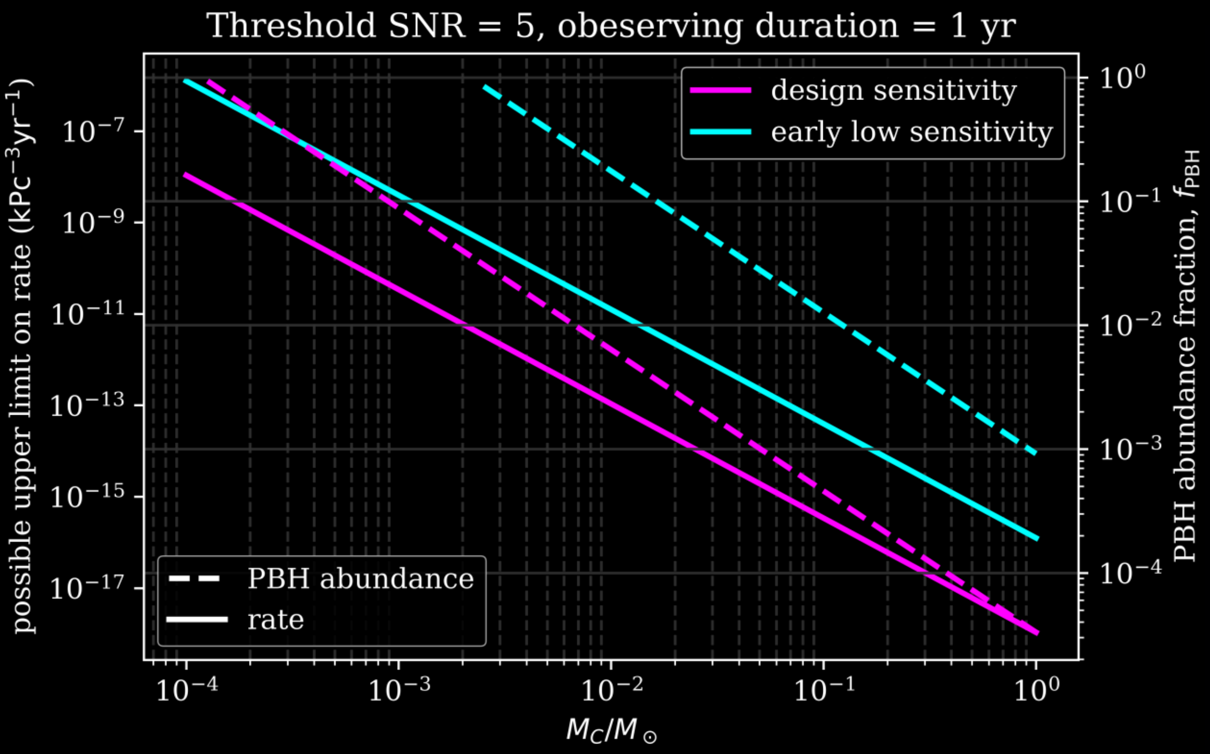
FUTURE DIRECTION 1: XYLOPHONE



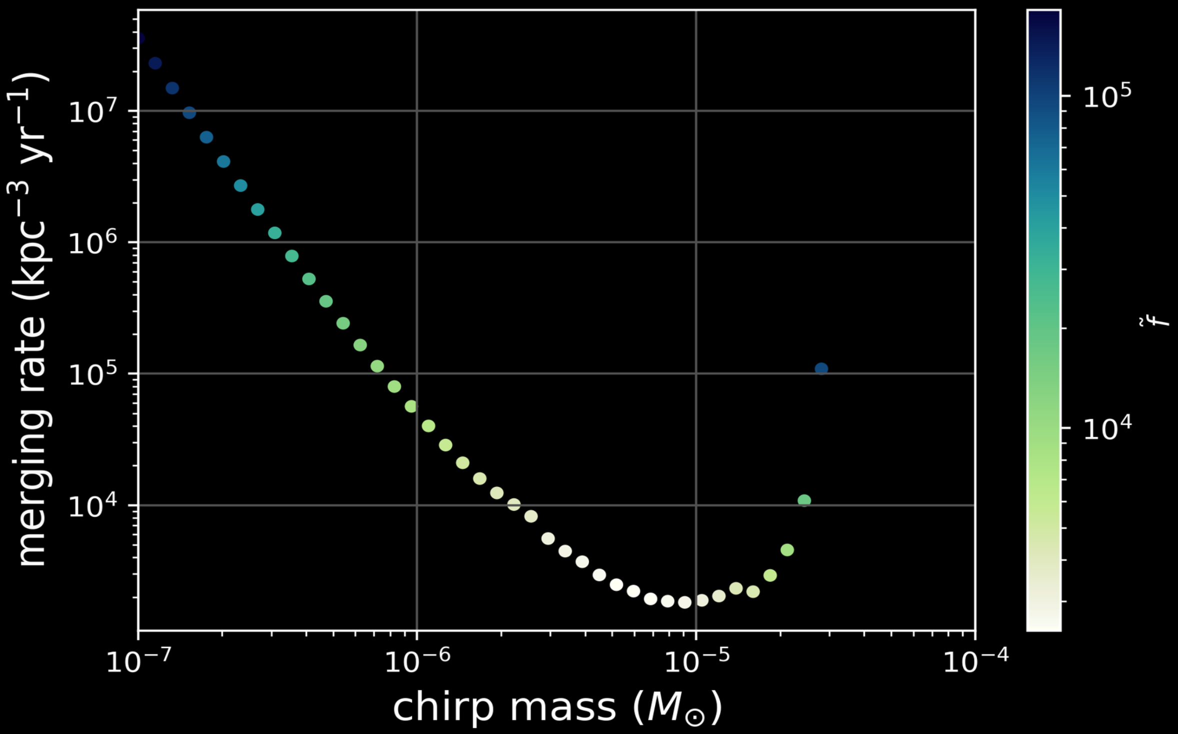


Preliminary: Aggarwal et al.

EXCLUSION W/ LIGO



Preliminary: Aggarwal et al. (see LIGO T2000423)

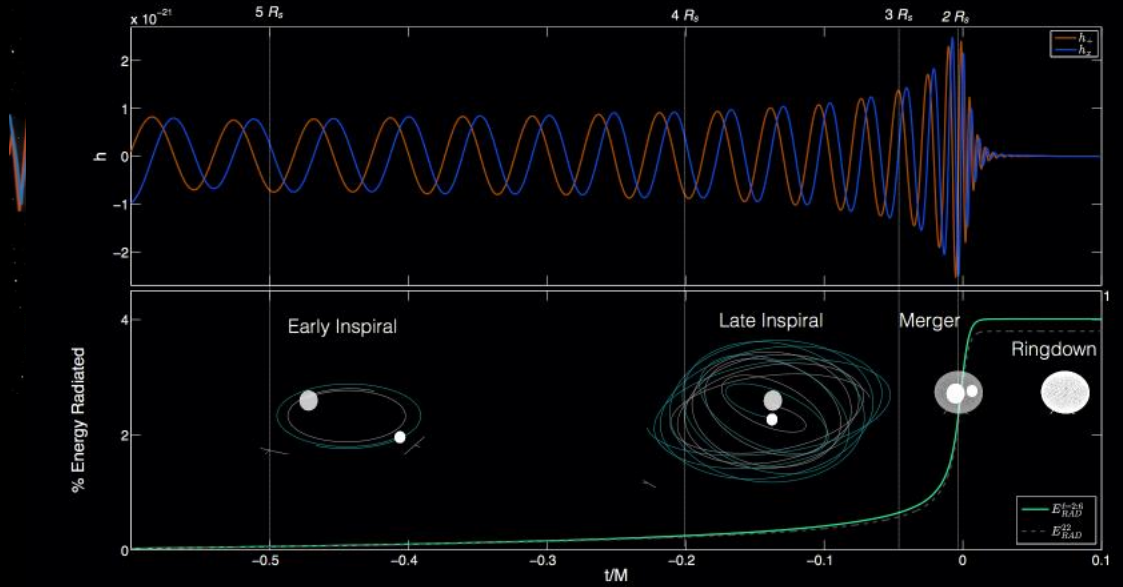


Miller, A., Aggarwal, N., A. *et al*. Constraints on planetary and asteroid-mass primordial black holes from continuous gravitational wave searches. PRD, 2022

CBC VS CW SEARCHES


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

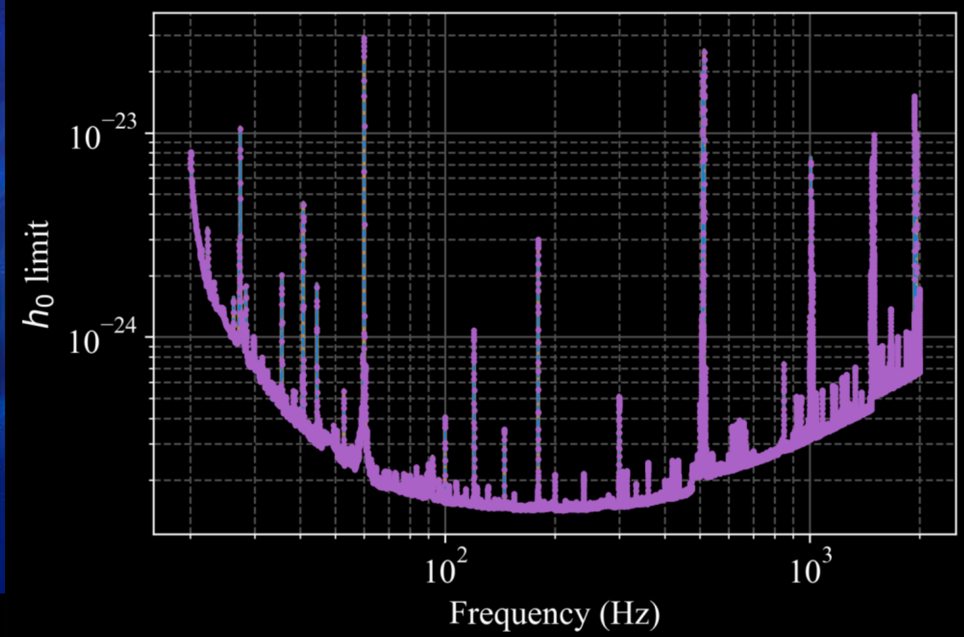
“Chirping” GW



Monochromatic GW

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

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



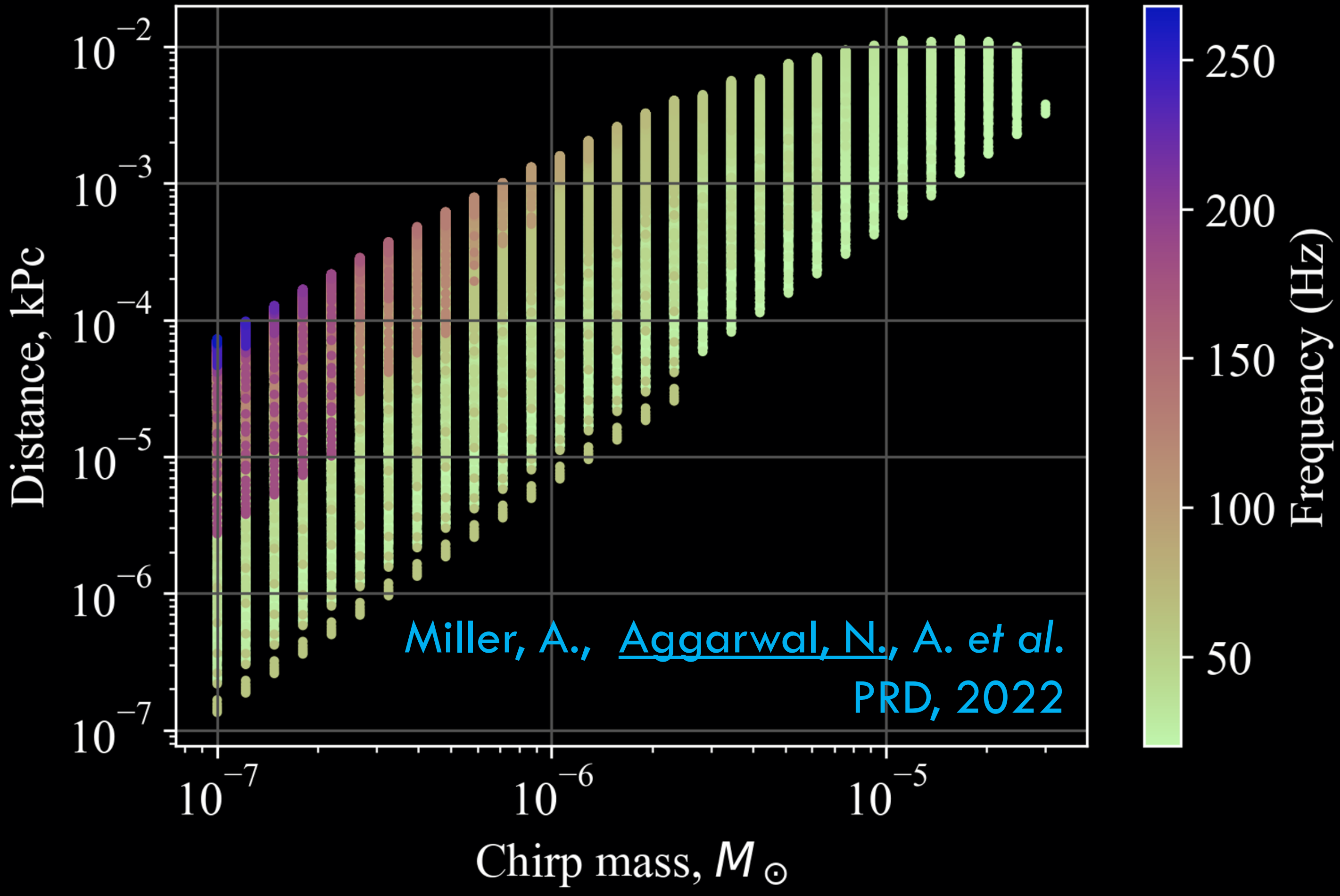
DISTANCE LIMIT FOR EACH M_c AND f_{GW}

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

CW constraints:

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

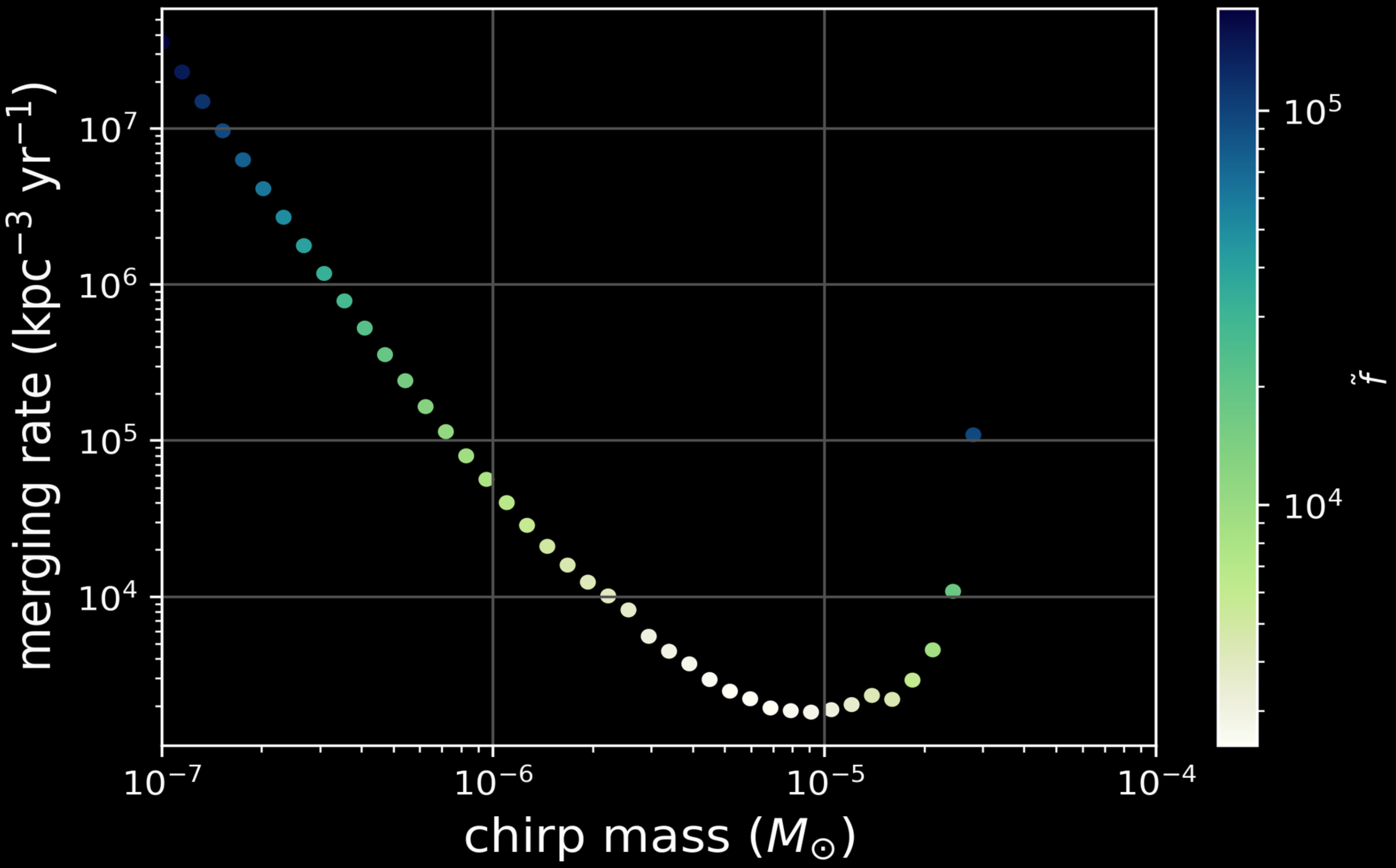
$$f_{GW}(t) = f_{GW}(t_0) + \dot{f}(t - t_0)$$



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

EXCLUSION W/ LIGO

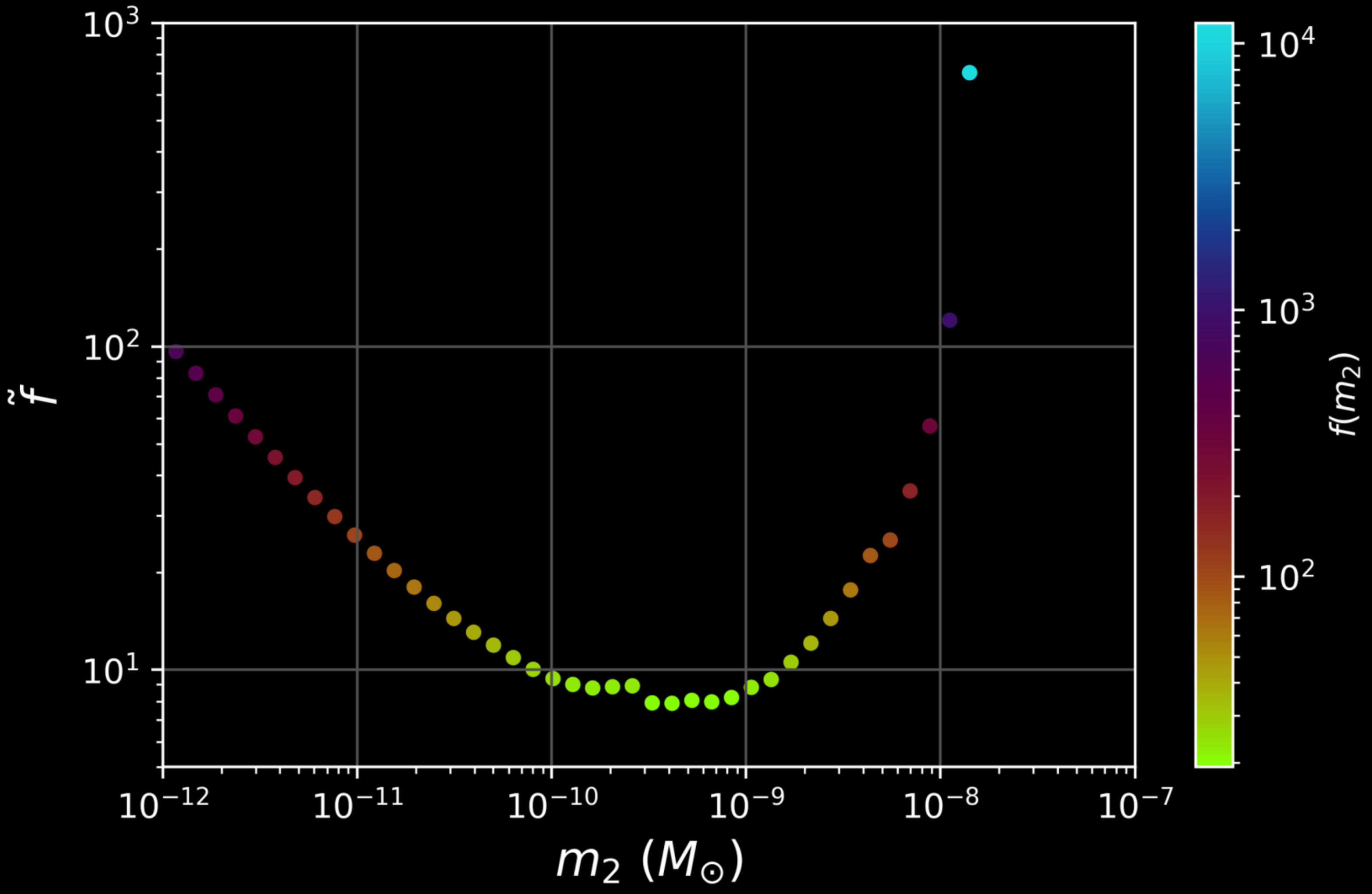
Miller, A., Aggarwal, N., A. *et al*. Constraints on planetary and asteroid-mass primordial black holes from continuous gravitational wave searches. PRD, 2022



CONSTRAINTS WITH ASYMMETRIC MASS RATIO

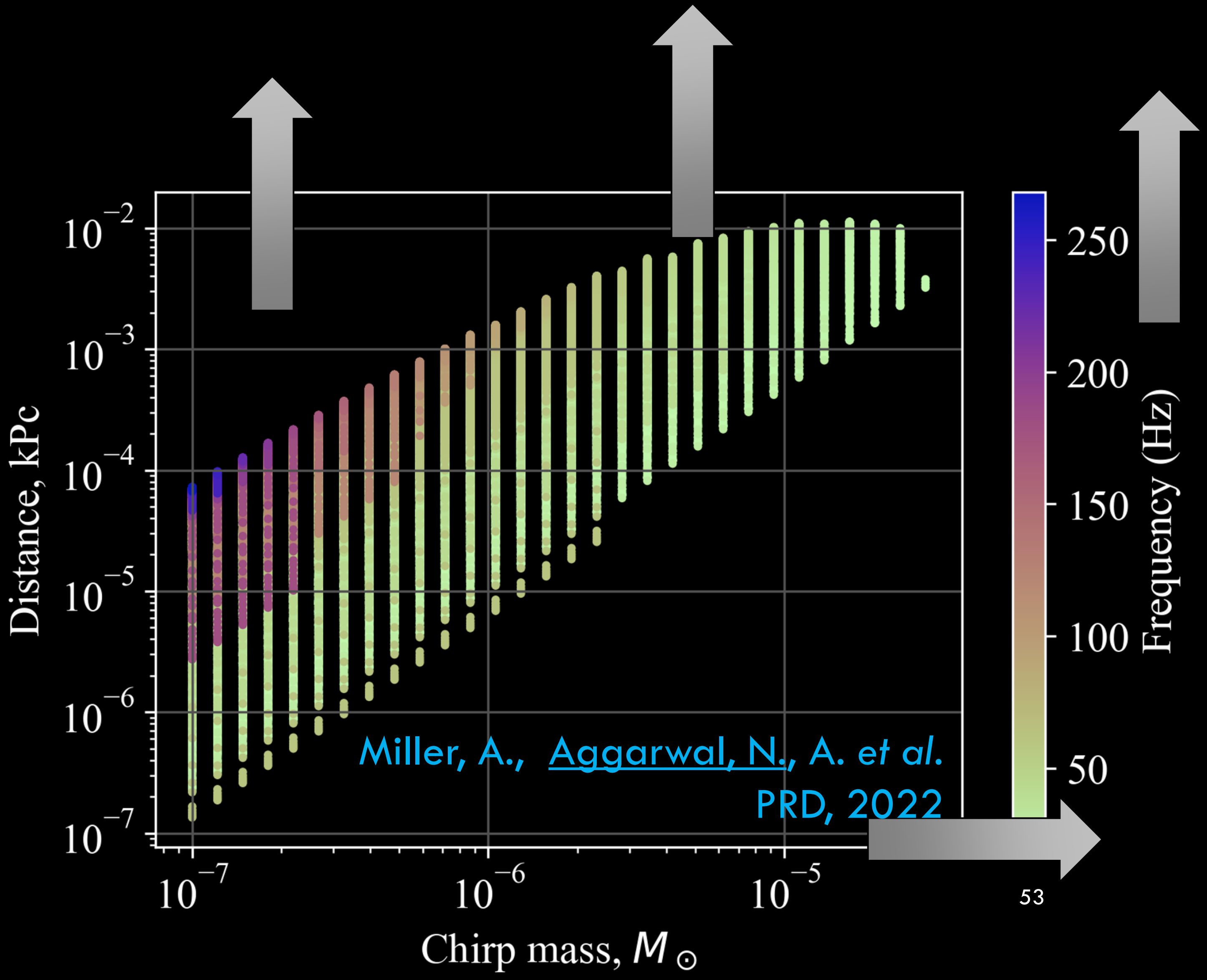
$m_1 = 2.5\ M_\odot$

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



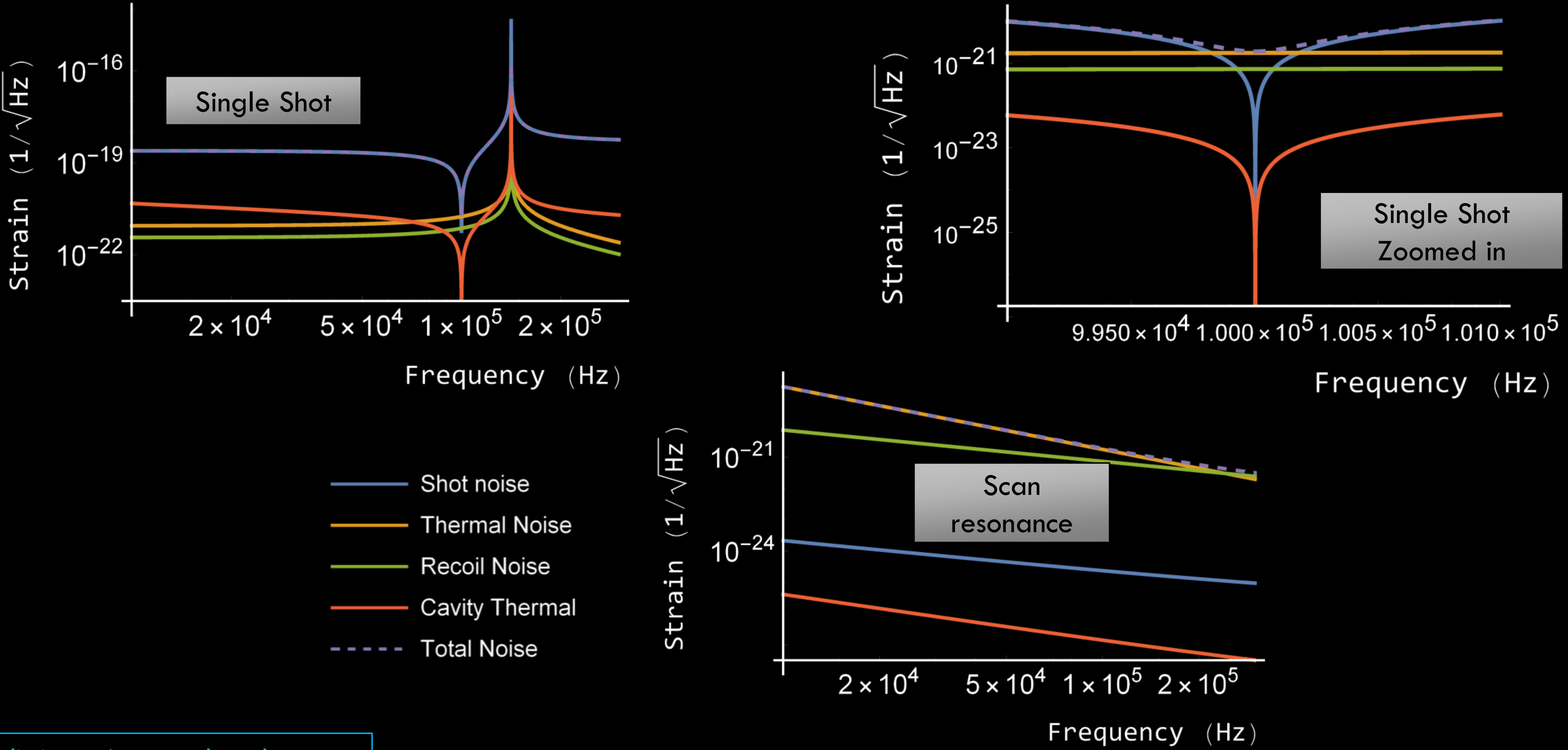
UPPER LIMITS ON PRIMORDIAL BLACK HOLES

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

DETAILED NOISE BUDGET



Preliminary Aggarwal et al