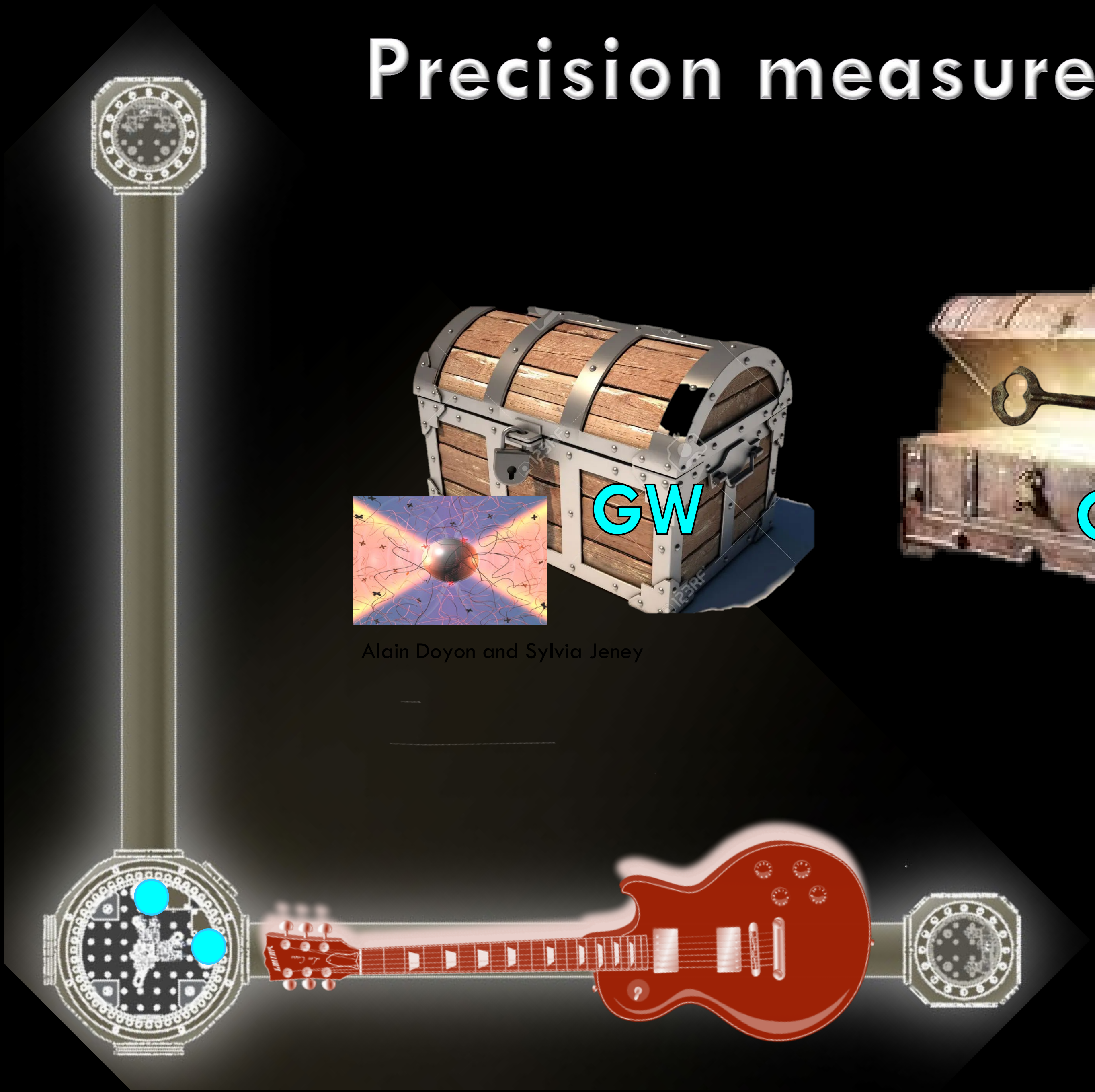
Precision measurements searching for UL DM and GWs



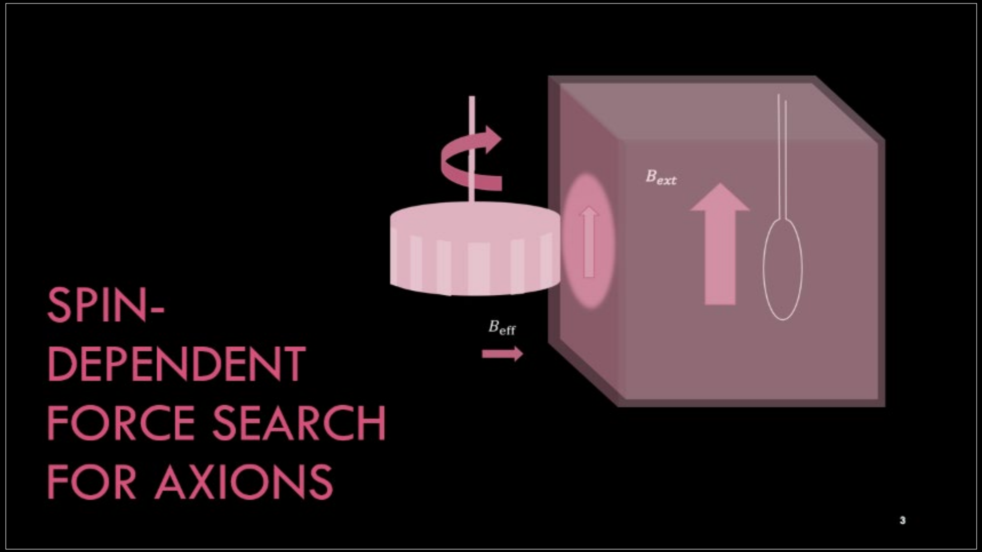
Alain Doyon and Sylvia Jeney

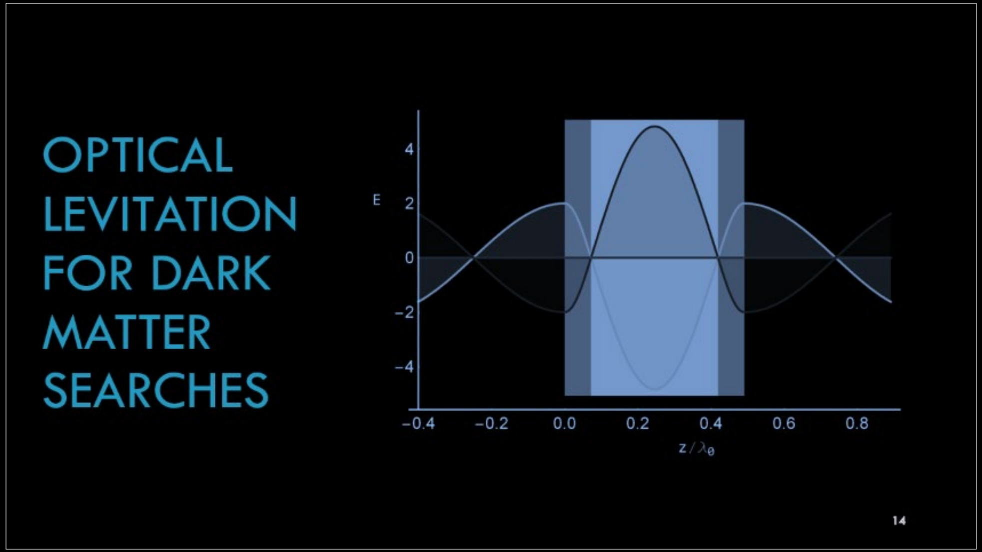
FUTURE OF PARTICLE PHYSICS

ASPEN, MARCH 25, 2024

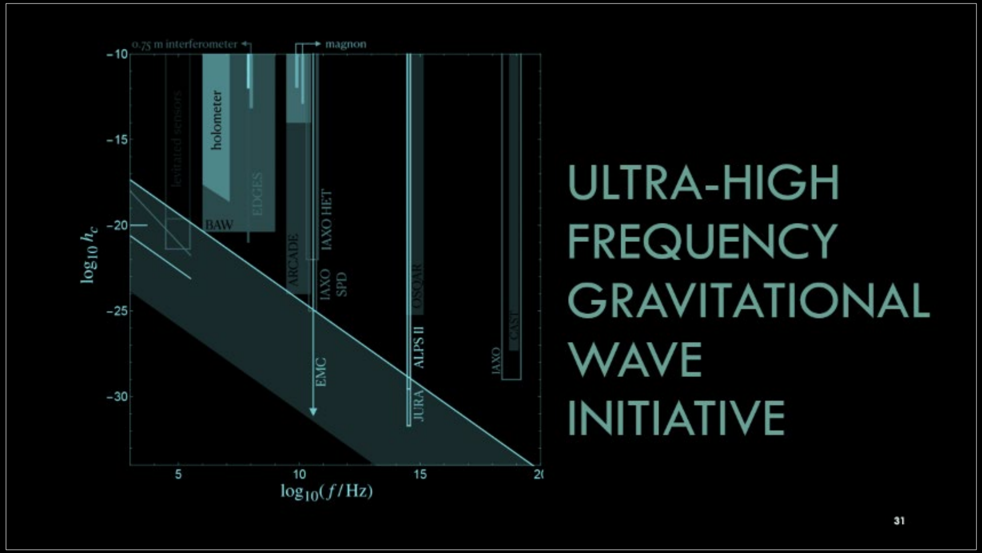
Nancy Aggarwal
University of California, Davis

TODAY'S MENU

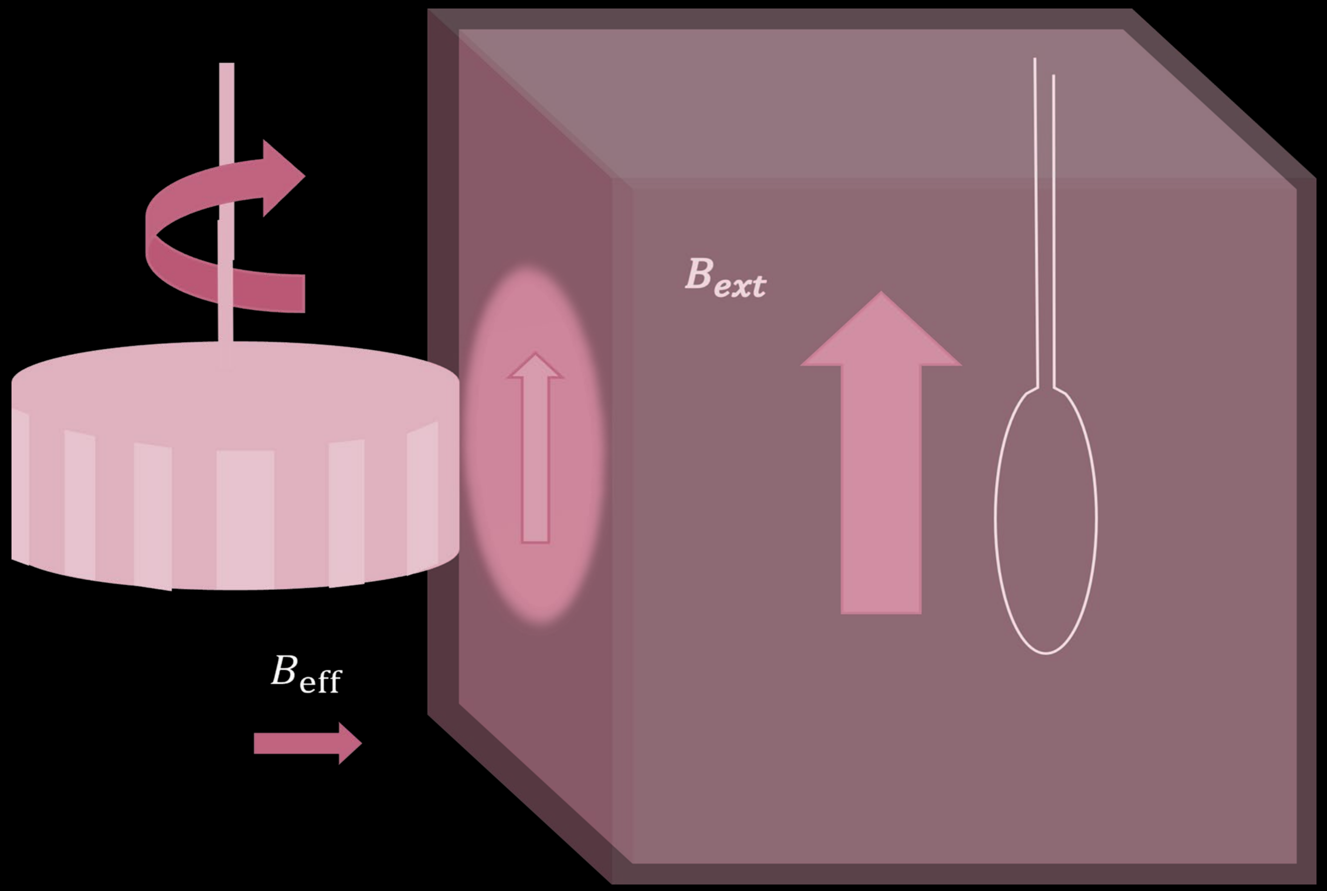

SPIN-
DEPENDENT
FORCE SEARCH
FOR AXIONS
B_{ext}
B_{eff}
3


OPTICAL
LEVITATION
FOR DARK
MATTER
SEARCHES
E
z/λ_0
14


DM SEARCHES
IN AUDIO-
BAND GW
DETECTORS
Andreus/Depositphotos
22


ULTRA-HIGH
FREQUENCY
GRAVITATIONAL
WAVE
INITIATIVE
0.75 m interferometer
magnon
holometer
BAW
EDGES
ARCADE
IAXO HET
IAXO SPD
EMC
ALPS II
JURA
OSQAR
IAXO
CAST
$\log_{10} h_c$
$\log_{10}(f/\mathrm{Hz})$
31

SPIN-DEPENDENT FORCE SEARCH FOR AXIONS



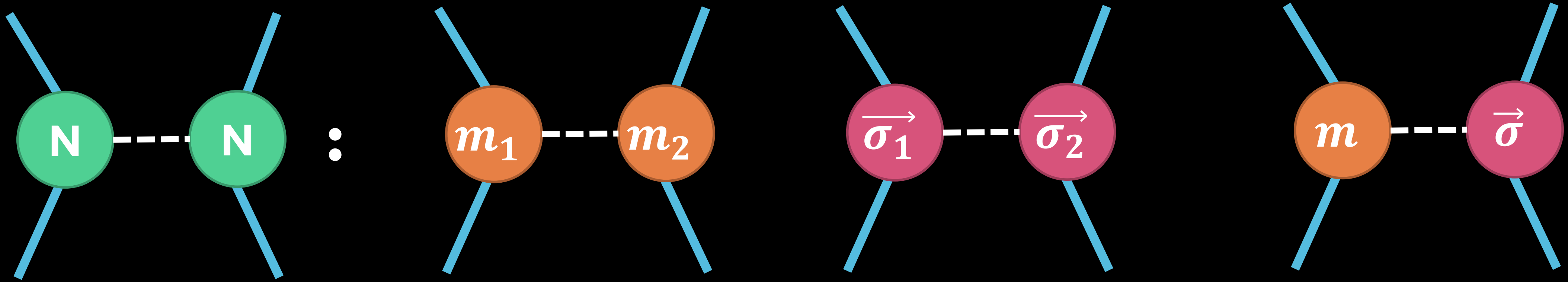
ARIADNE GOAL

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

Source	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	

Coupling

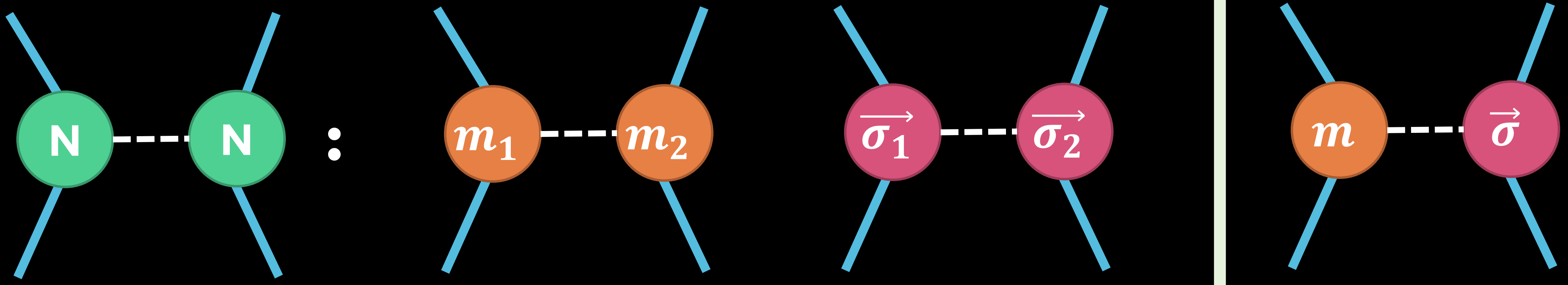
AXION-MEDIATED INTERACTIONS BETWEEN NUCLEONS



$U_{ss} \propto g_{s_1} g_{s_2}$ $\quad U_{pp} \propto g_{p_1} g_{p_2}$ $\quad U_{sp} \propto g_s g_p$

Refs: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.30.130

AXION-MEDIATED INTERACTIONS BETWEEN NUCLEONS



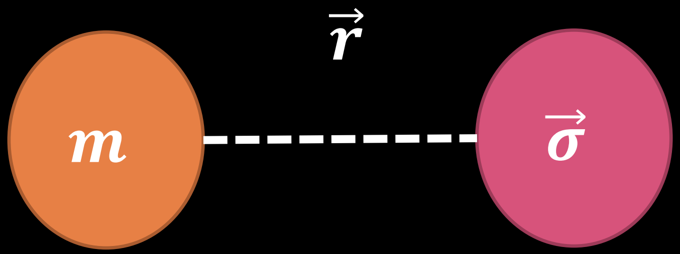
$U_{ss} \propto g_{s_1} g_{s_2}$

$U_{pp} \propto g_{p_1} g_{p_2}$

$U_{sp} \propto g_s g_p$

Refs: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.30.130

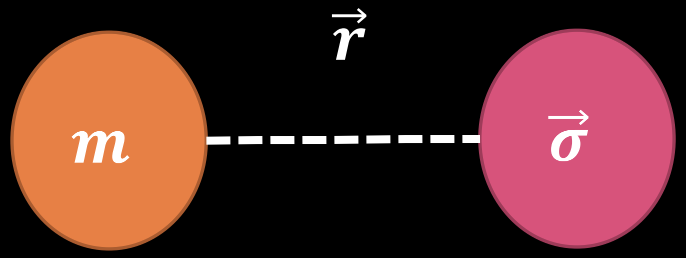
MONOPOLE-DIPOLE FORCES DUE TO AXION



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

Refs: 2010.03889, https://journals.aps.org/prd/abstract/10.1103/PhysRevD.30.130, https://www.science.org/doi/10.1126/sciadv.abm9928, 2006:12508, 1801.08127

MONOPOLE-DIPOLE FORCES DUE TO AXION



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

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

Refs: 2010.03889, https://journals.aps.org/prd/abstract/10.1103/PhysRevD.30.130, https://www.science.org/doi/10.1126/sciadv.abm9928, 2006:12508, 1801.08127

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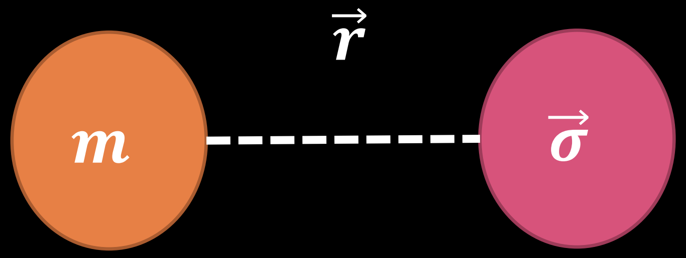

$$U_{sp}(r) = \frac{\hbar^2 g_s^N g_p^N}{8\,\pi\, m_N}\left(\frac{1}{r\,\lambda_a} + \frac{1}{r^2}\right) e^{-\frac{r}{\lambda_a}} (\hat{\sigma}\cdot\hat{r})$$

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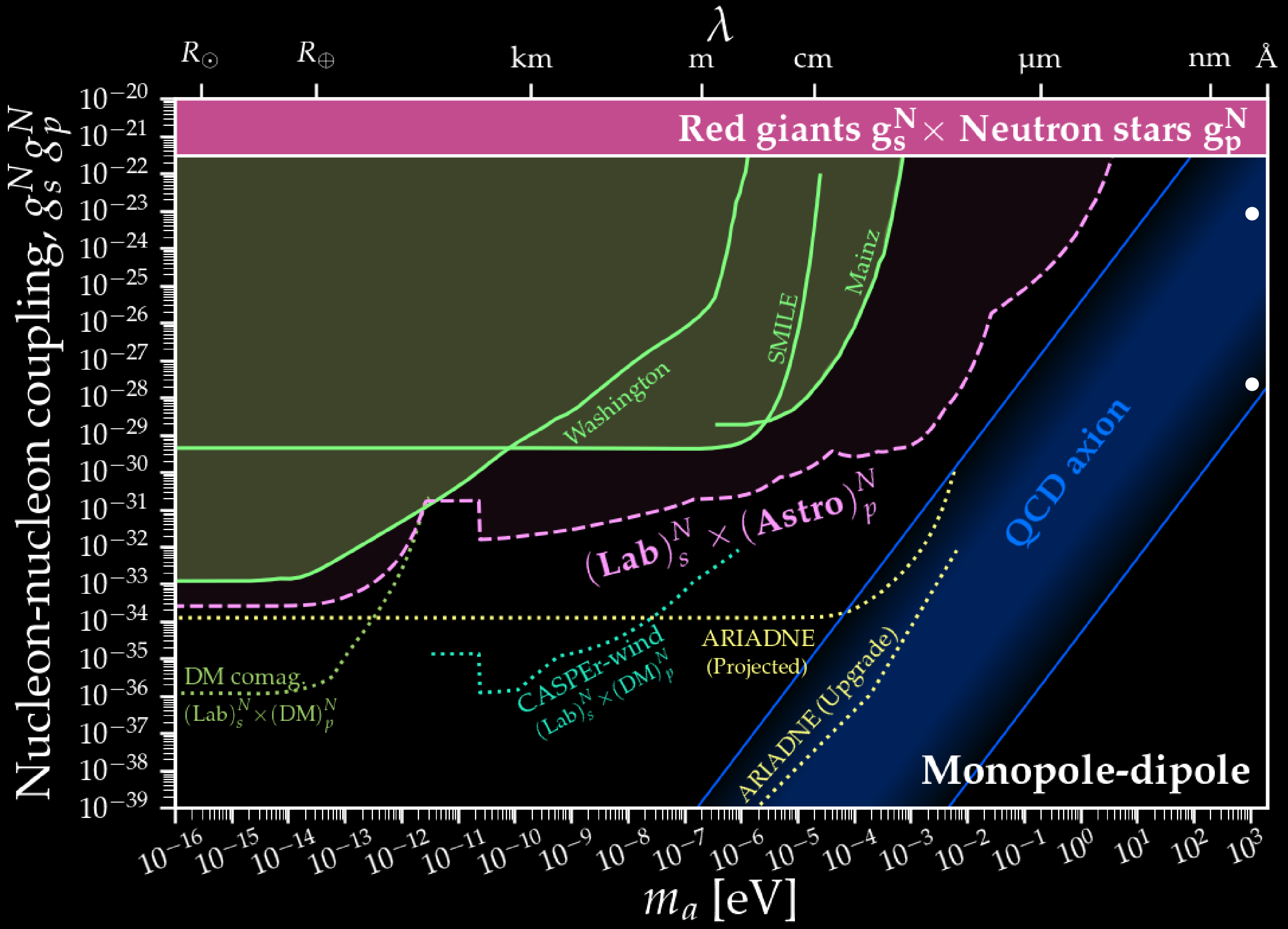
$g_s^N\ g_p^N$ range predicted by various theoretical models ~ $10^{-38} - 10^{-30}$, (depend on mass/f_a)

Refs: 2010.03889, https://journals.aps.org/prd/abstract/10.1103/PhysRevD.30.130, https://www.science.org/doi/10.1126/sciadv.abm9928, 2006:12508, 1801.08127

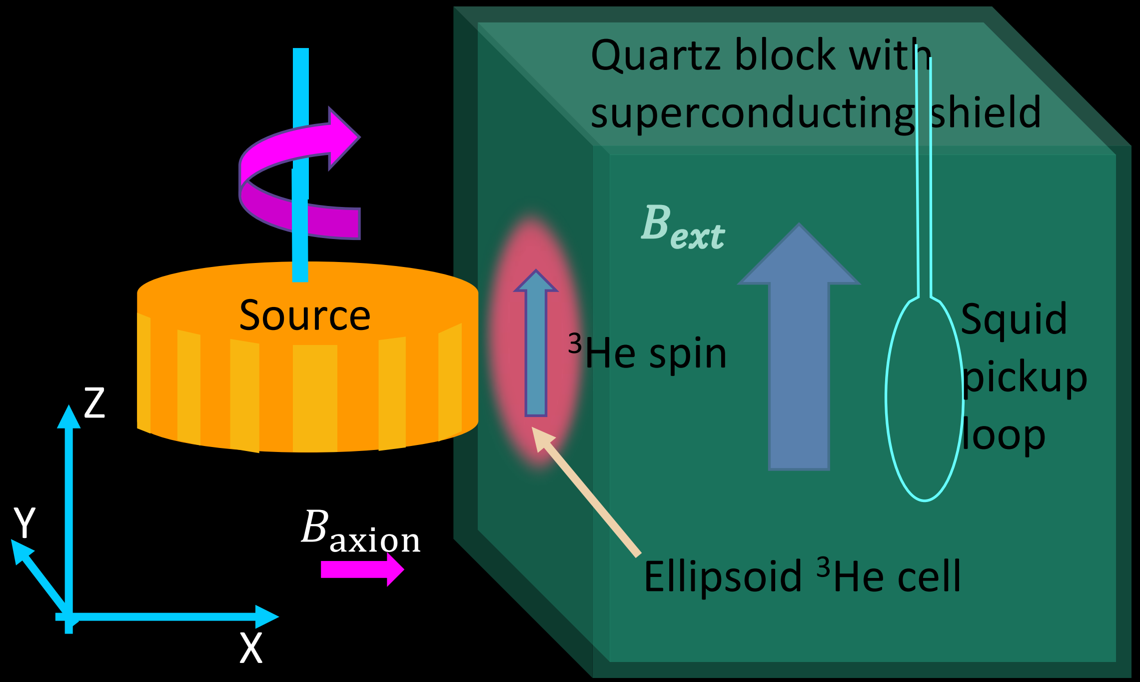
STATE OF THE ART IN $g_s g_p$



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

O'Hare & Vitagliano, PRD 102 115026 2021

ARIADNE EXPERIMENT CONCEPT

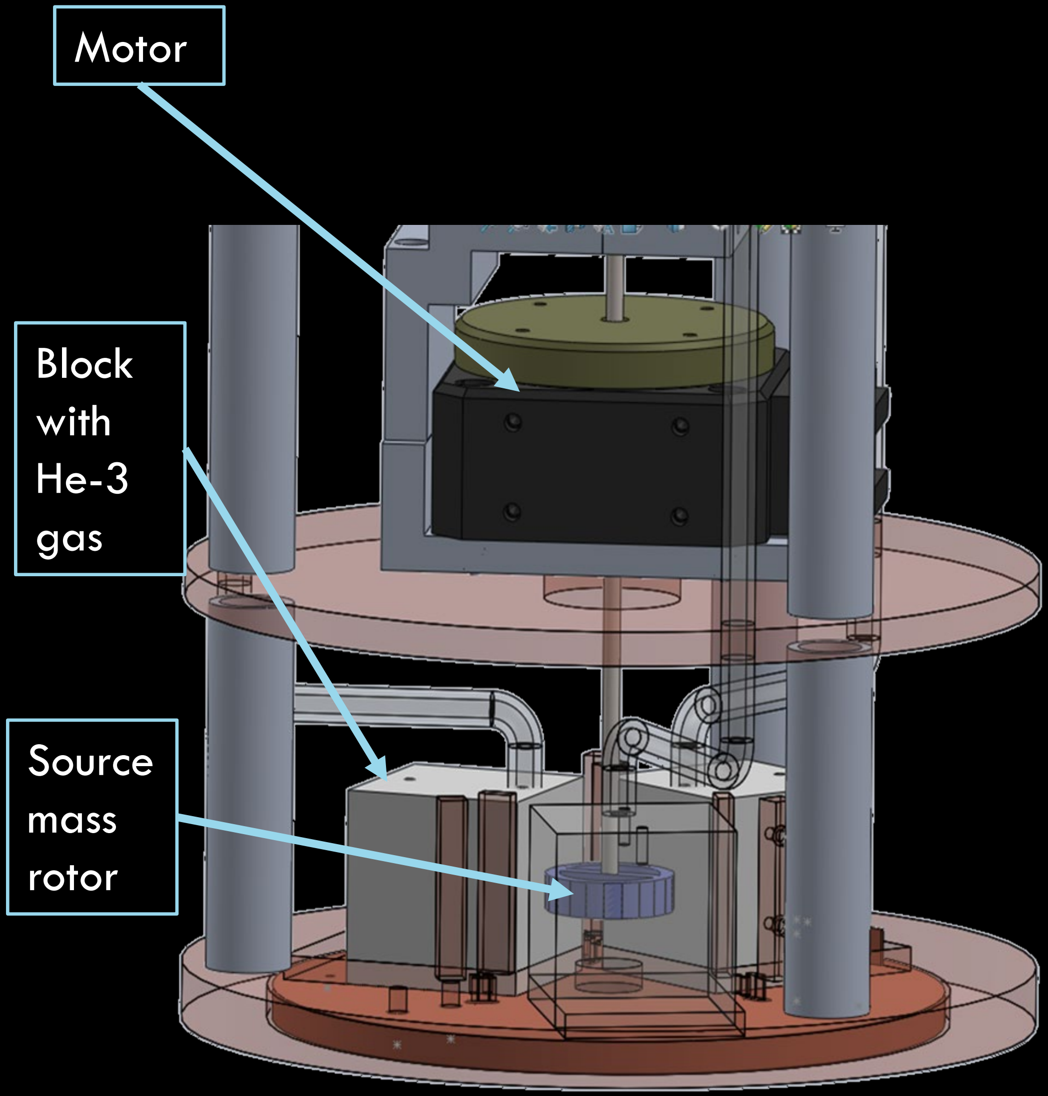


$$U_{sp}(r) = \frac{\hbar^2 g_s^N g_p^N}{8\,\pi\, m_N}\left(\frac{1}{r\,\lambda_a} + \frac{1}{r^2}\right) e^{-\frac{r}{\lambda_a}} (\hat{\sigma}\cdot\hat{r})$$

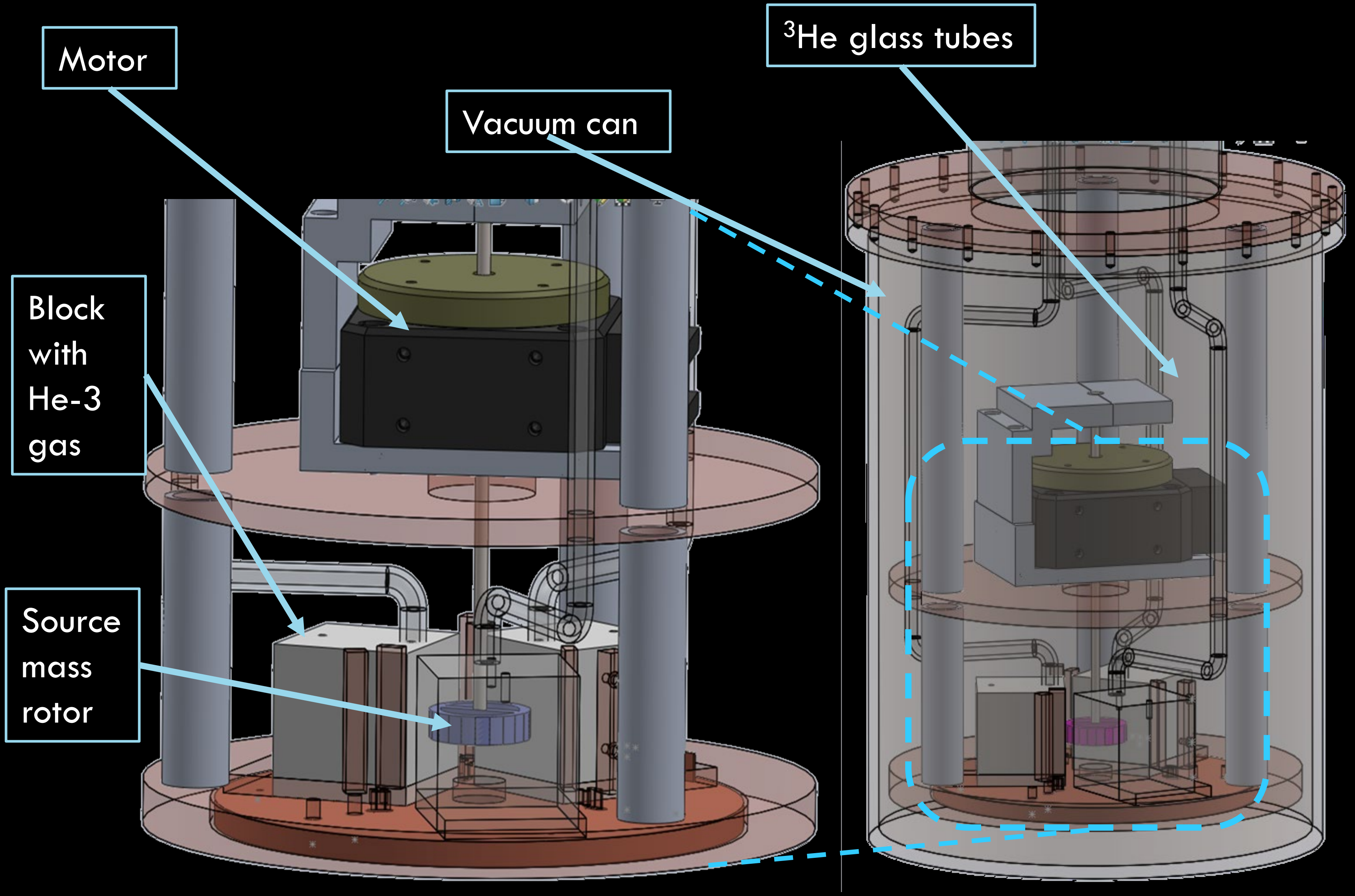
- Spins in hyperpolarized Helium-3 gas
- Transverse modulation by rotating a wheel with gear shaped pattern
- NMR-like transition if modulation matches He Larmor frequency
- Axion field doesn't obey Maxwell's equations, SM fields shielded using a superconductor

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

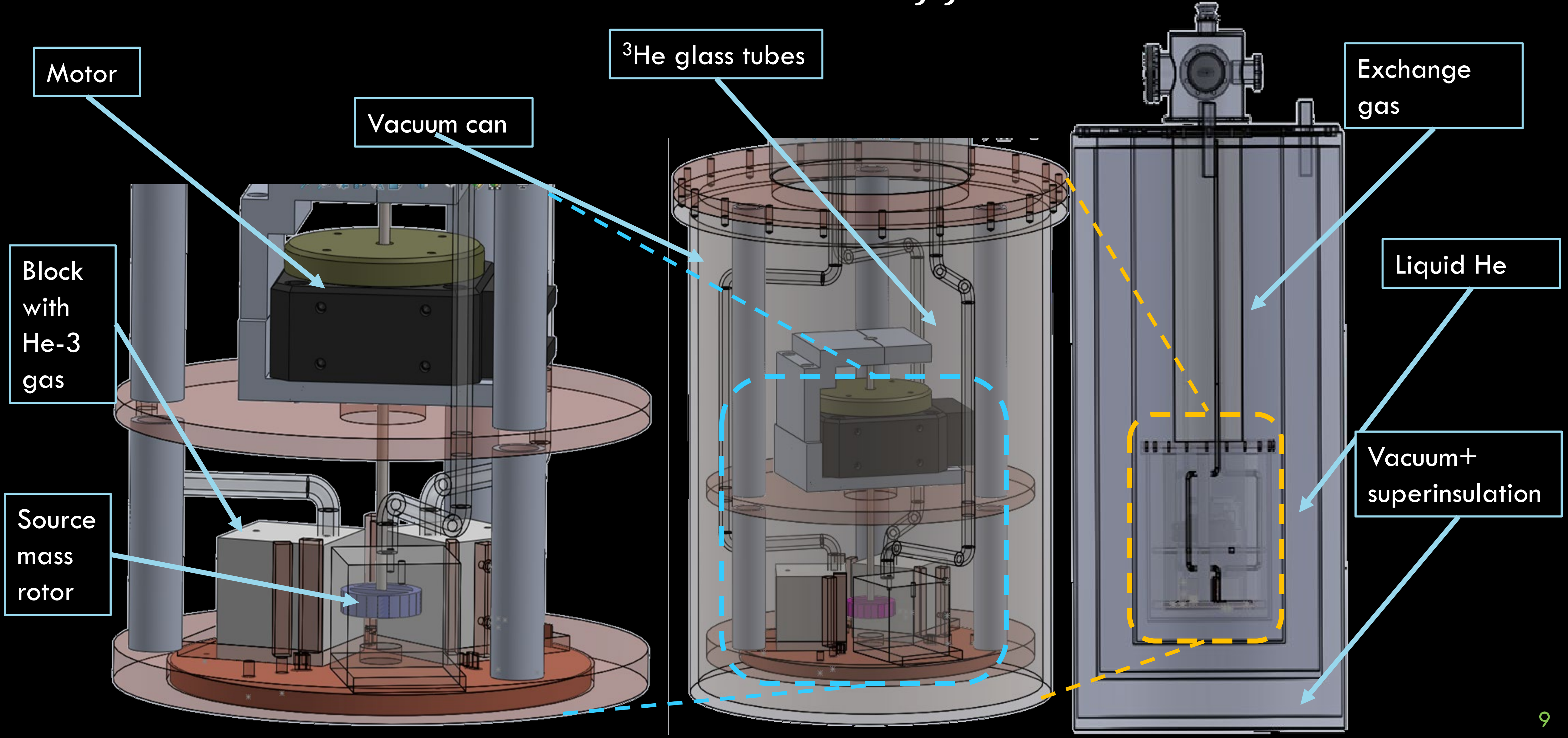
CUSTOM CRYO DESIGN FOR $B_{eff} \sim 10^{-21} T$



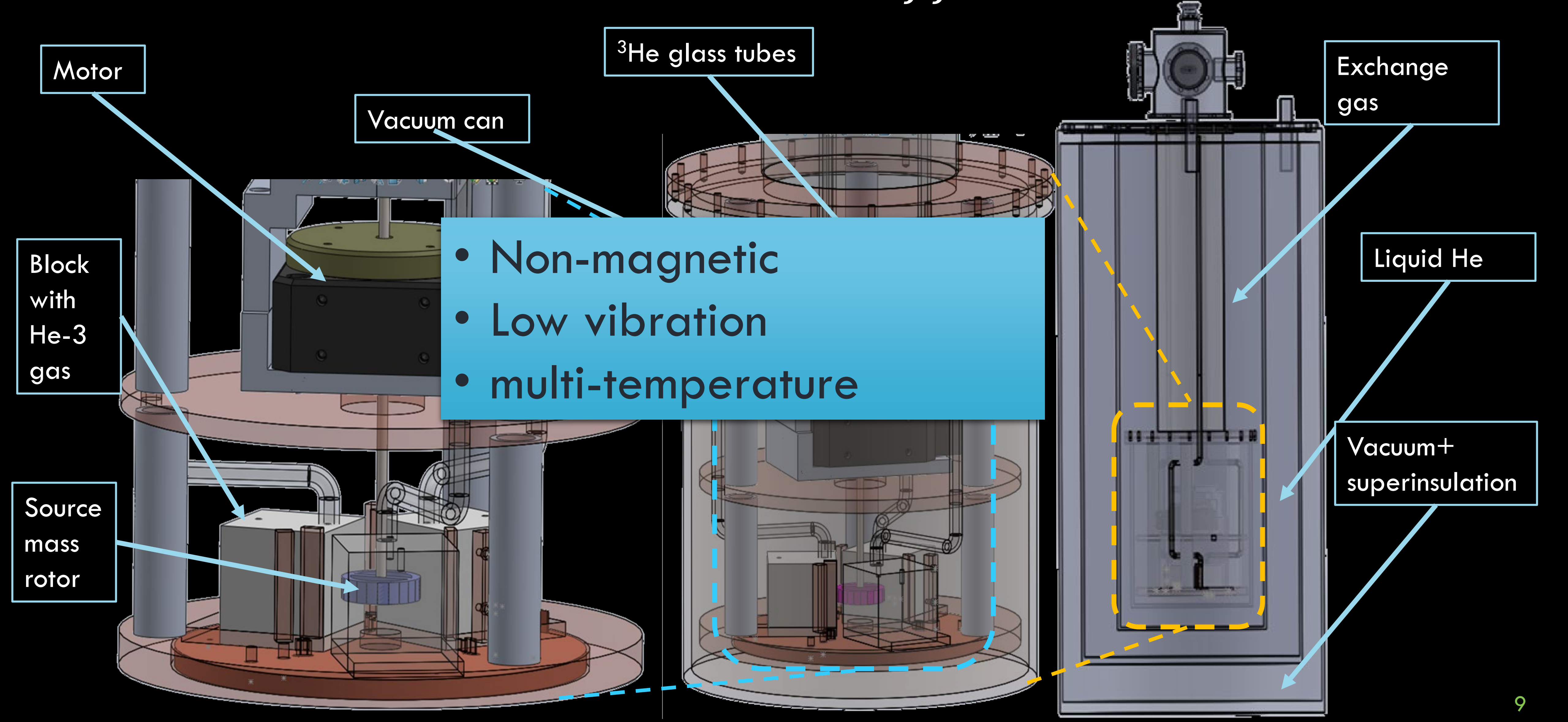
CUSTOM CRYO DESIGN FOR $B_{eff} \sim 10^{-21} T$



CUSTOM CRYO DESIGN FOR $B_{eff} \sim 10^{-21} T$

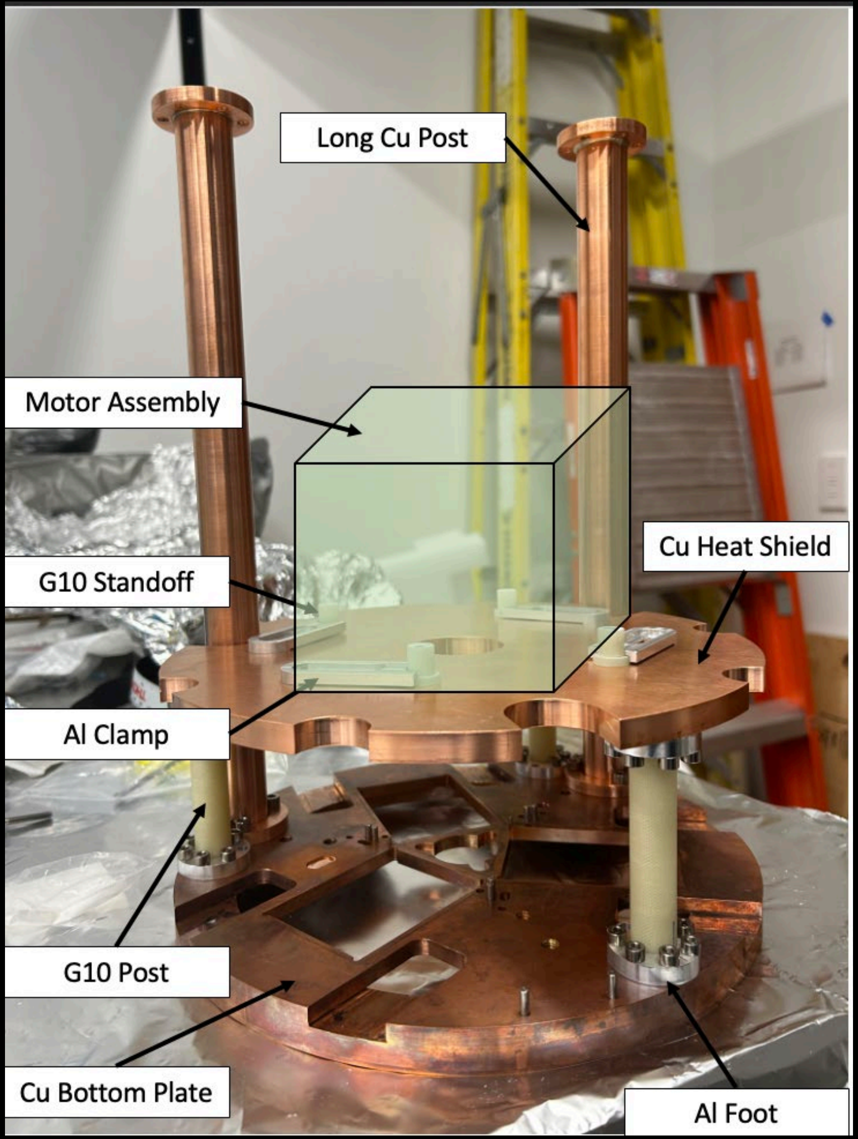


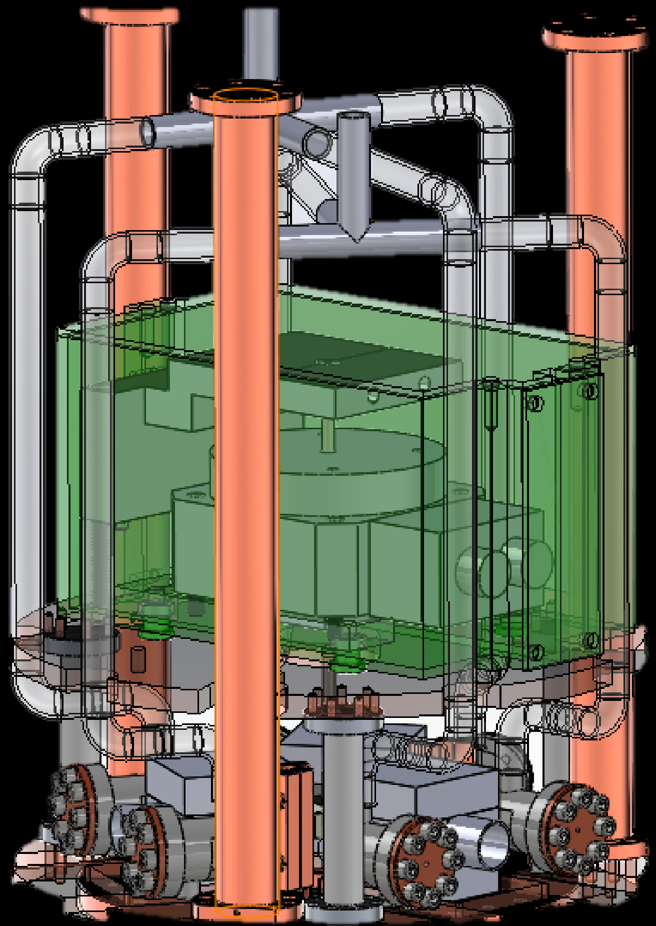
CUSTOM CRYO DESIGN FOR $B_{eff} \sim 10^{-21} T$

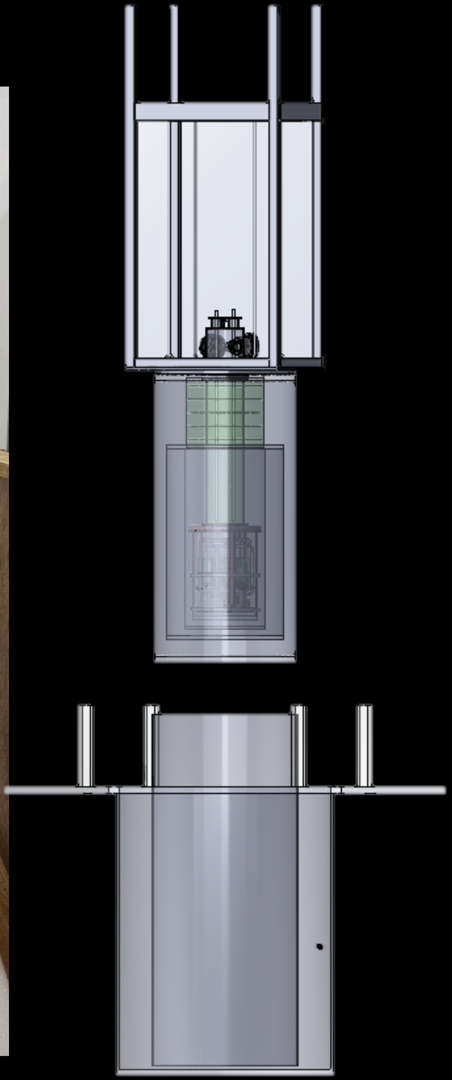


- Non-magnetic
- Low vibration
- multi-temperature

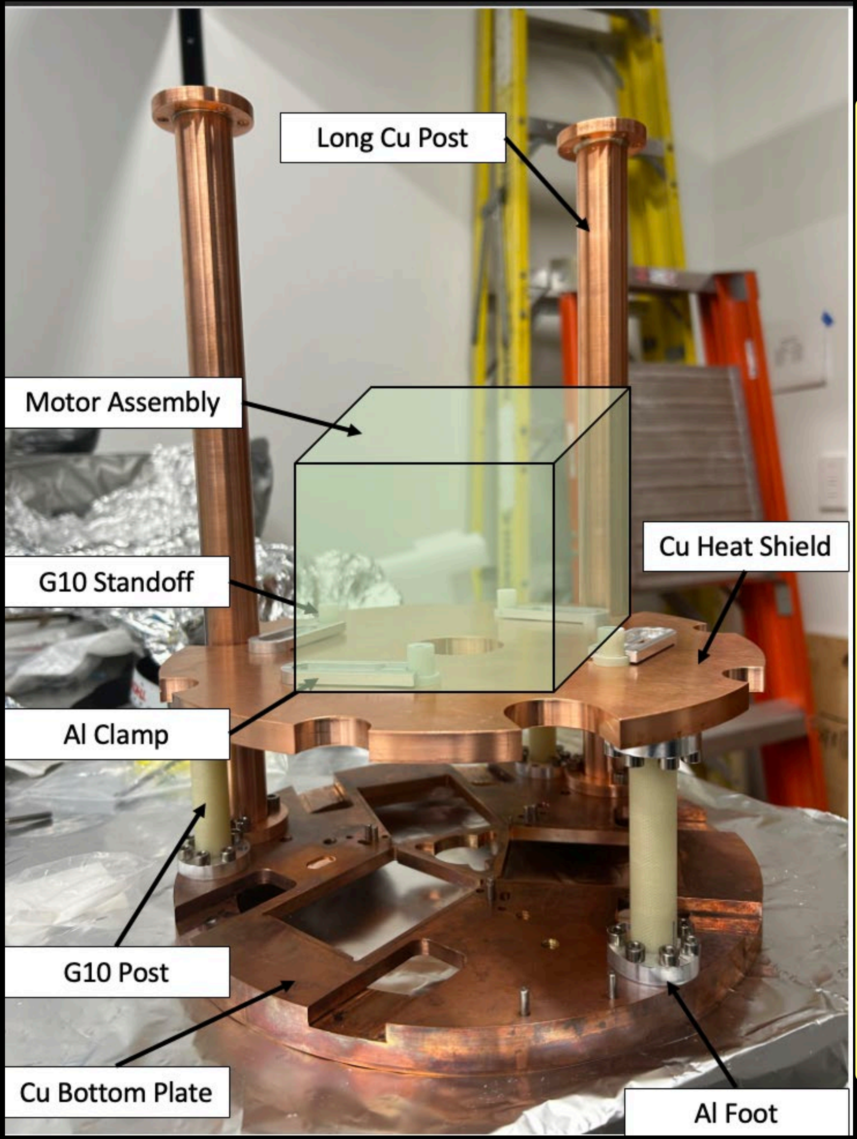
PARTS FINALLY DELIVERED AFTER MANY YEARS COVID DELAY!

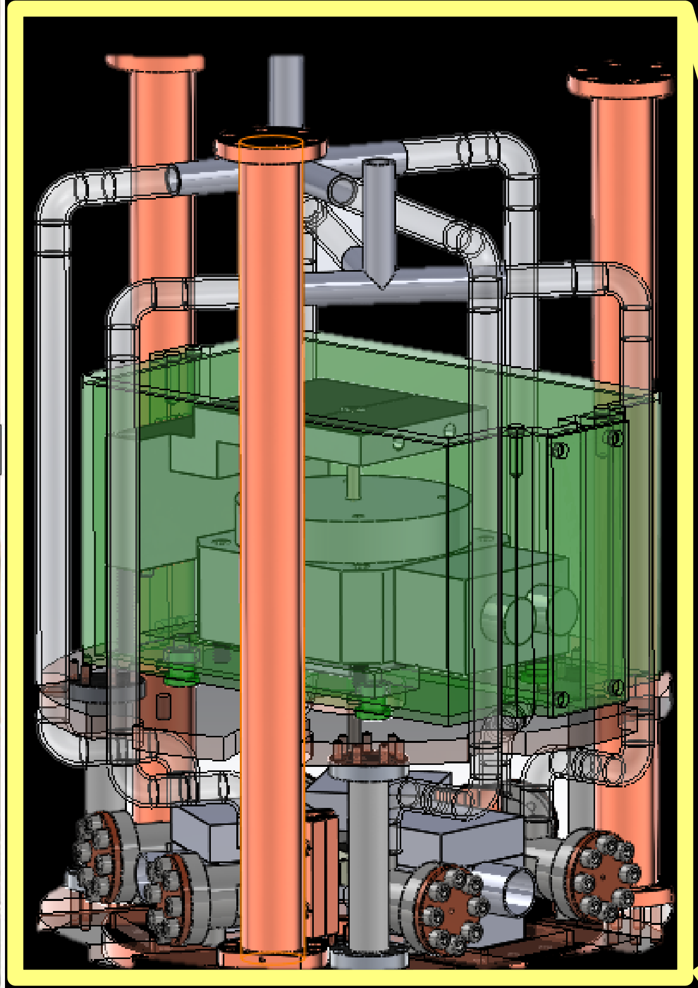


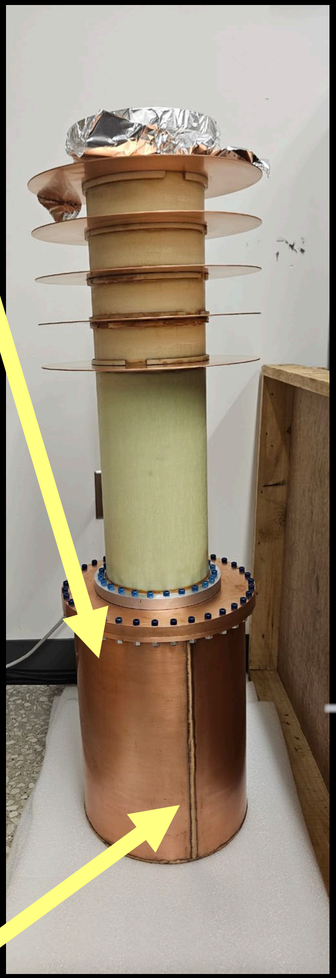


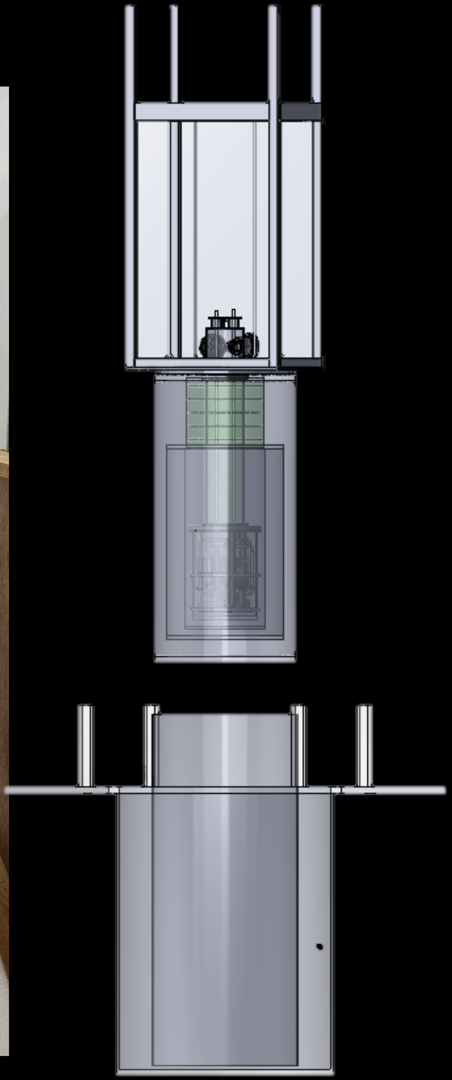


PARTS FINALLY DELIVERED AFTER MANY YEARS COVID DELAY!









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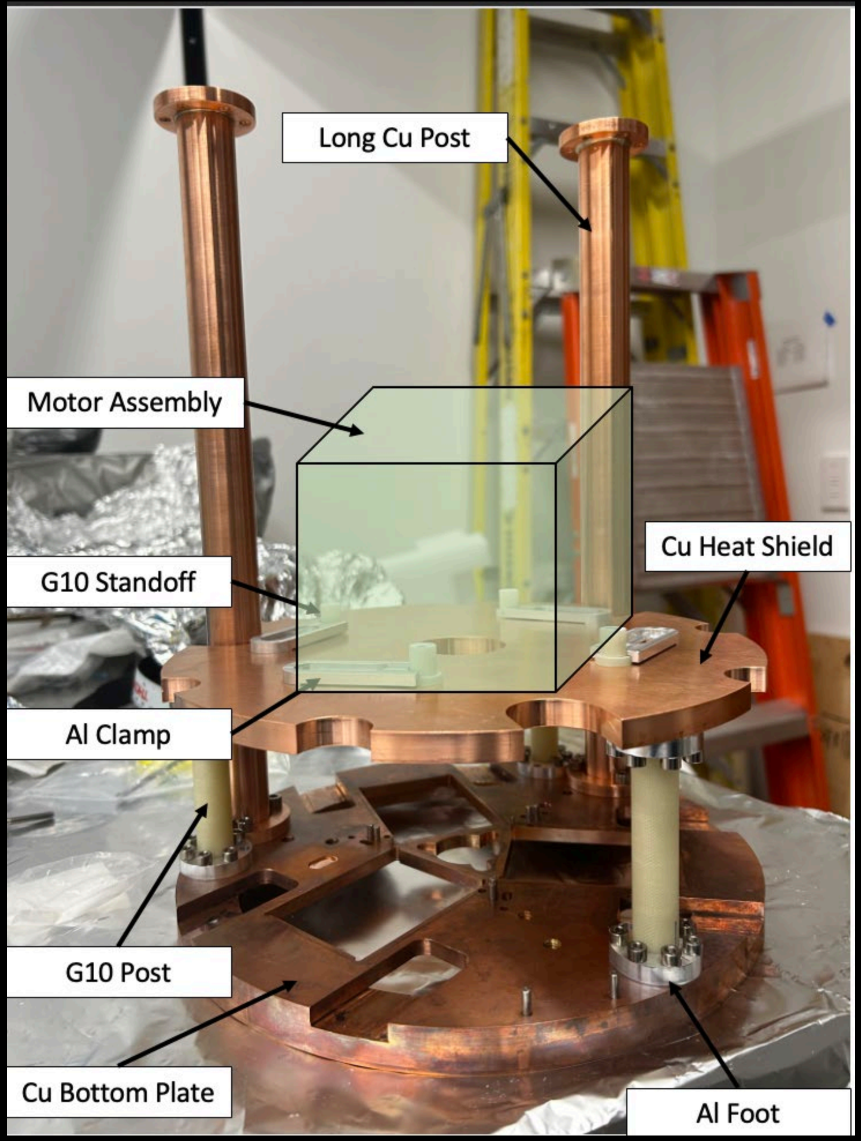
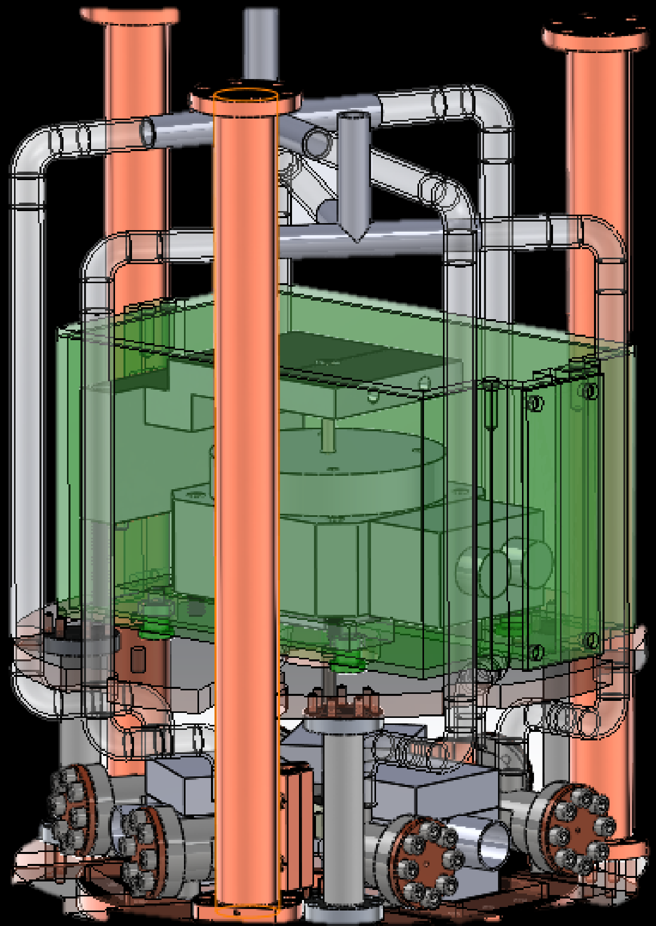
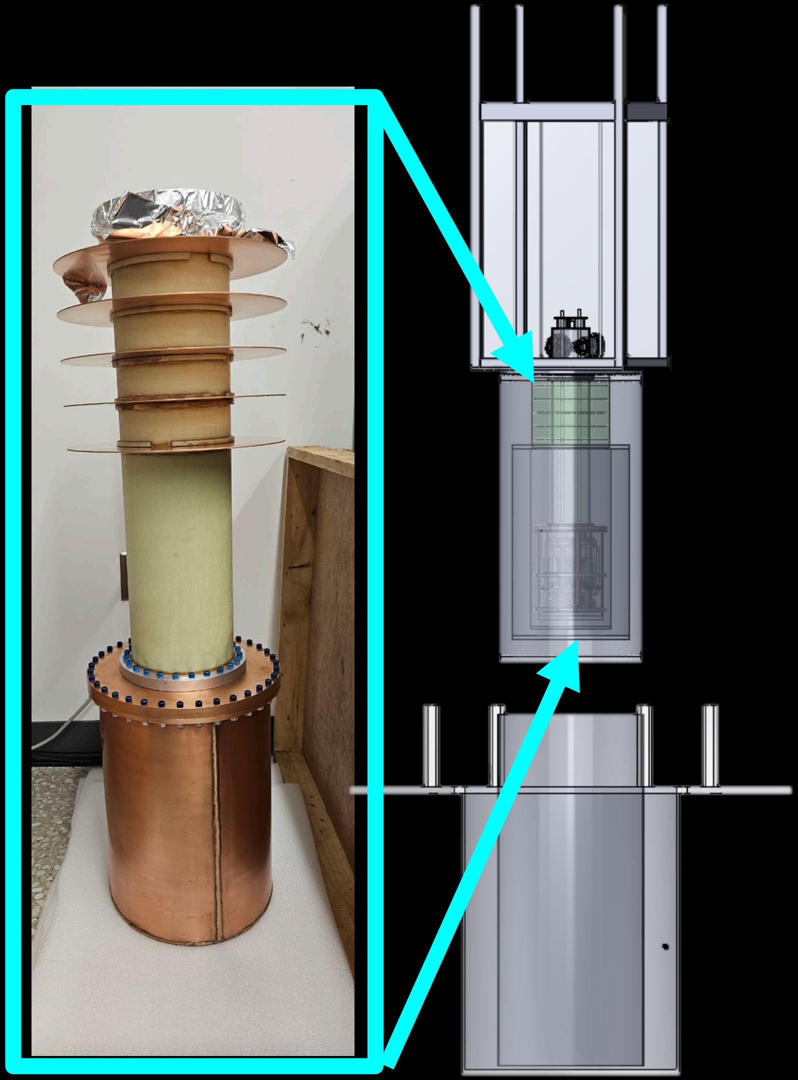
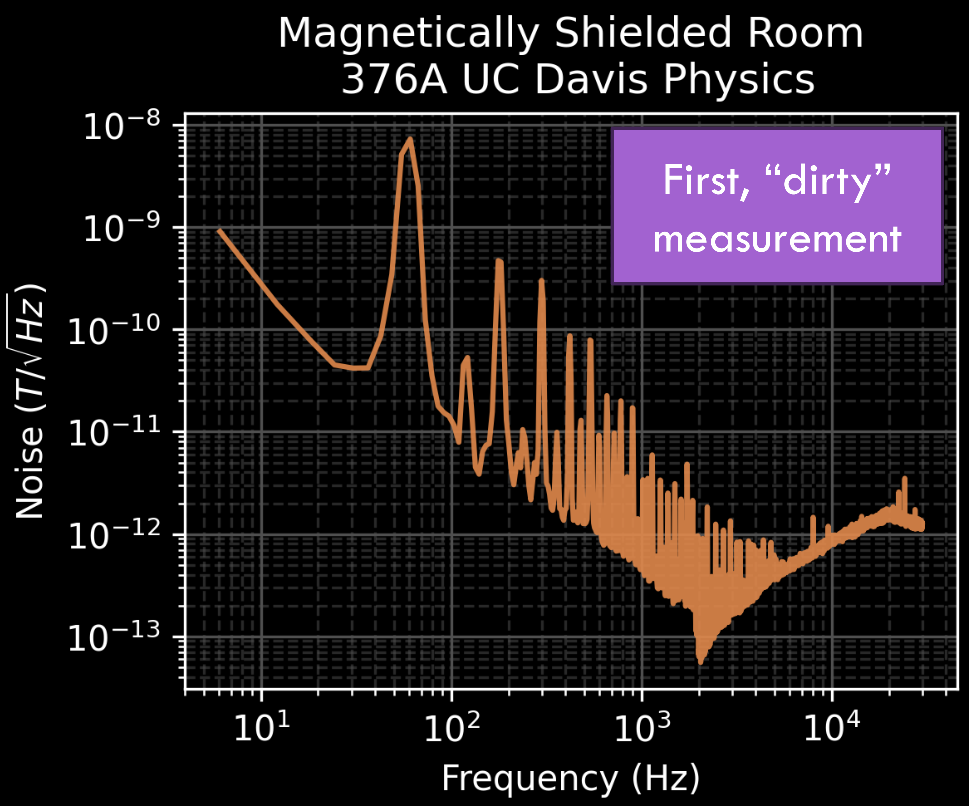




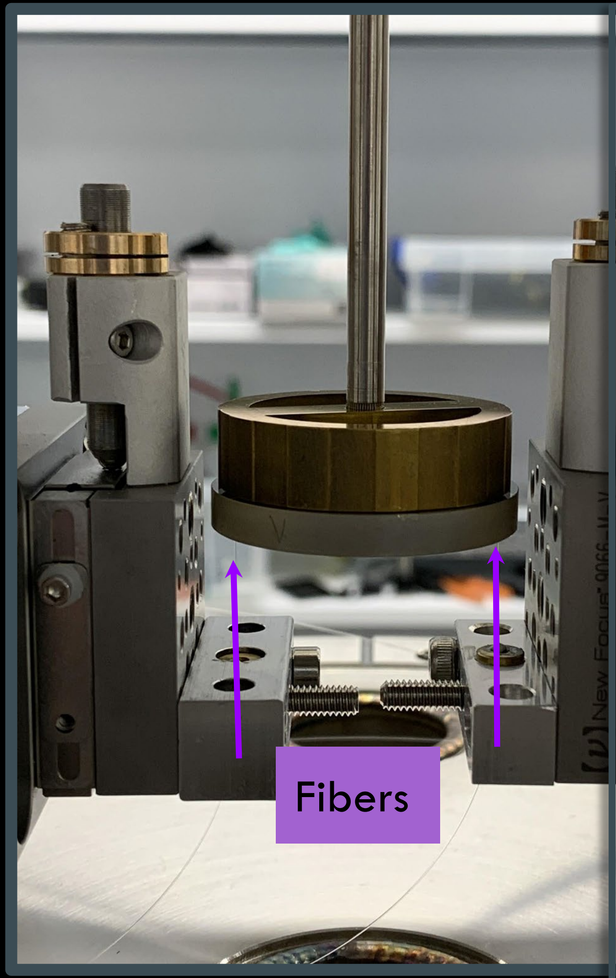


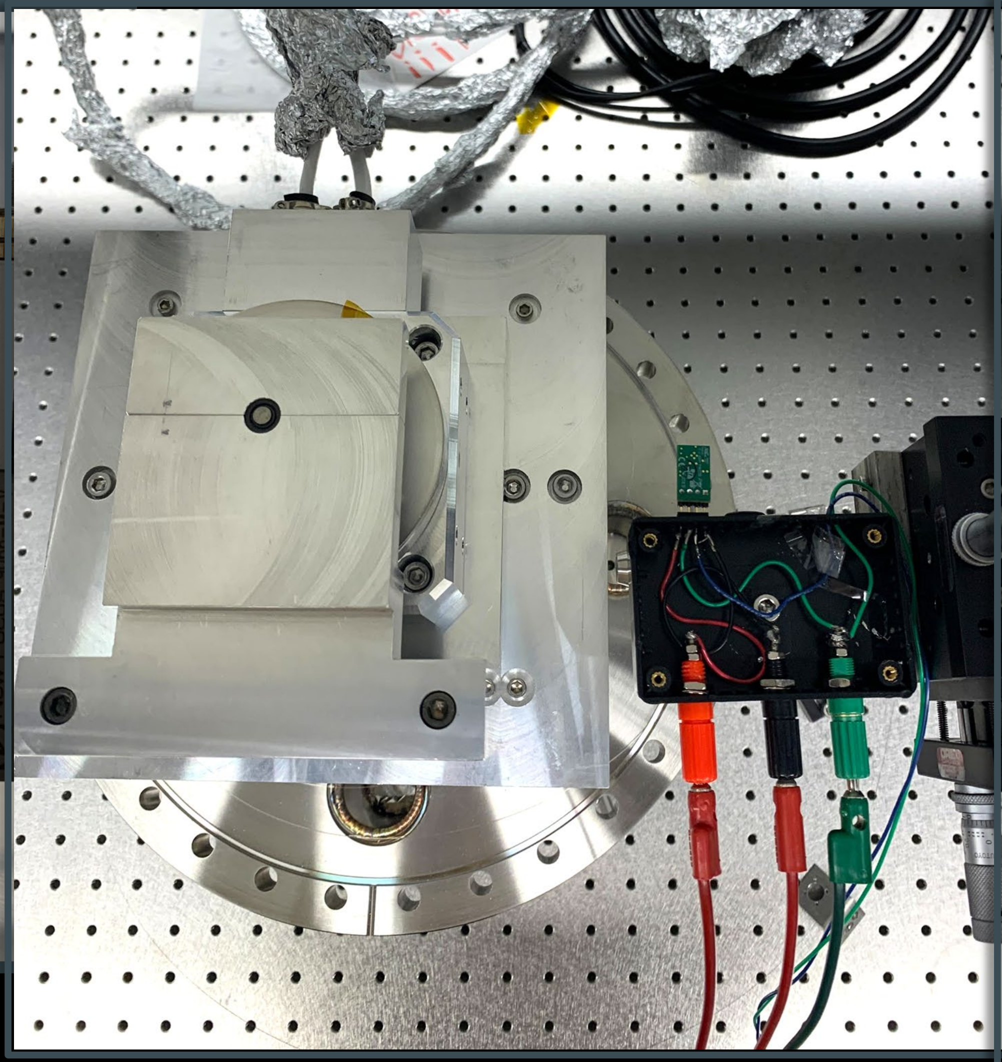
PRECISION MAGNETOMETRY AT UC DAVIS

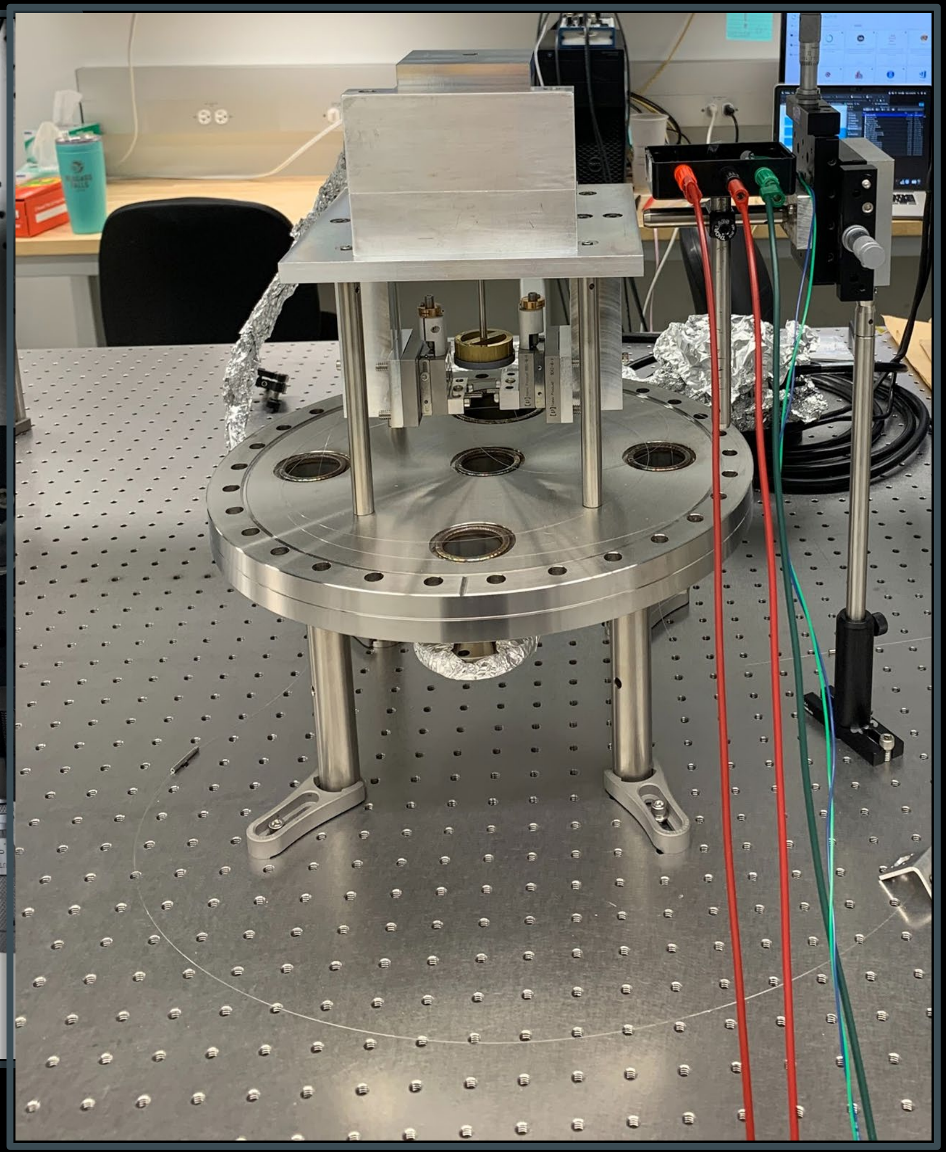
- large volume magnetically shielded room – undergoing characterization and renovation



ARIADNE ROTATION ASSEMBLY

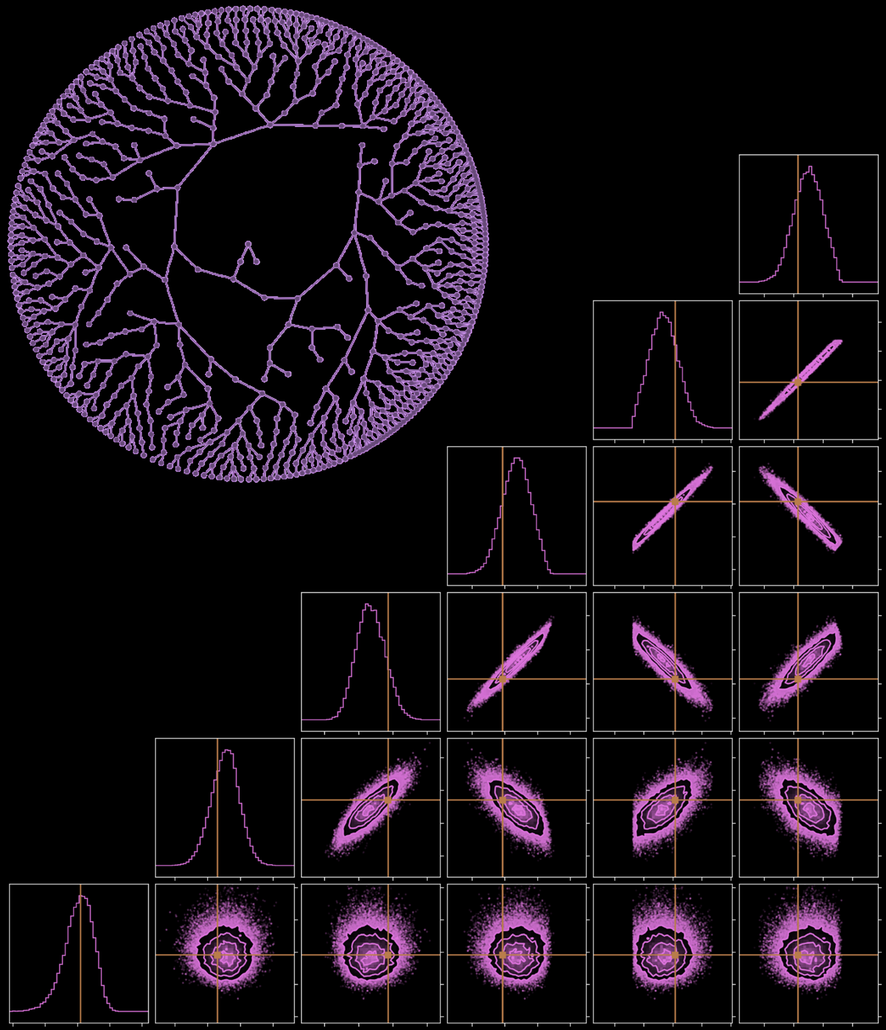


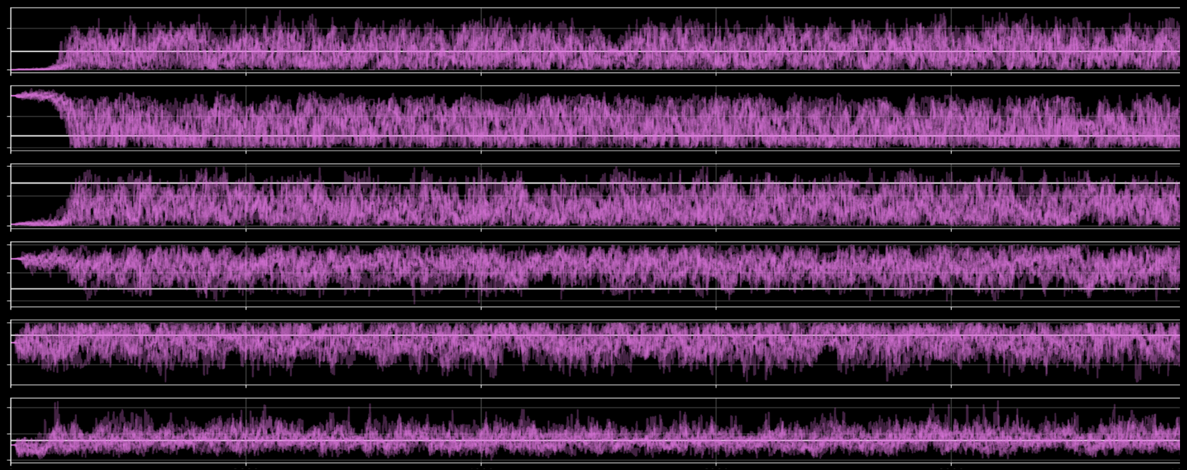




BACKGROUND AND DATA ANALYSIS

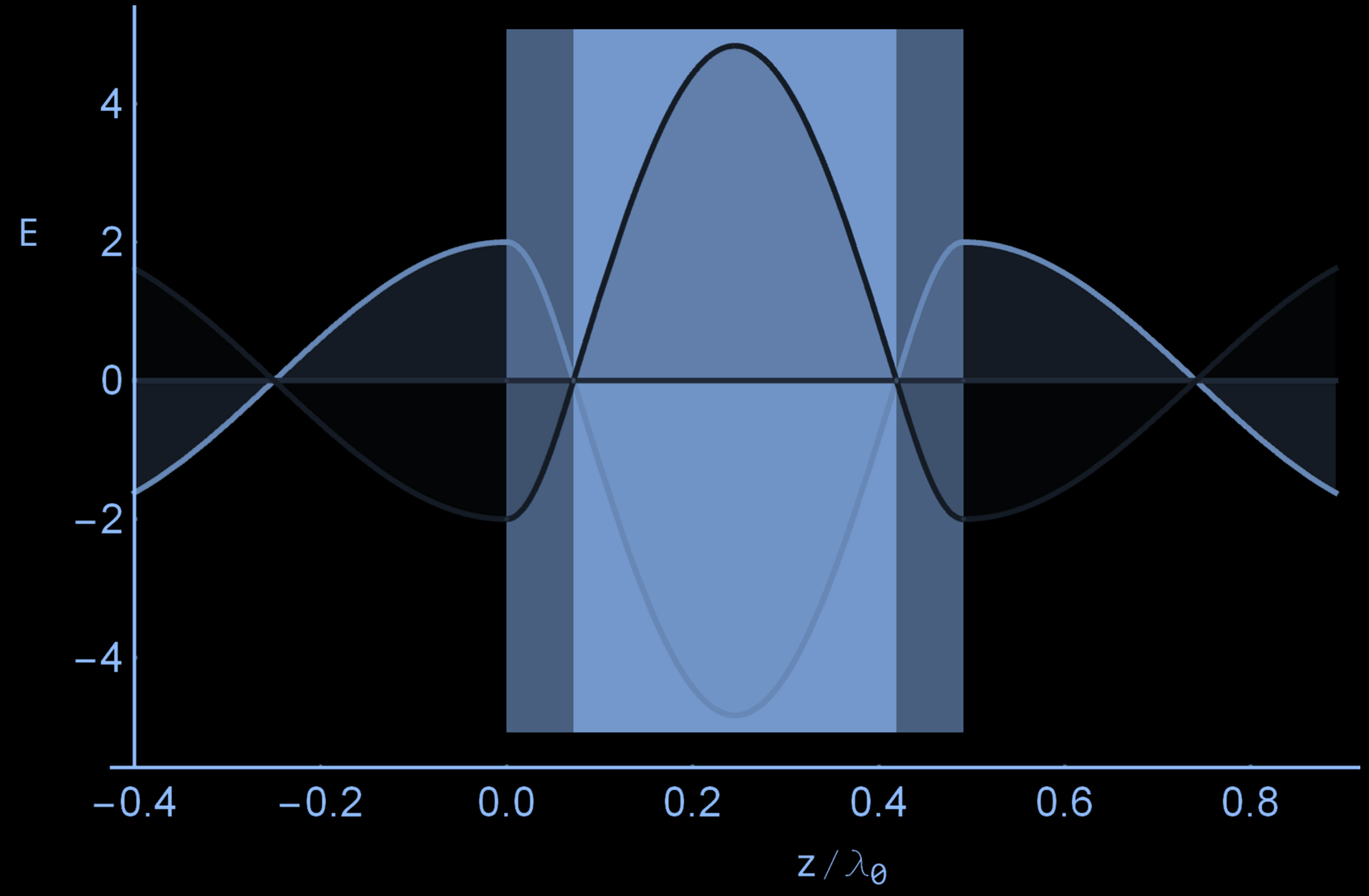
1. Improved background estimate from impurities
   - PTMCMC
   - Include correlation with rotational speed measurement
2. Background from susceptibility and Barnett effect
3. Noise modeling, measurement, analysis
4. Signal analysis
   - Correlation of axion signal with rotation speed,
   - correlation between sample cells
   - Subtraction in SQUID gradiometer



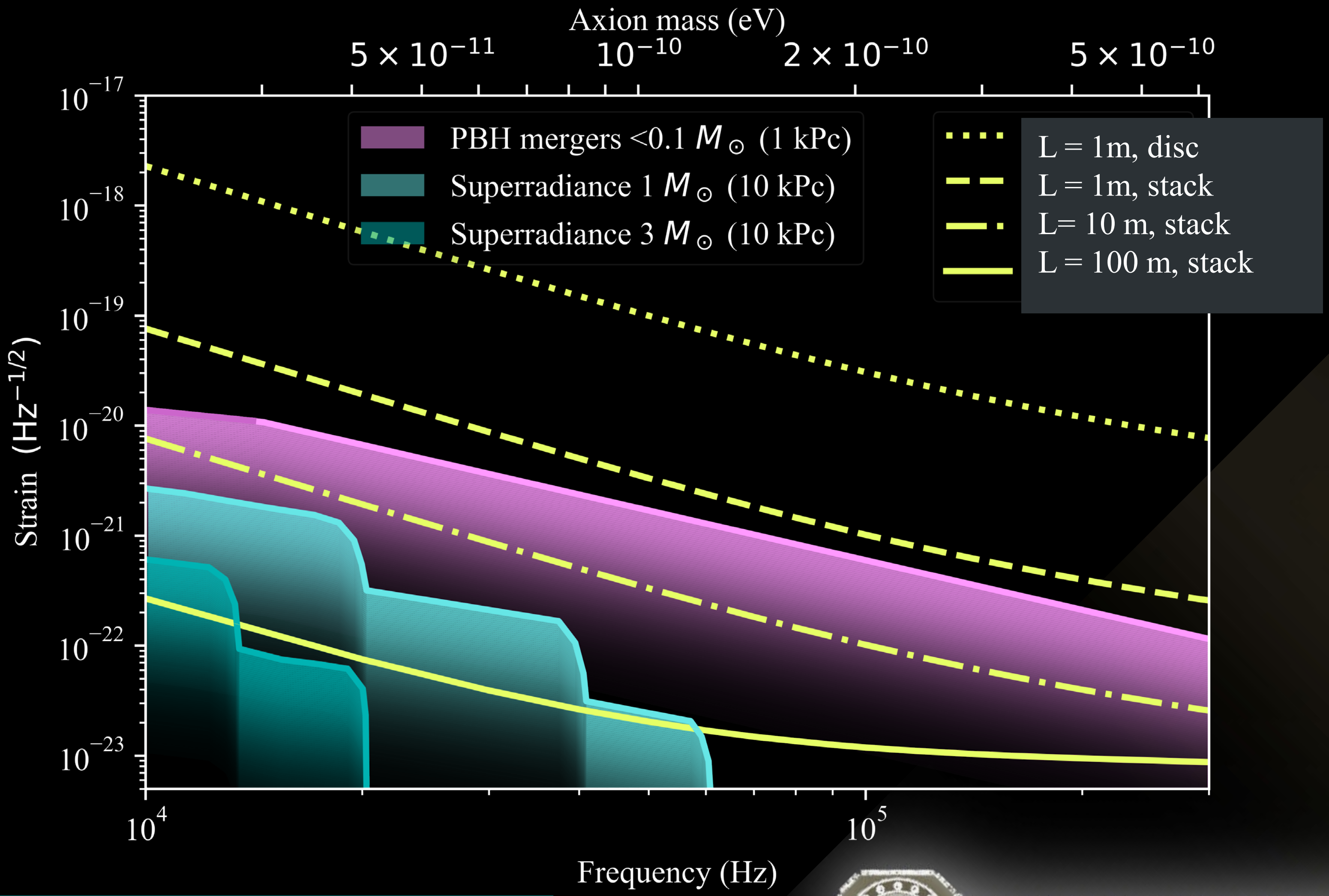


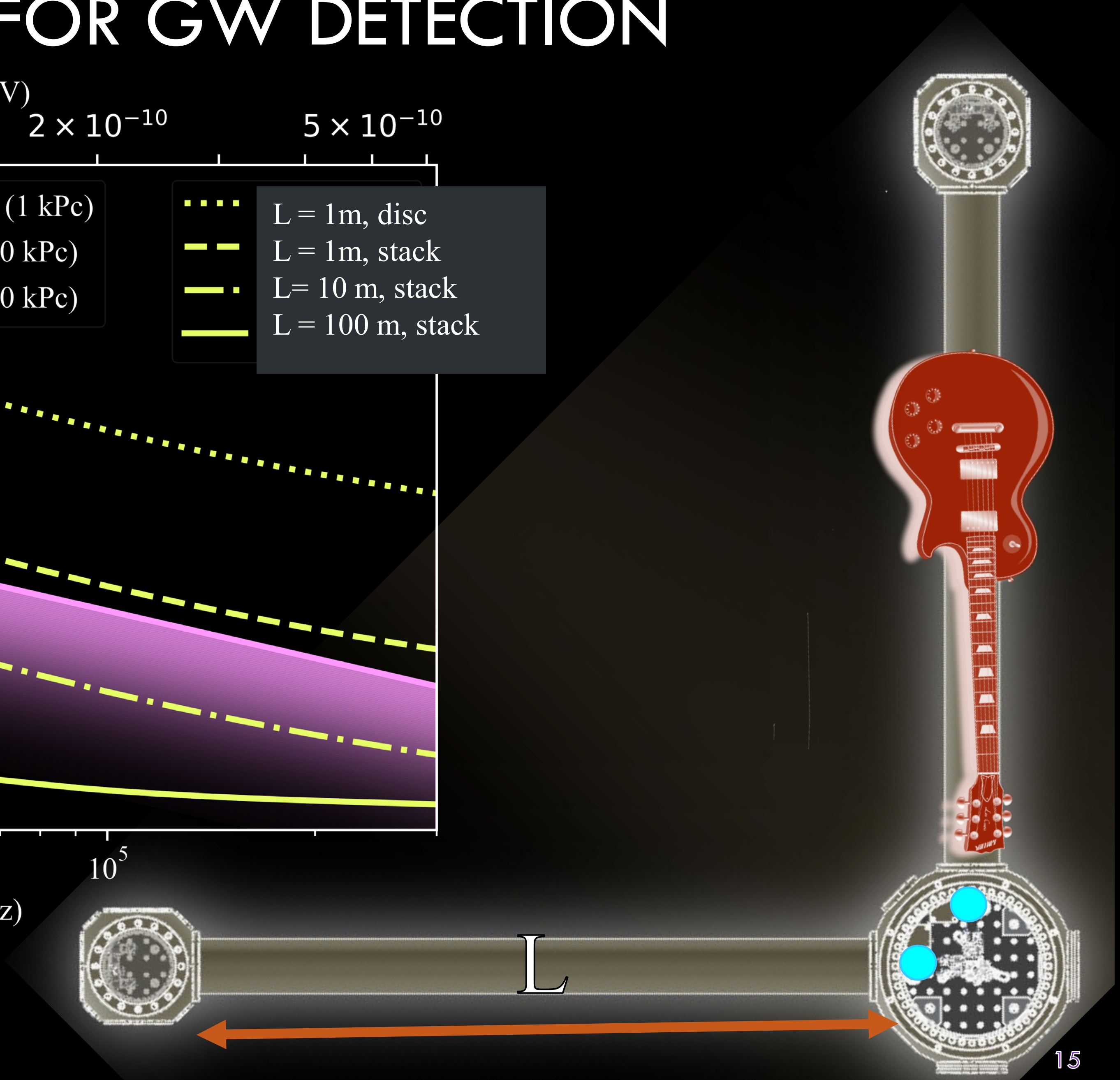
Plots created by Masters student Shreya Agarwal

OPTICAL LEVITATION FOR DARK MATTER SEARCHES



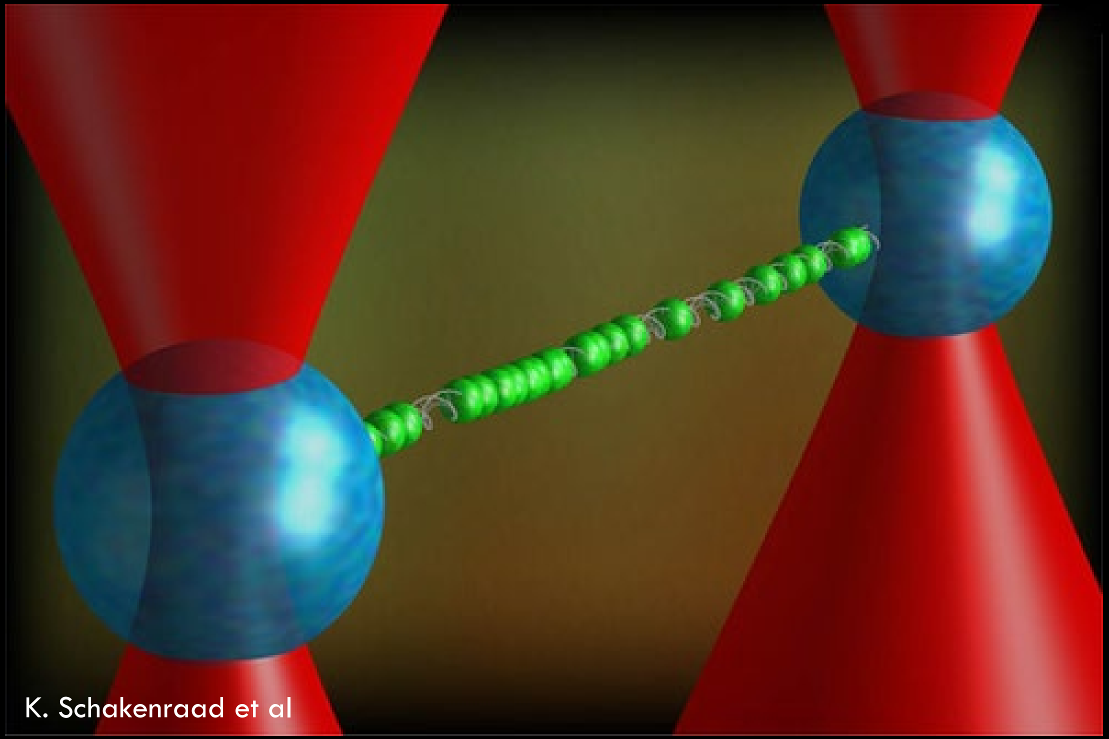
OPTICAL TRAPPING FOR GW DETECTION



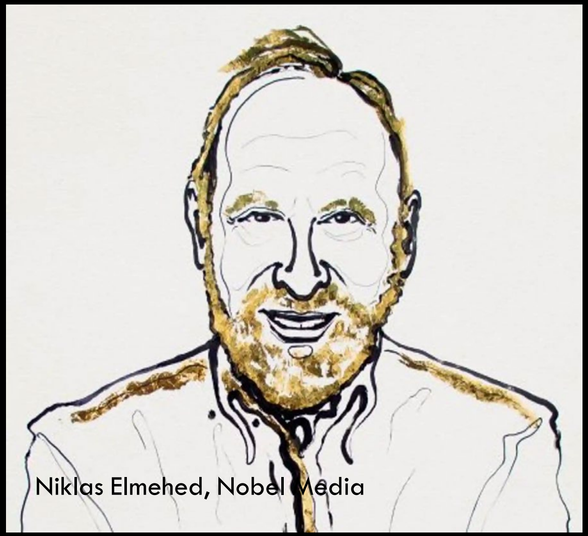


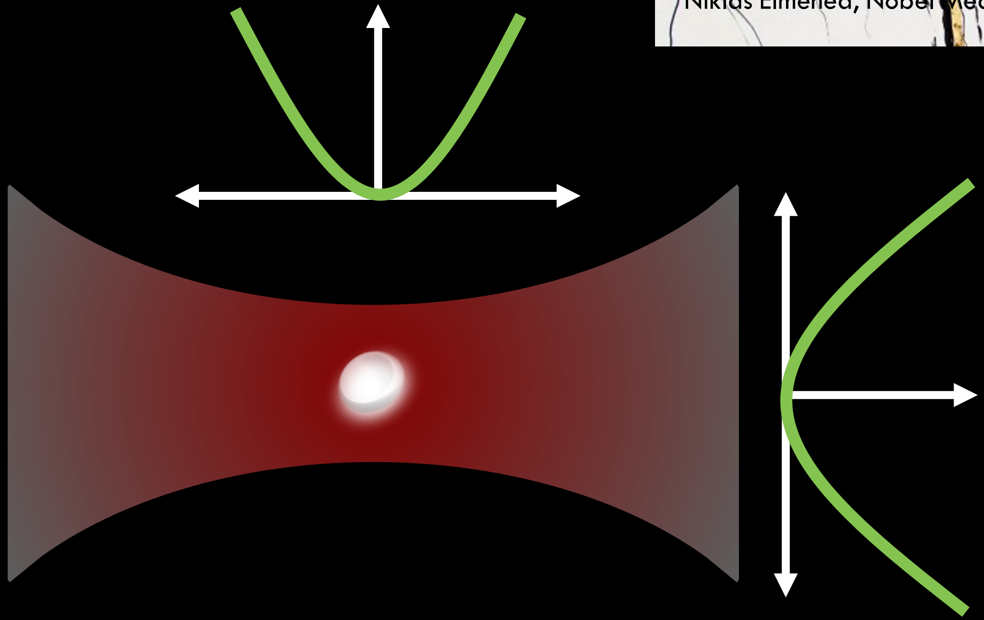
Searching for new physics with a levitated-sensor-based GW detector
Aggarwal et al PRL 128, 111101

OPTICAL TRAPPING

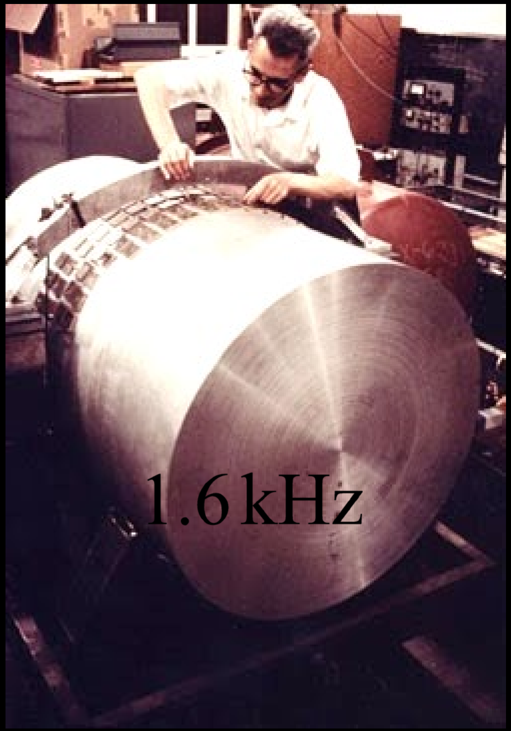


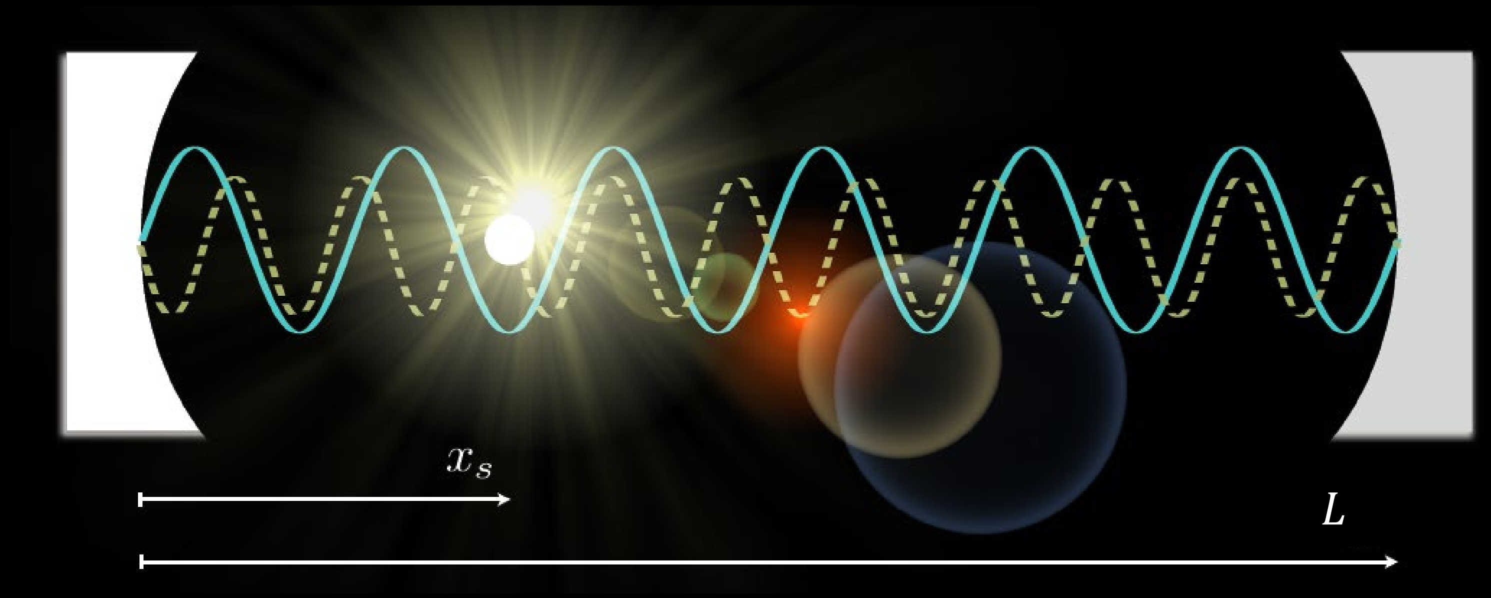
$$U(\vec{r}) = -\frac{1}{2}\alpha(\vec{r})\,E^2(\vec{r})$$





GW DETECTOR USING OPTICAL TRAPS





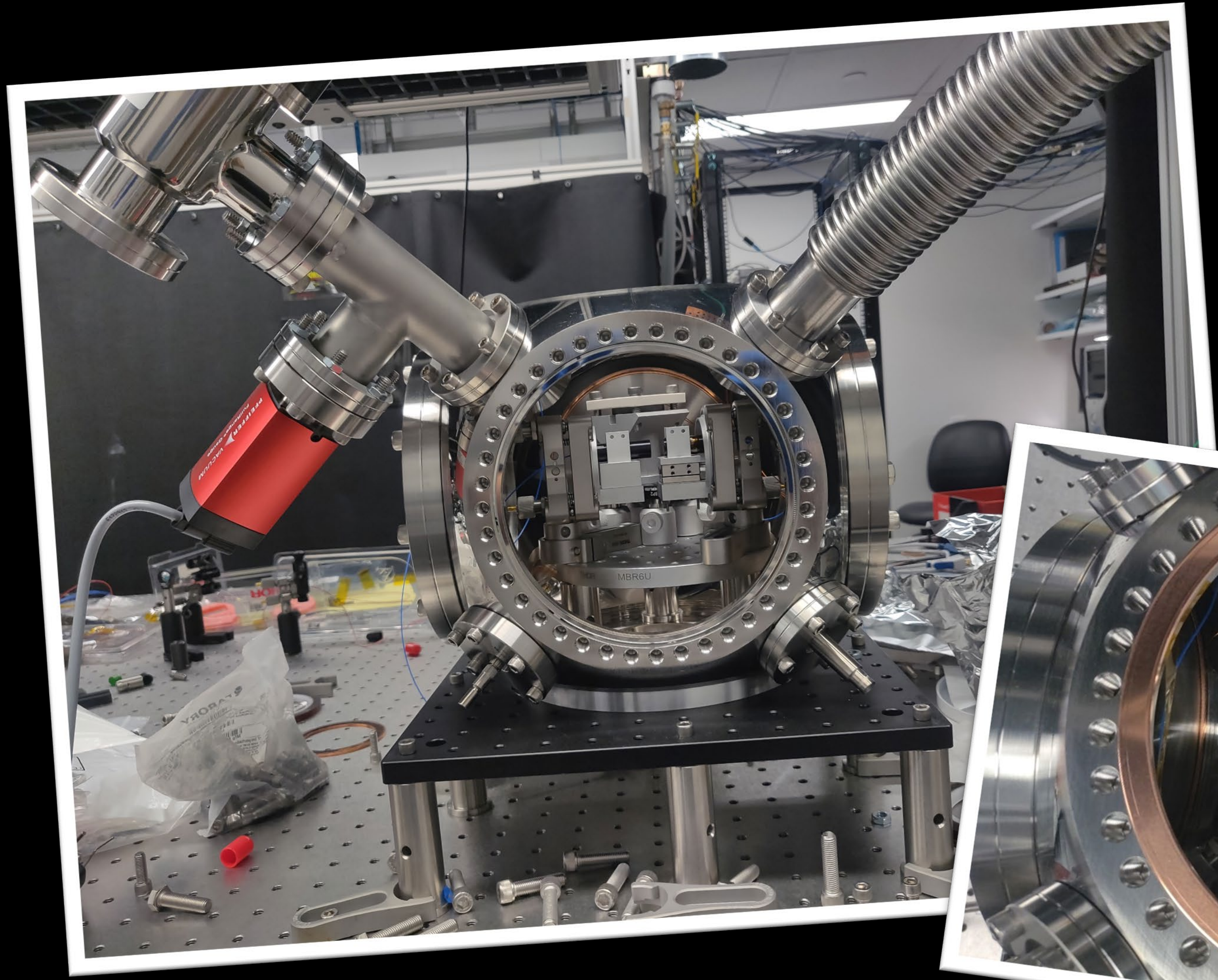
Arvanitaki and Geraci,
PRL 110, 071105 (2013)

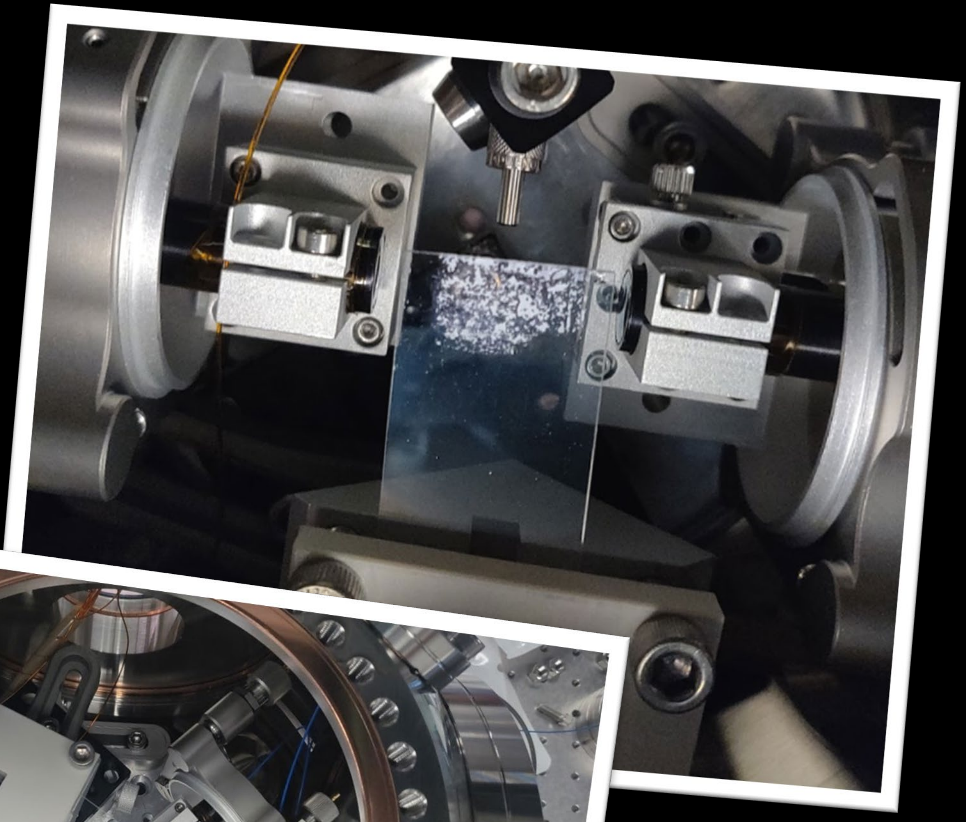
$$\Delta L = \frac{h}{2} L, \qquad \Delta x_a = \Delta L, \qquad \Delta x_s = \frac{h}{2} x_s$$

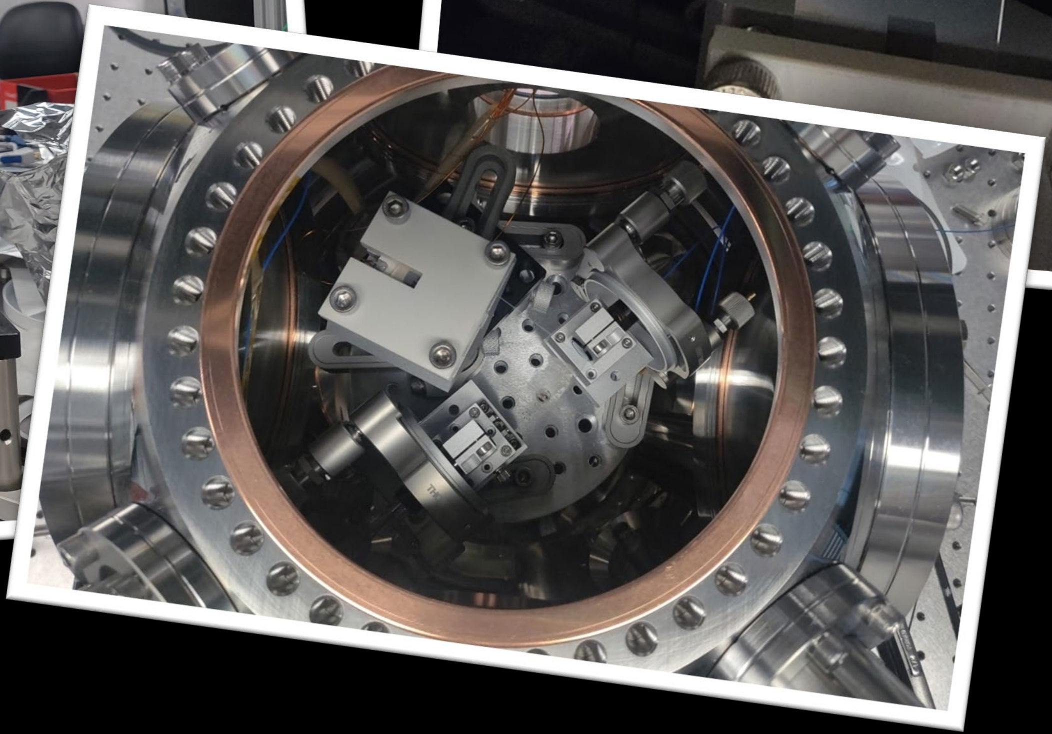
$$\Delta x_{GW} = \Delta x_s - \Delta x_a = \frac{h}{2}(x_s - L), \text{ maximized at } x_s \to 0$$

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

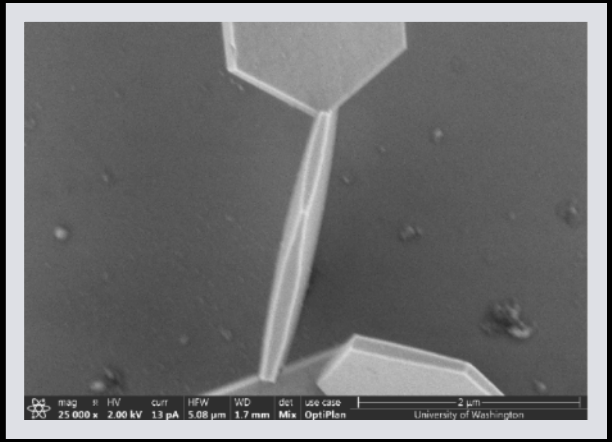
TRAPPING OF FLAT OBJECTS IN THE LAB…

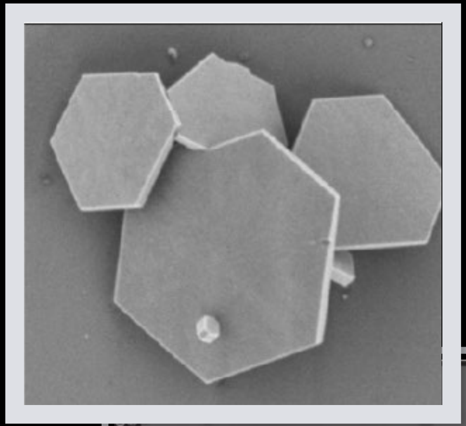


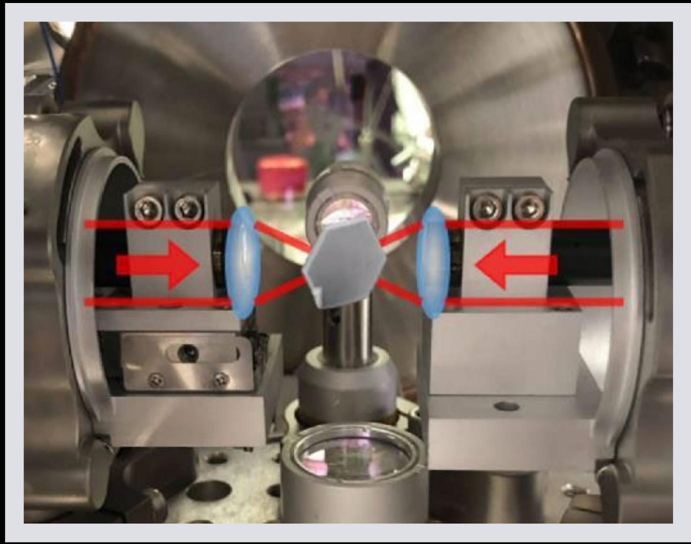


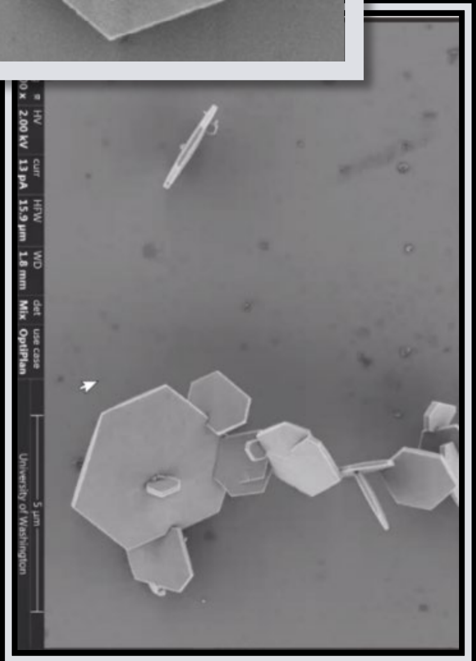


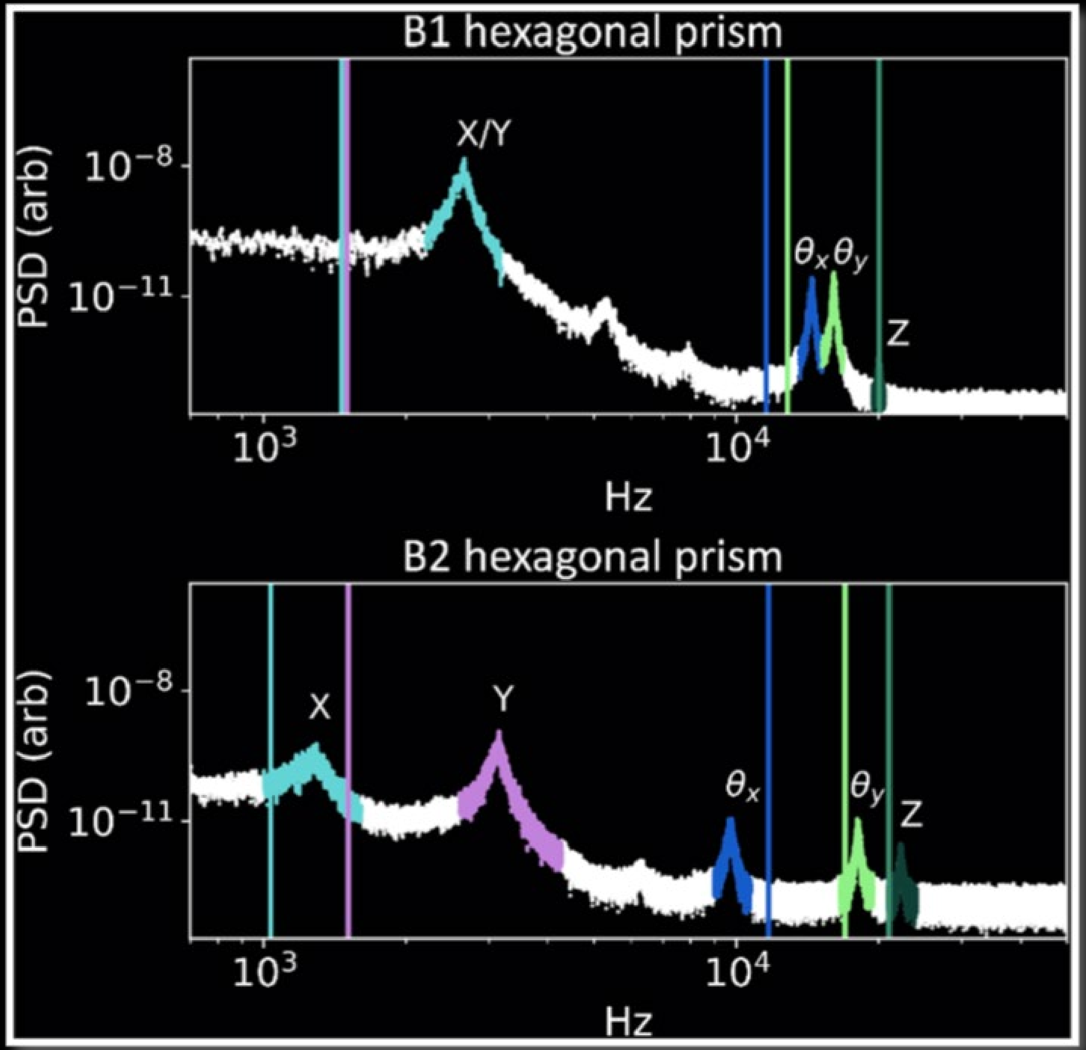
TRAPPING OF NAYF HEXAGON PLATES



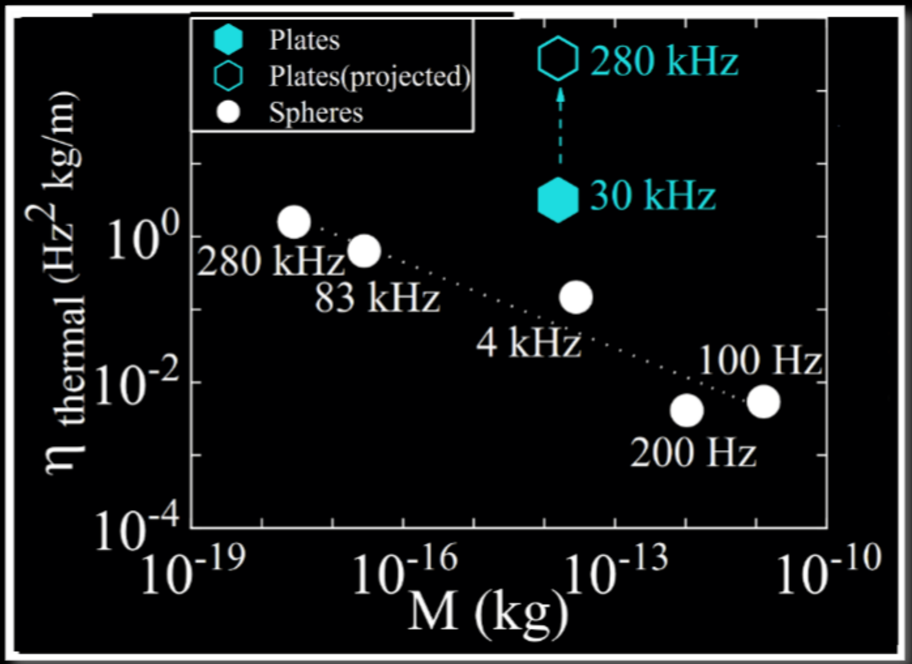


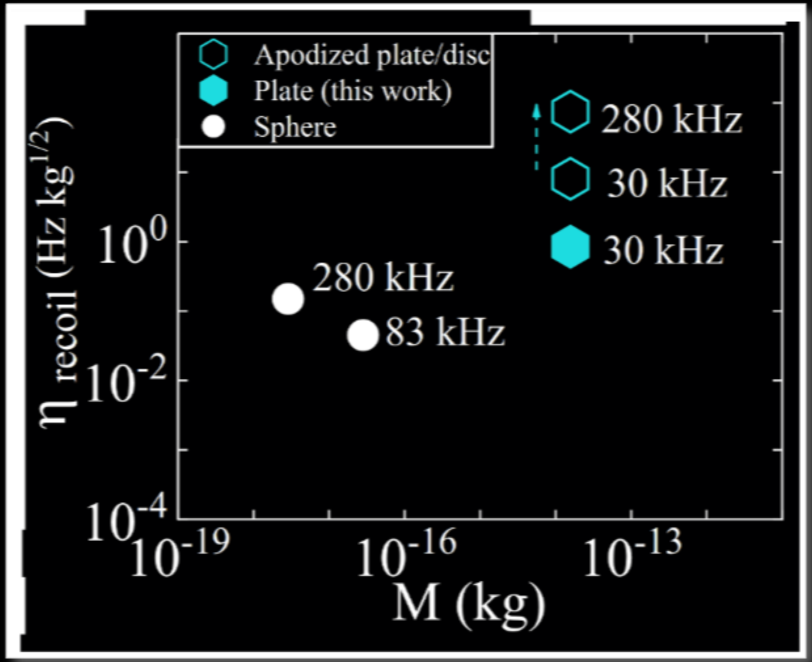






STATE OF THE ART IN OPTICAL TRAPPING





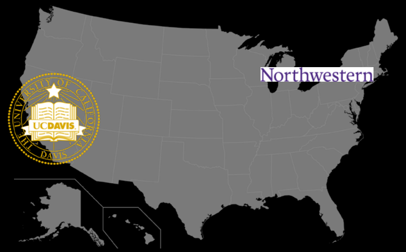
$$\eta_{\mathrm{thermal}} = \left(\frac{\Omega_z}{2\pi}\right)^2 \sqrt{M\rho\tau}$$

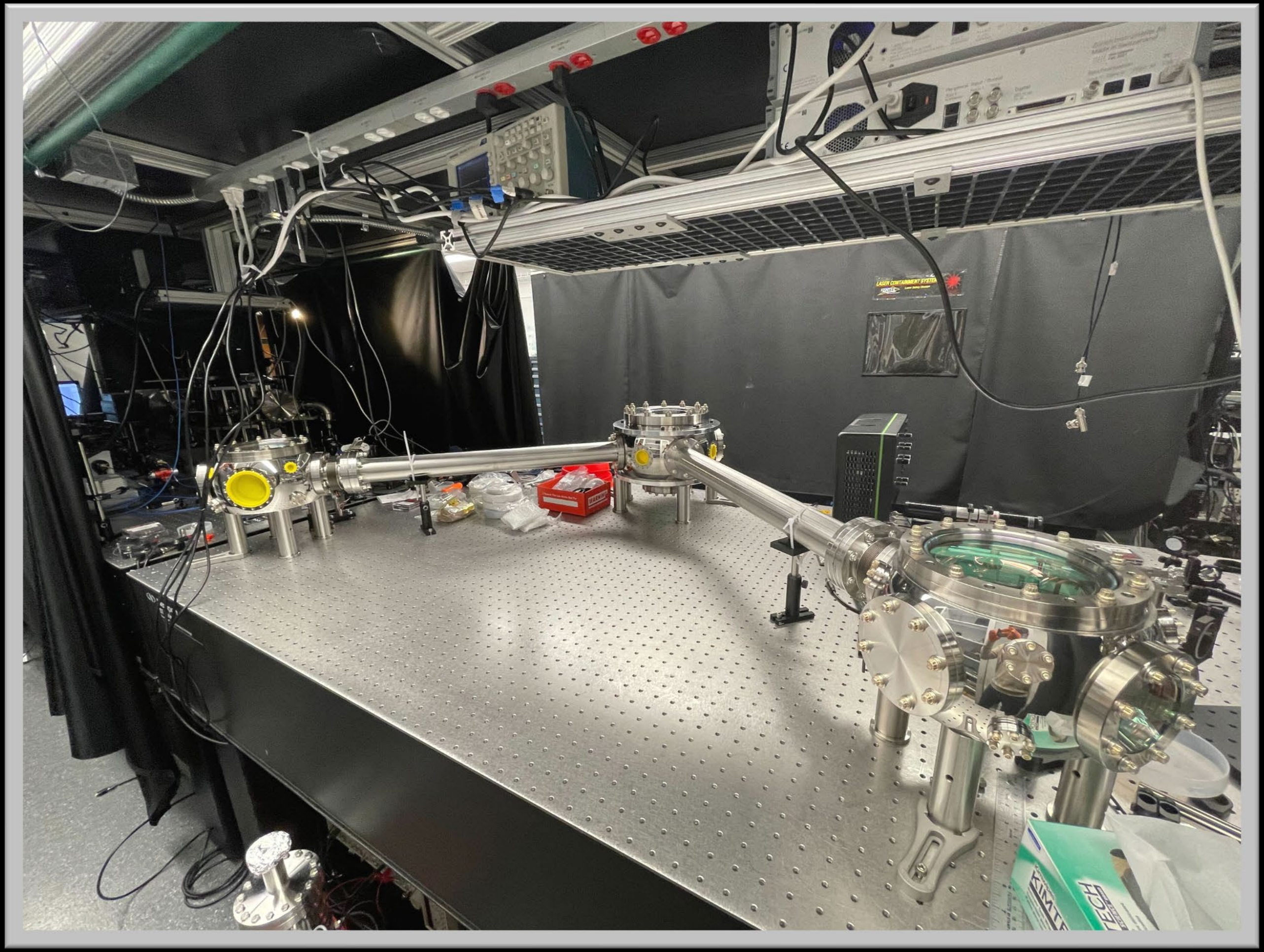
$$(\gamma_g \propto 1/\rho\tau)$$

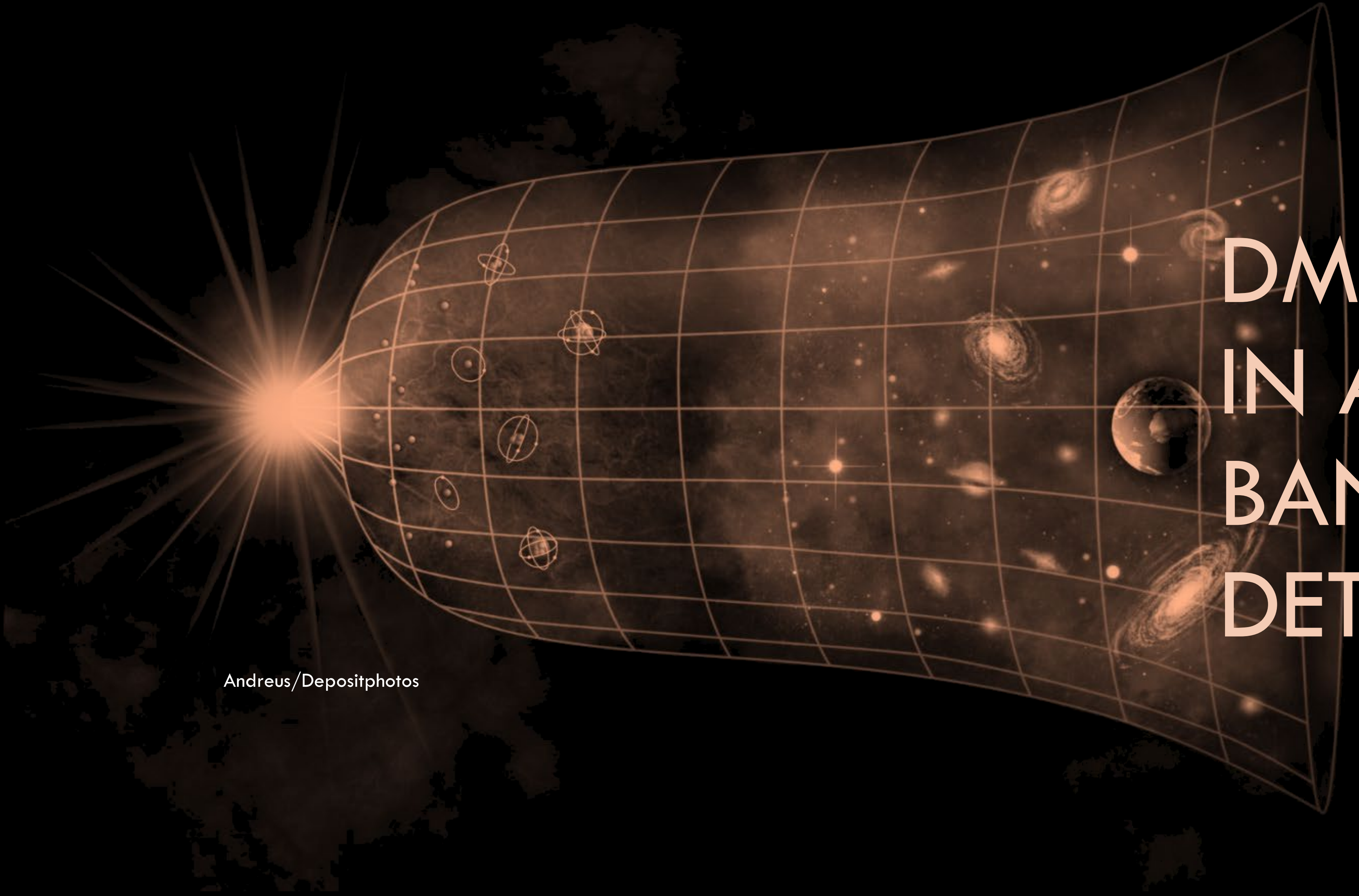
$$\eta_{\mathrm{recoil}} = \left(\frac{\Omega_z}{2\pi}\right)^{3/2} \sqrt{\frac{M}{\gamma_{sc}}}$$

STAY TUNED…

- 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







Andreus/Depositphotos

DM SEARCHES IN AUDIO-BAND GW DETECTORS

WHAT DOES LIGO HAVE TO SAY ABOUT DARK MATTER?

Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run

R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration)
Phys. Rev. D **105**, 063030 – Published 31 March 2022

Search for Subsolar-Mass Ultracompact Binaries in Advanced LIGO's First Observing Run

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. **121**, 231103 – Published 7 December 2018

Search for ultralight bosons in Cygnus X-1 with Advanced LIGO

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Communications Physics **2**, Article number: 155 (2019) | Cite this article

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WHAT DOES LIGO HAVE TO SAY ABOUT DARK MATTER?

Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run

R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration)
Phys. Rev. D **105**, 063030 – Published 31 March 2022

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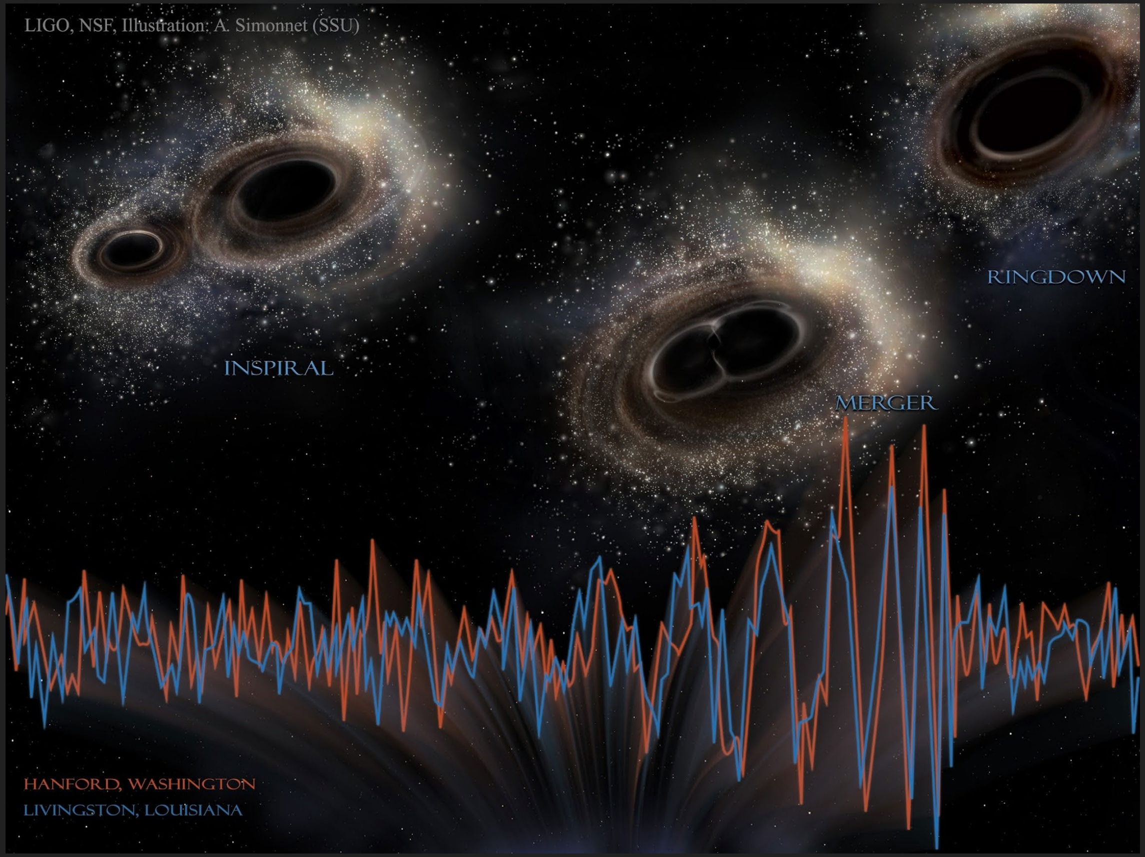
CBC Searches



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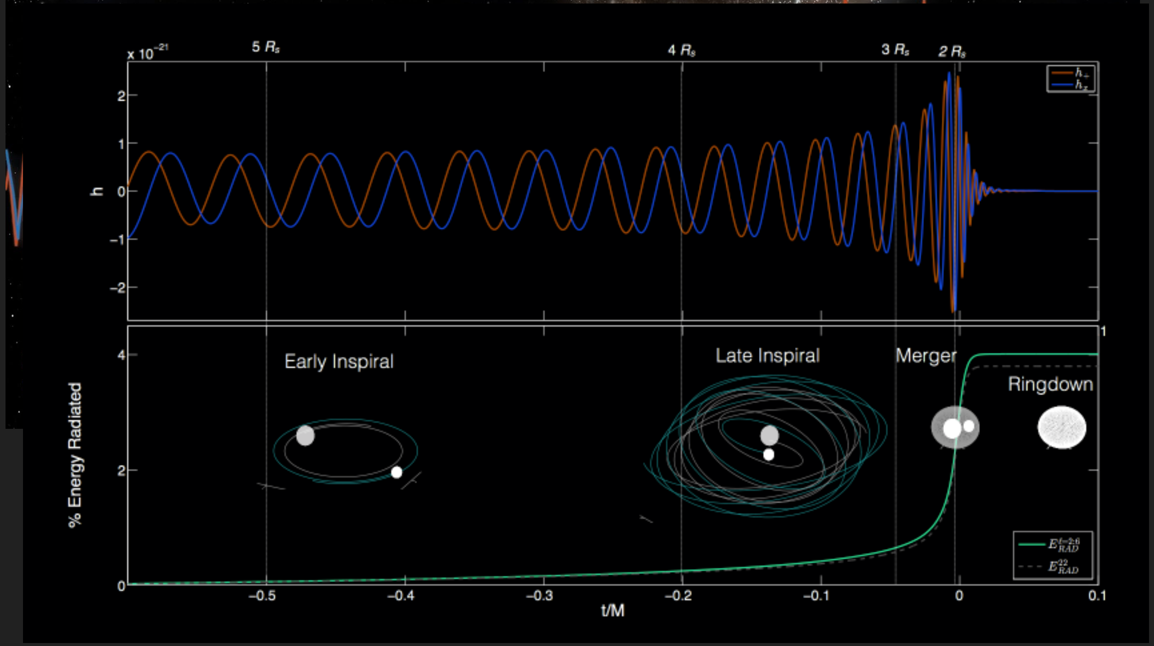

INSPIRAL GWS REFRESHER

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

$$\dot{f}_{GW} = \frac{95}{5}\pi^{8/3}\left(\frac{G\,\mathcal{M}}{c^2}\right)^{5/3} f_{GW}^{11/3}$$

- Low mass =
    - Low strain
    - Higher merger frequency
    - Slower frequency evolution

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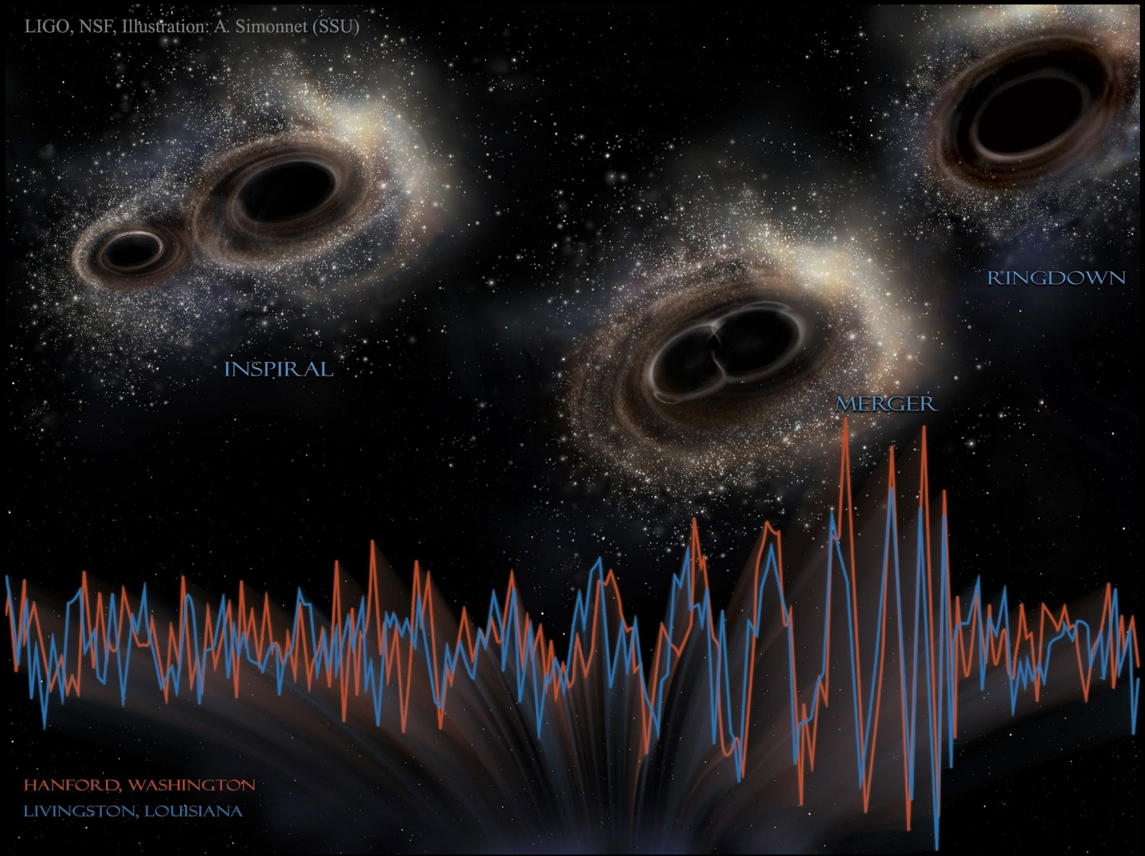
CBC VS CW SEARCHES



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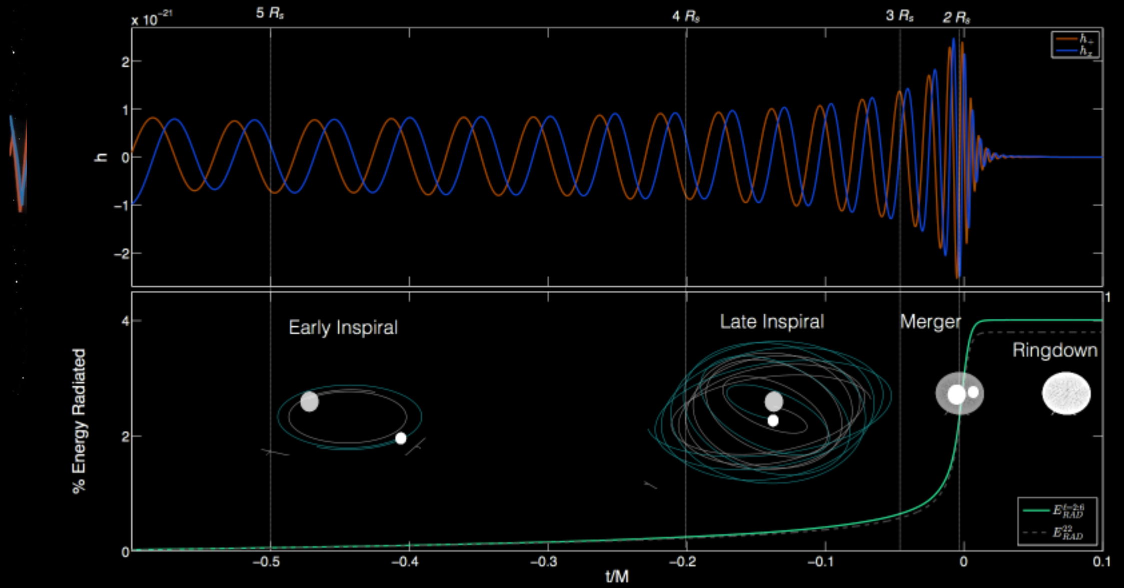
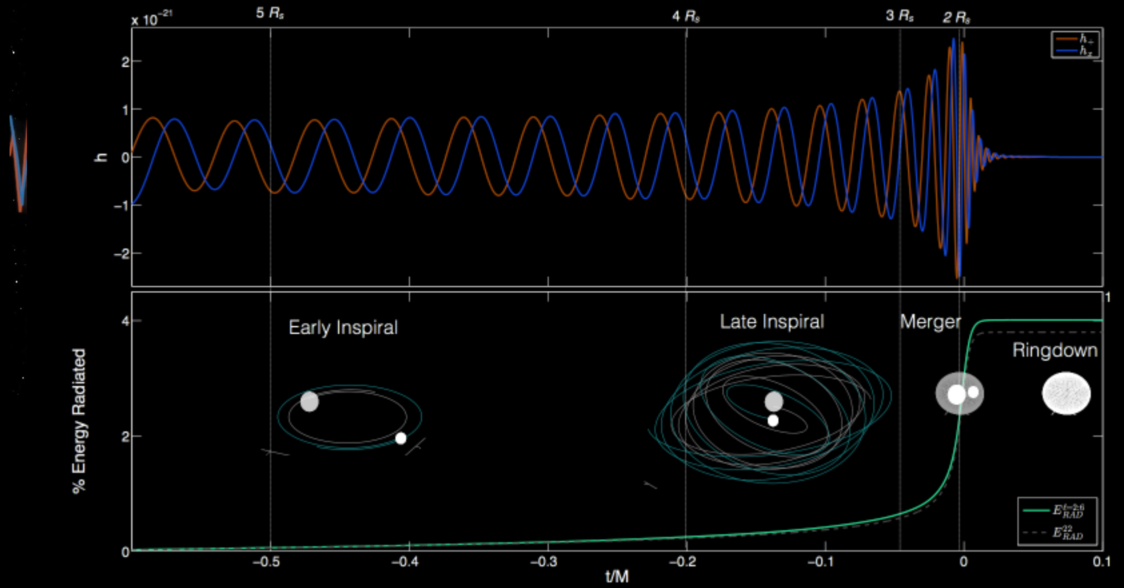


CBC VS CW SEARCHES

"Chirping" GW



Monochromatic GW

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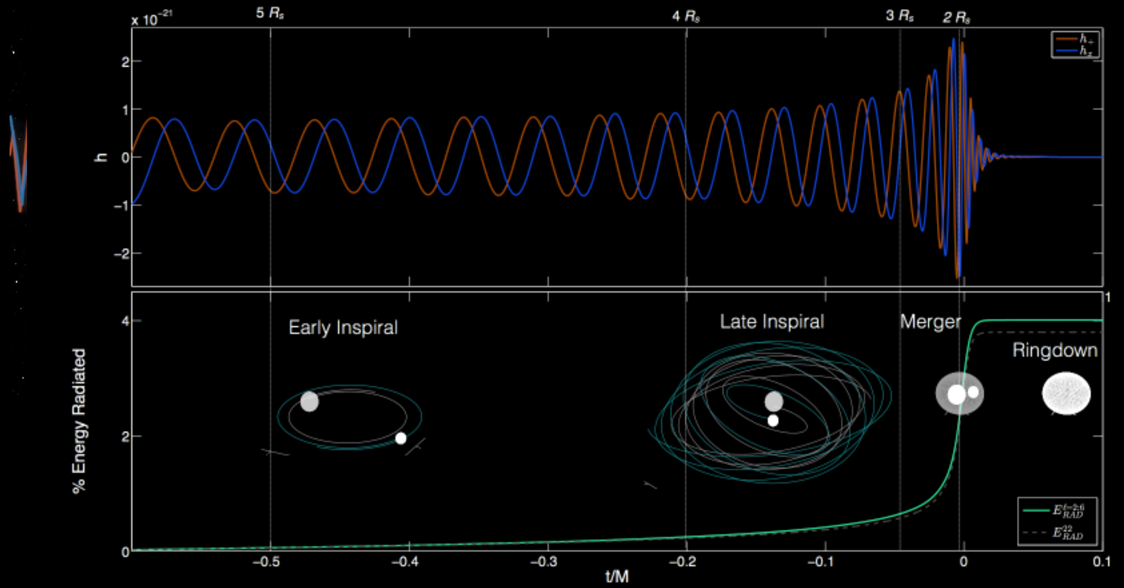

Monochromatic GW

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

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

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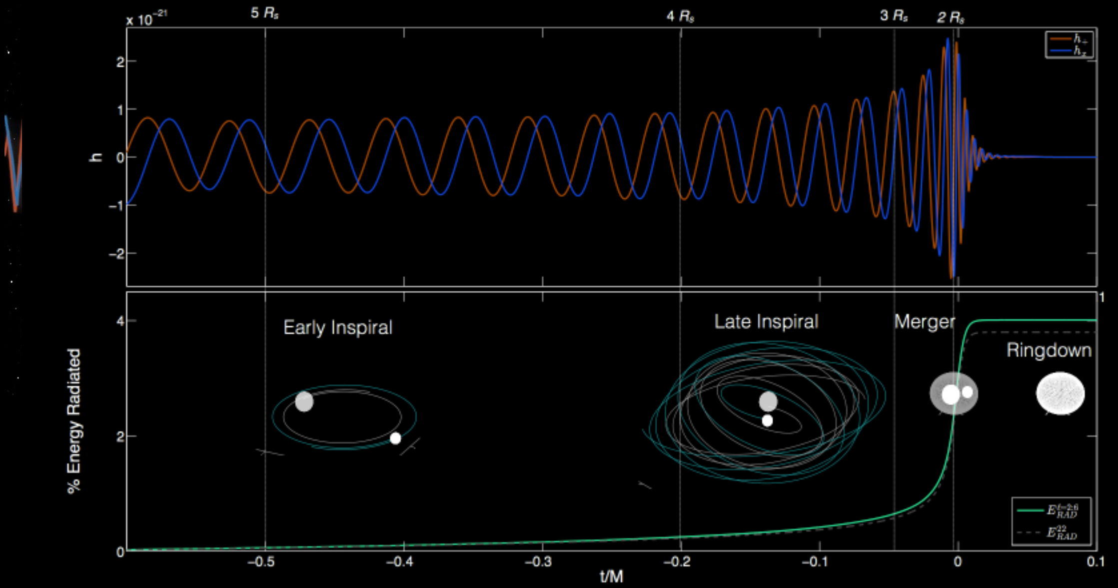

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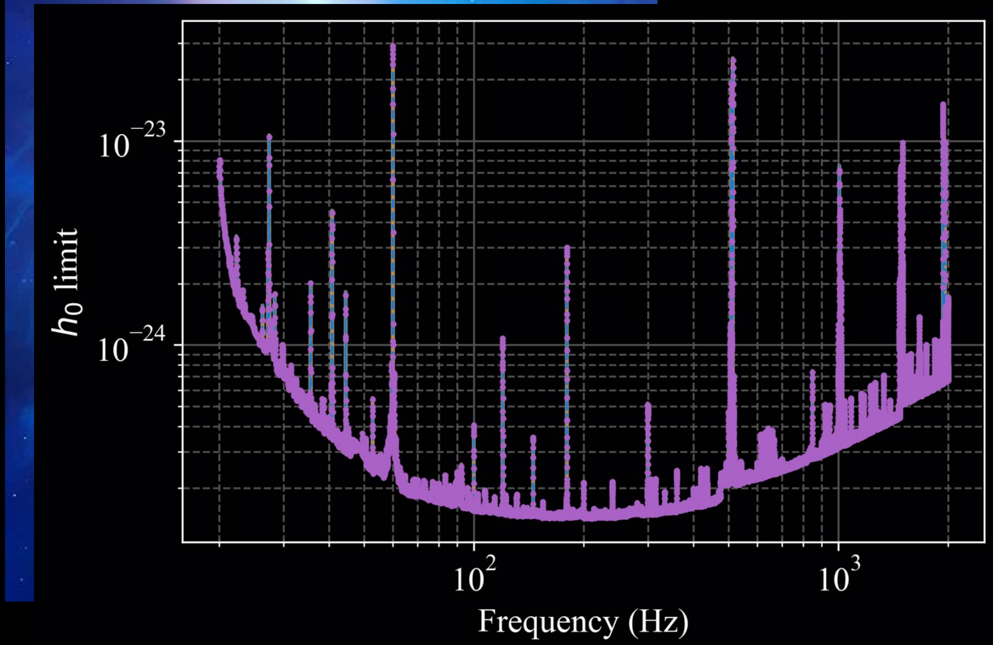
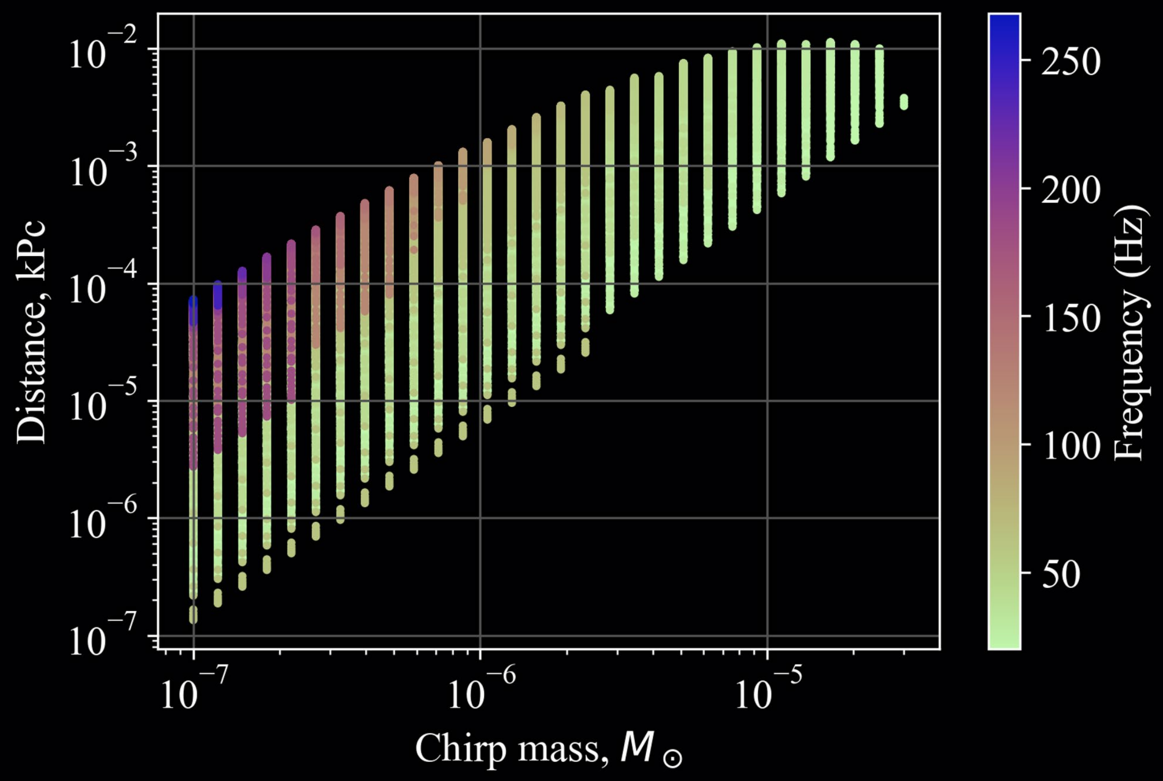


GWS FROM ULTRALIGHT PRIMORDIAL BLACK HOLES



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2. Establish joint limits from LIGO, levitated-sensor GW detectors, and 3G detectors

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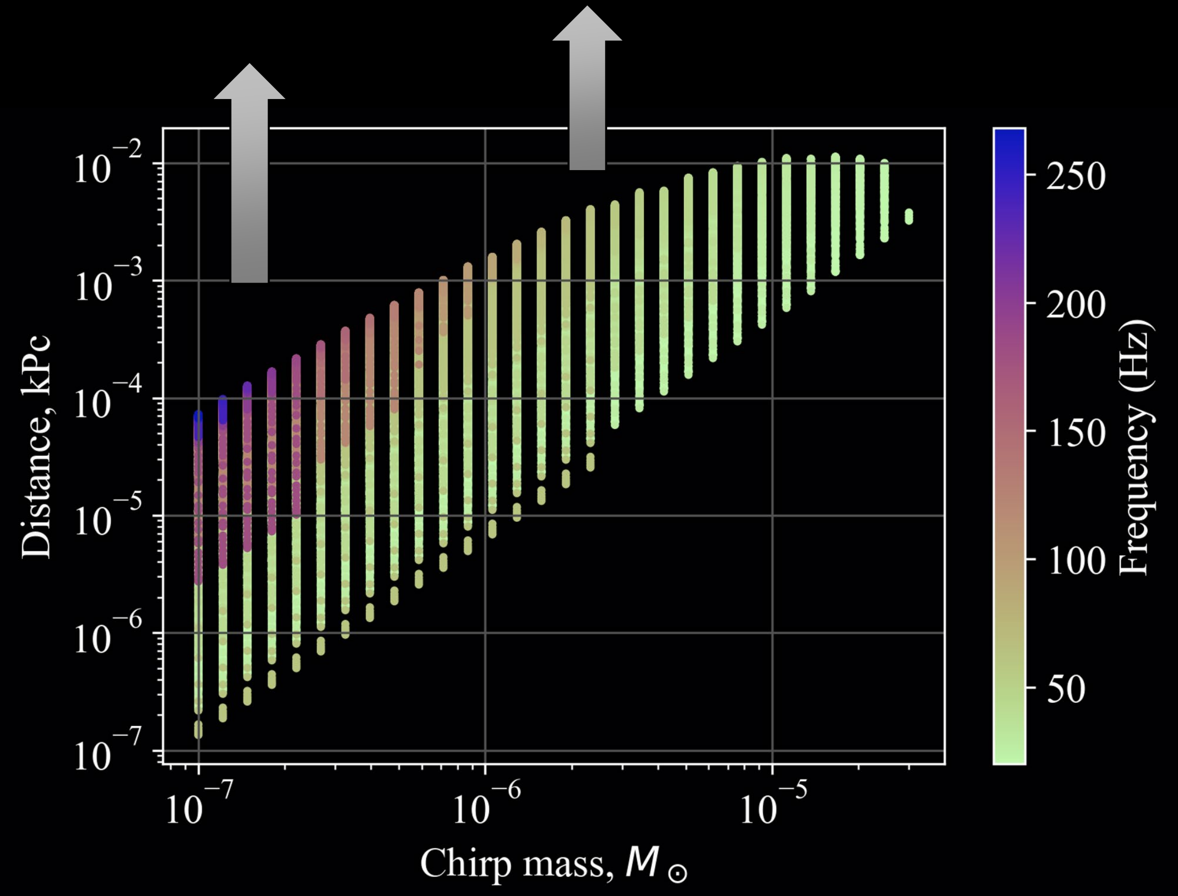

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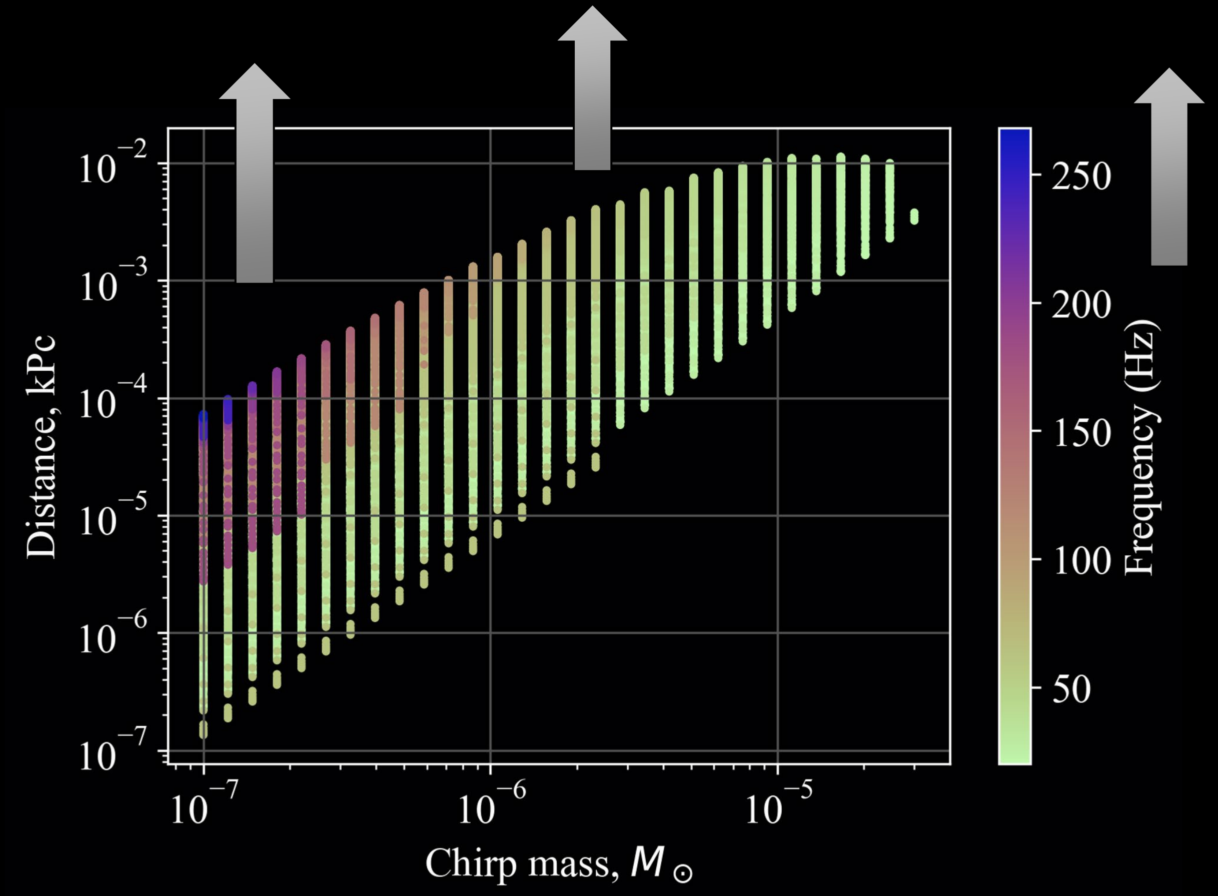

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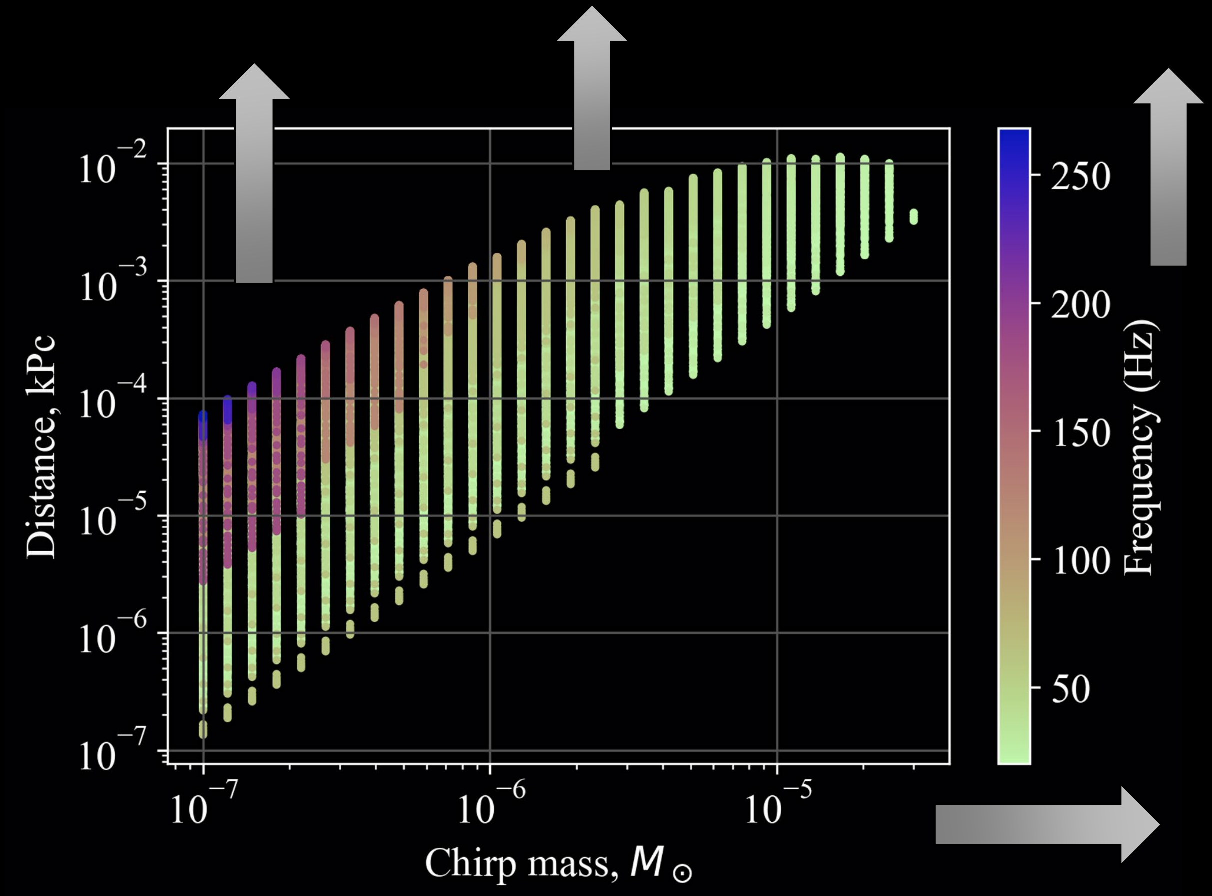

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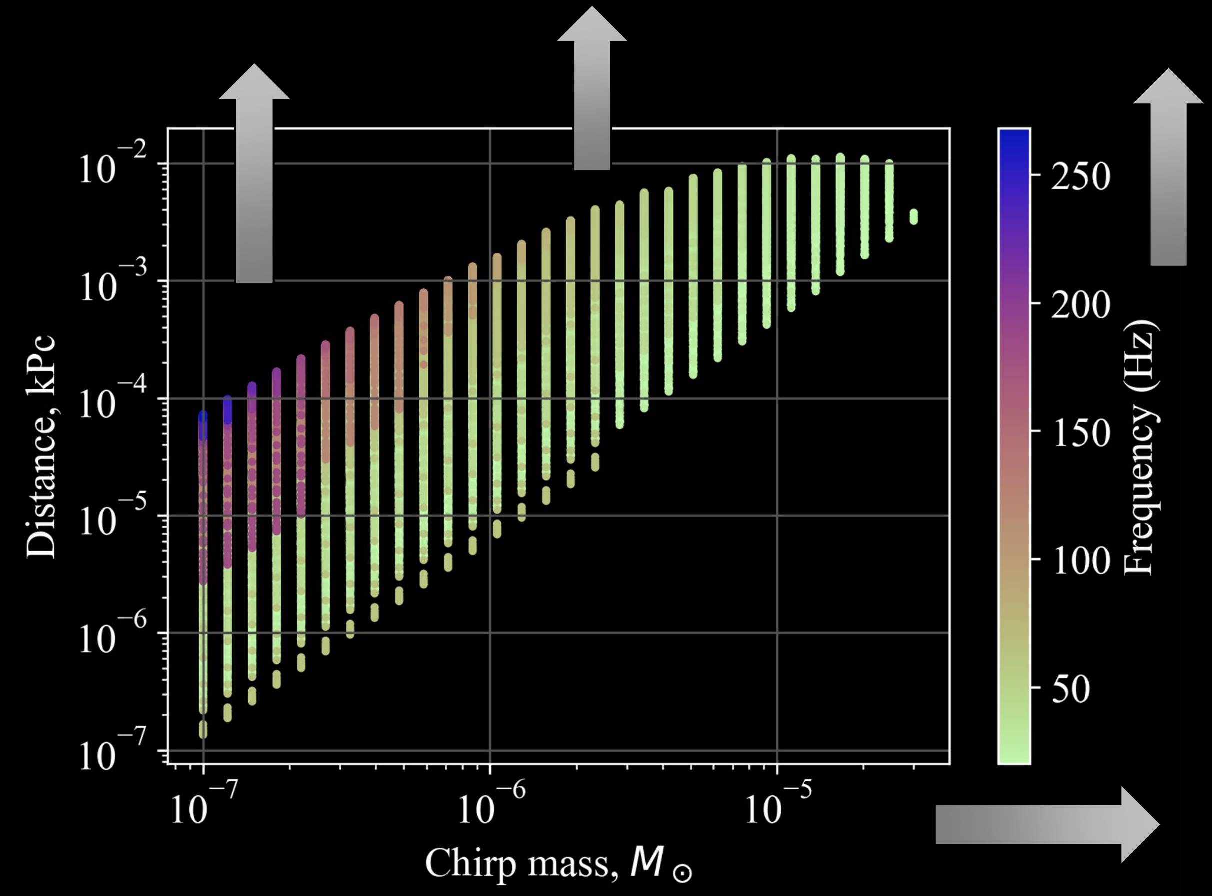

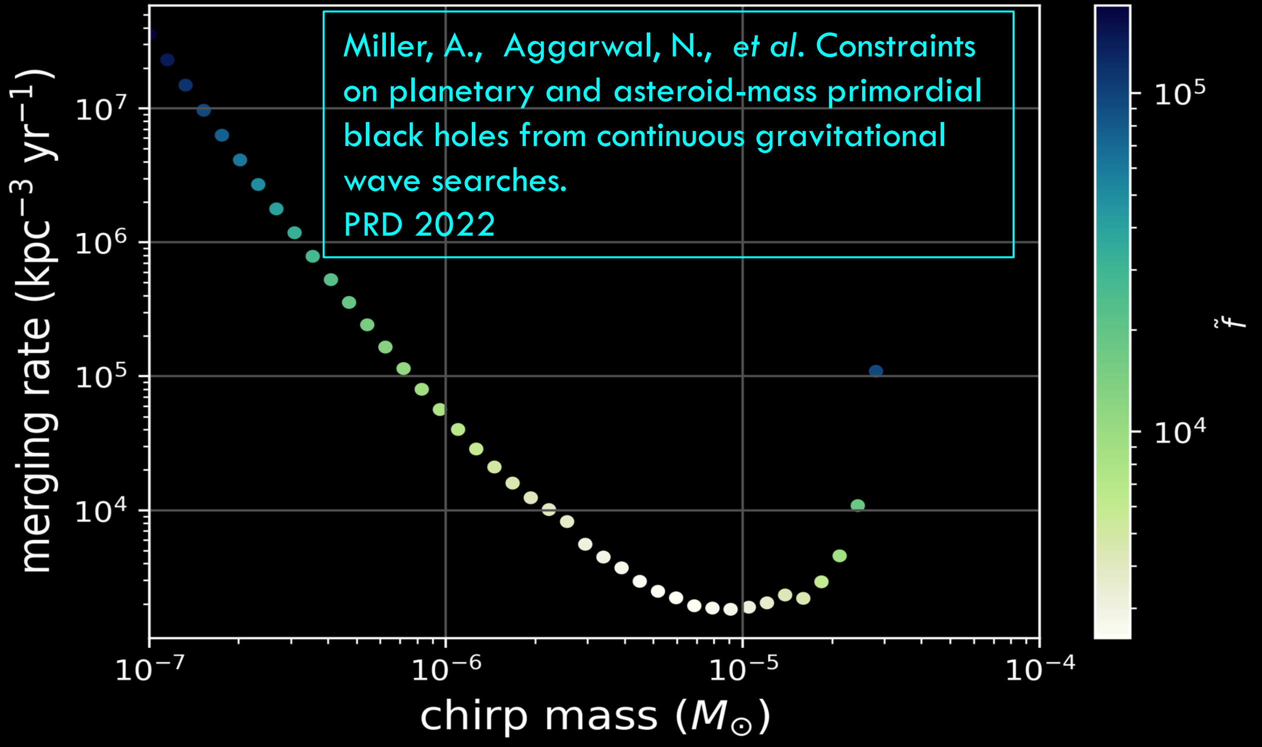

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GW Constraints ON Asteroid mass PBHs

$$m_1 = 2.5\ M_\odot$$

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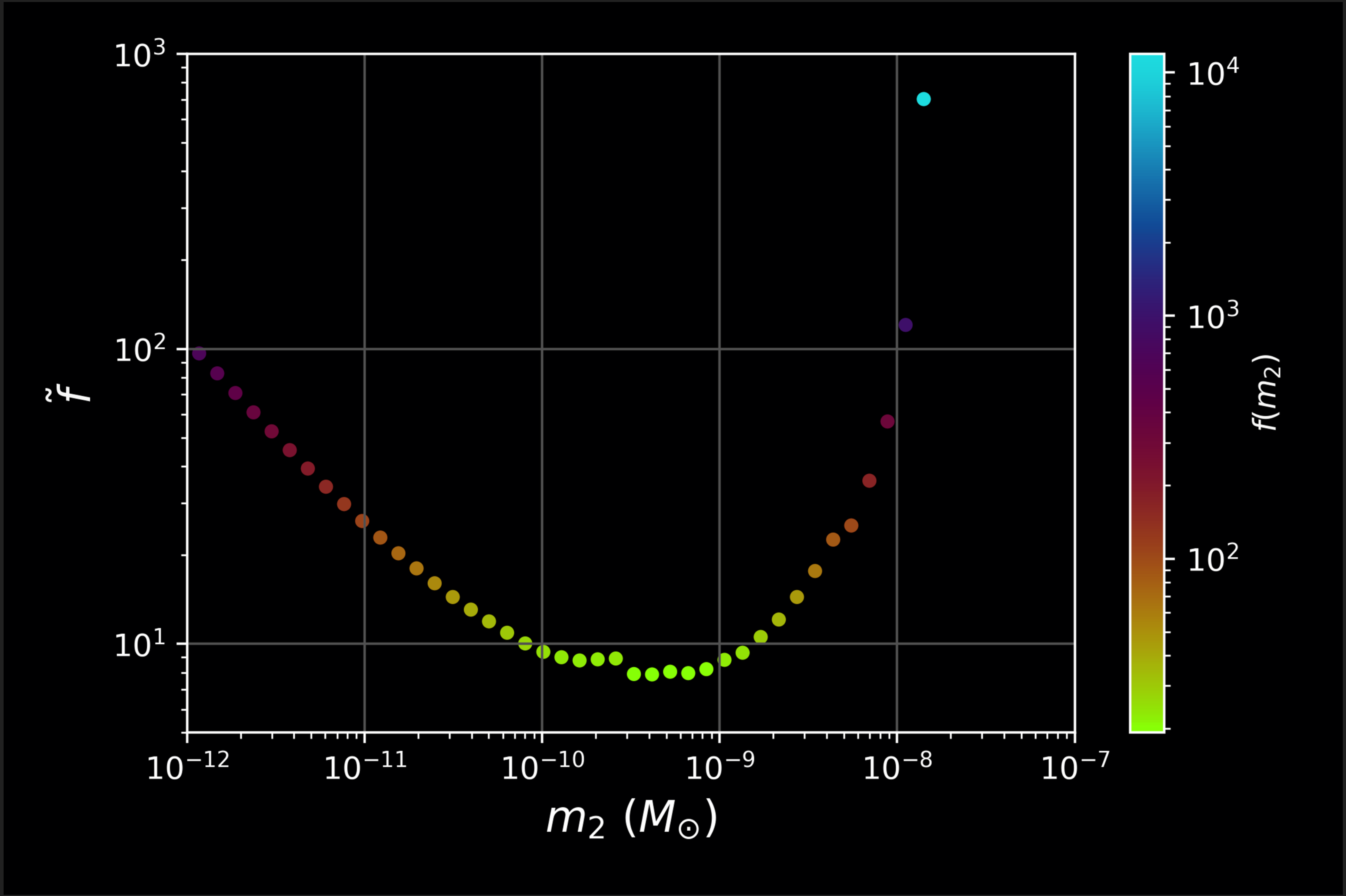

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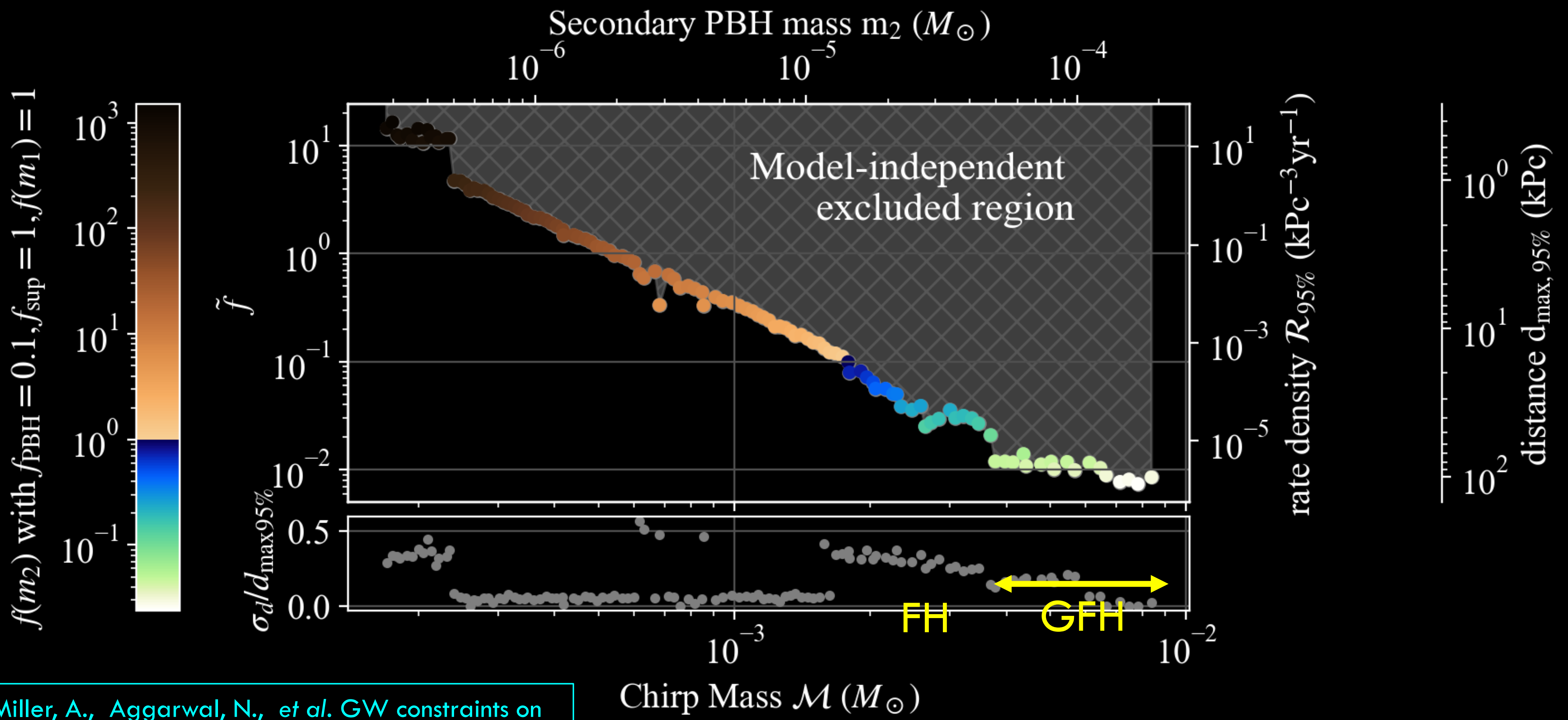

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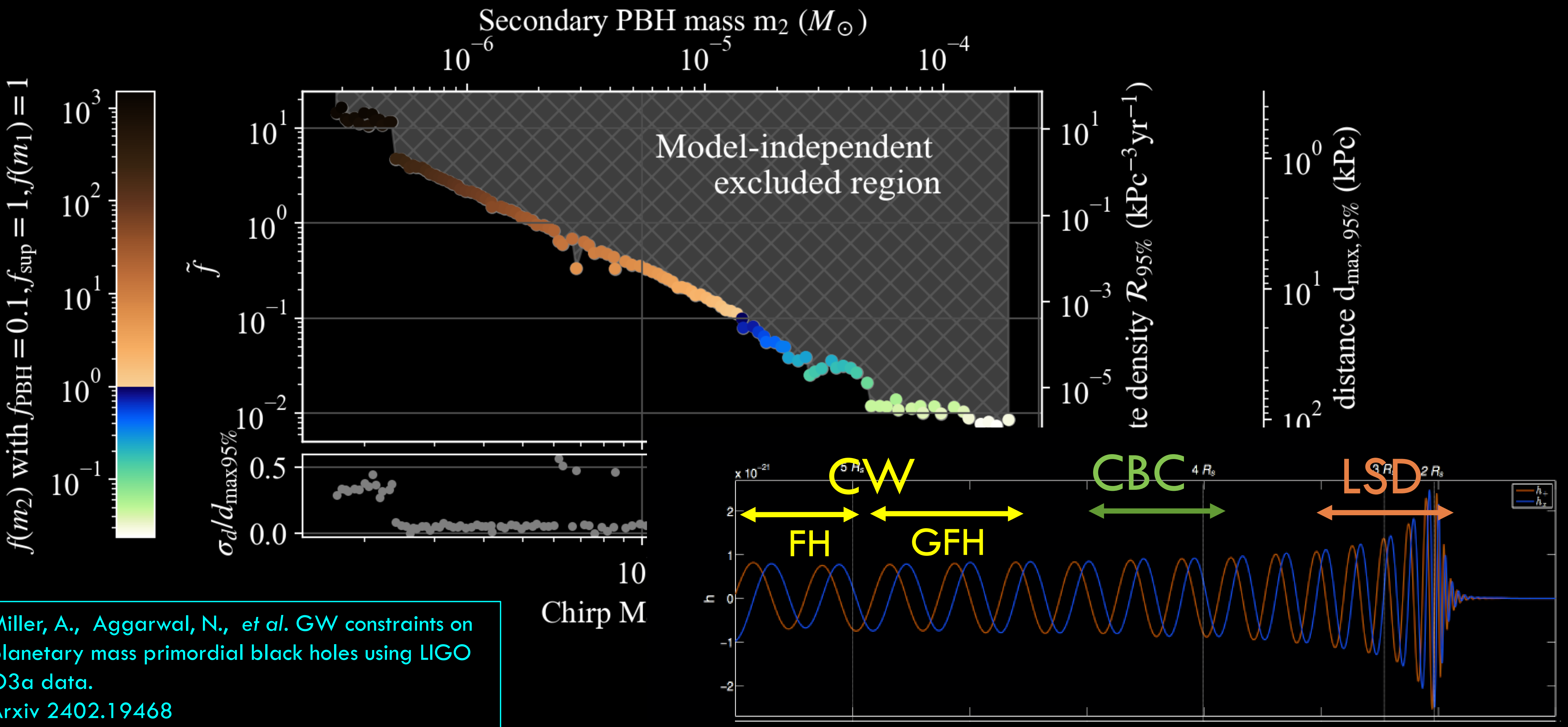

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ULTRALIGHT DILATONIC DARK MATTER DIRECT COUPLING WITH LIGO REFERENCE CAVITIES

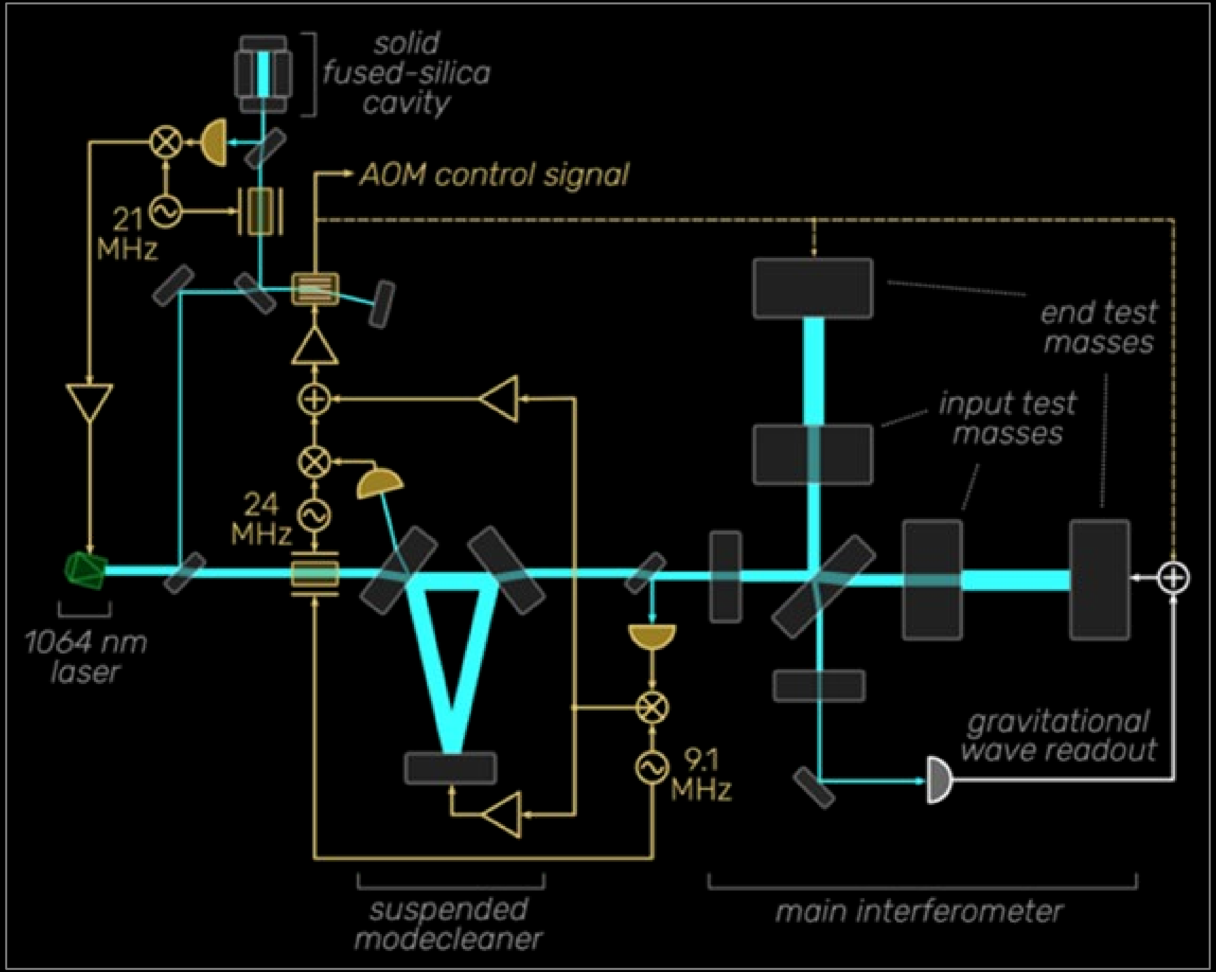

FIG. 1: Advanced LIGO frequency stabilization. Noise in the solid cavity, including noise from any dark matter signal that changes the length of the solid cavity, will appear on the control signal applied to the acousto-optic modulator (AOM). The various noise contributions to this control signal are given in Eq. (4).

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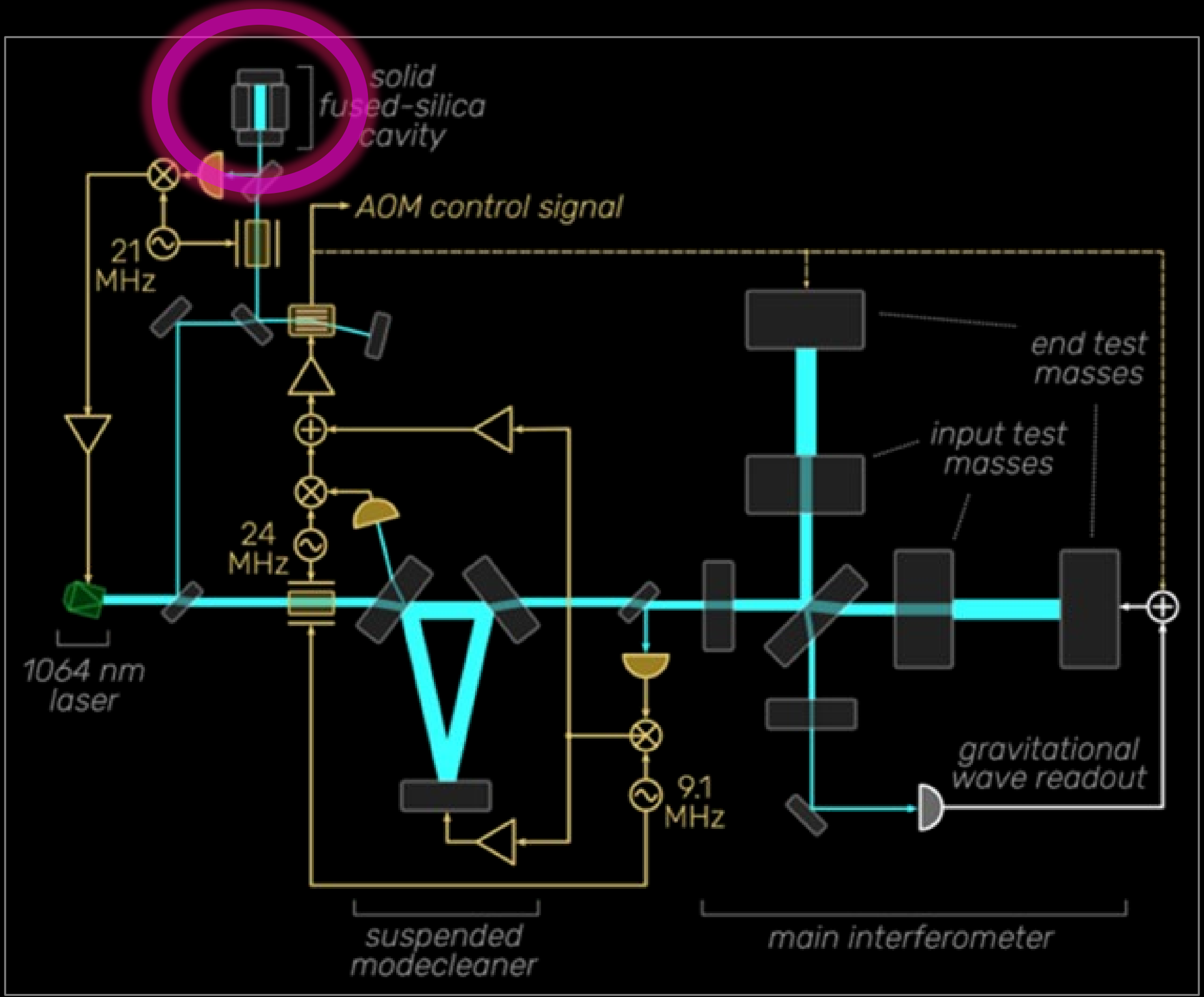

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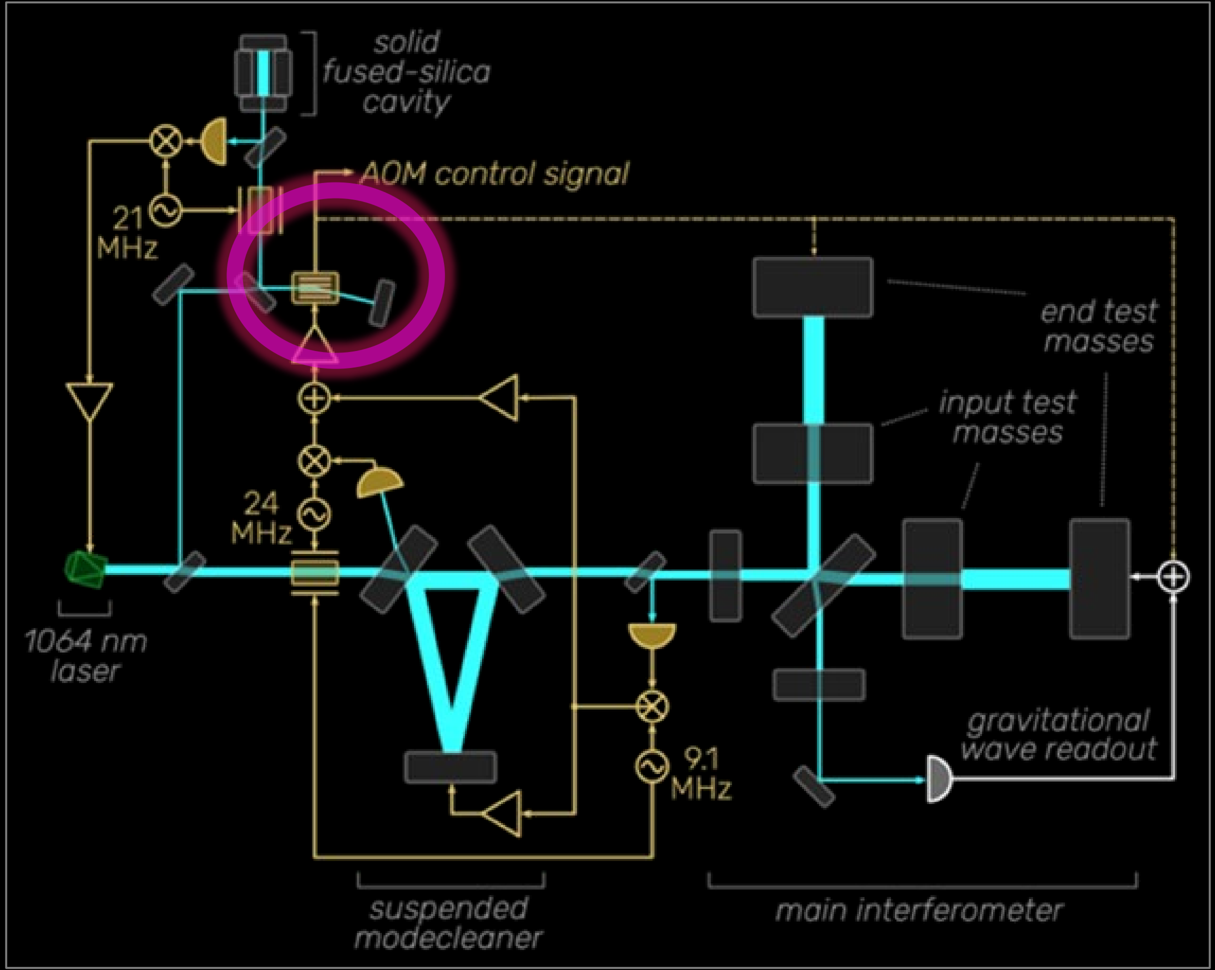

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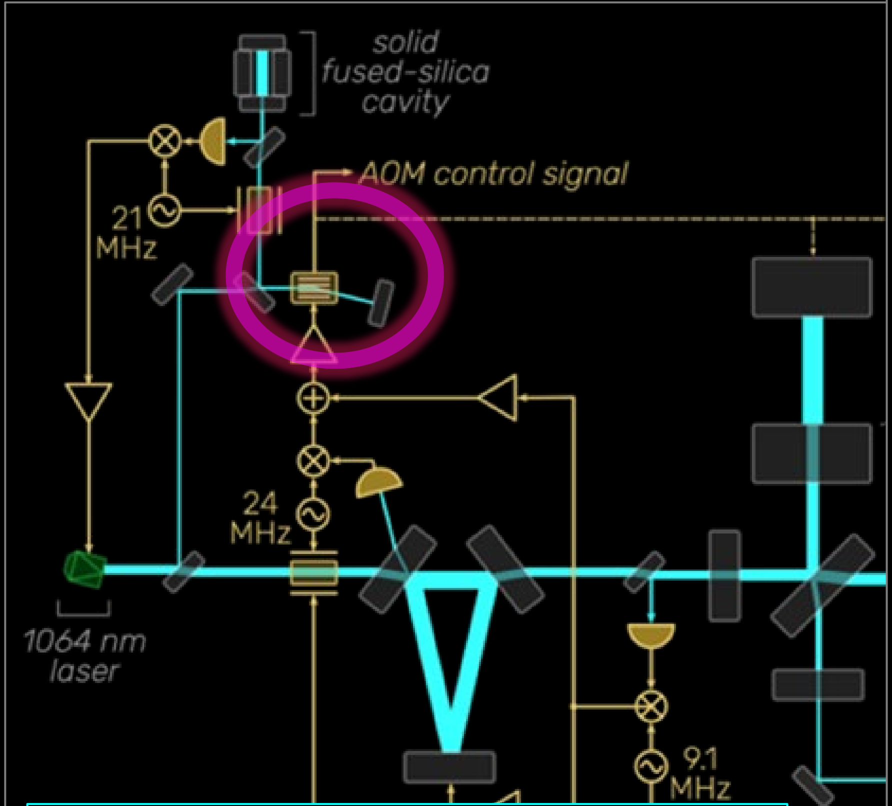

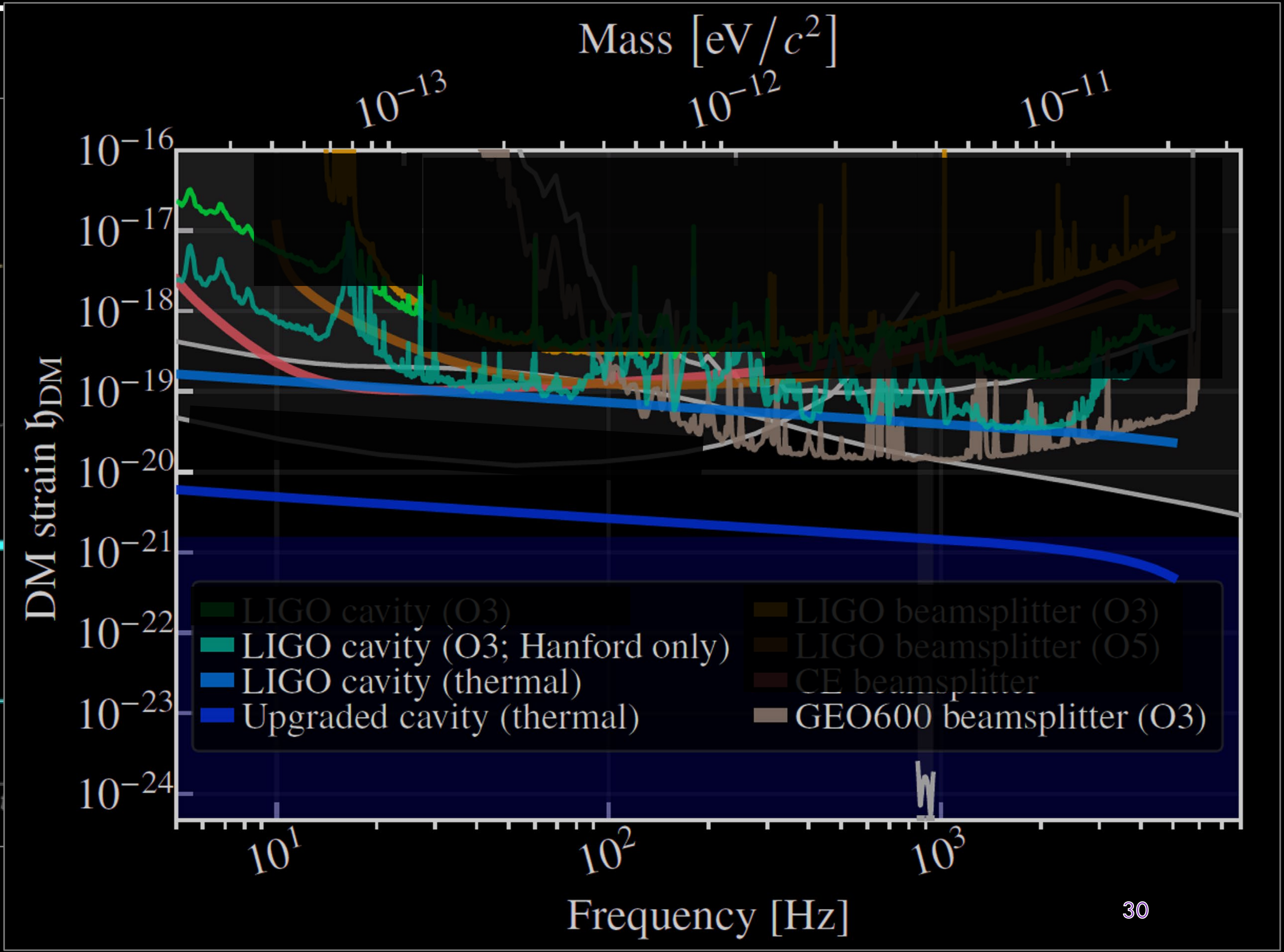

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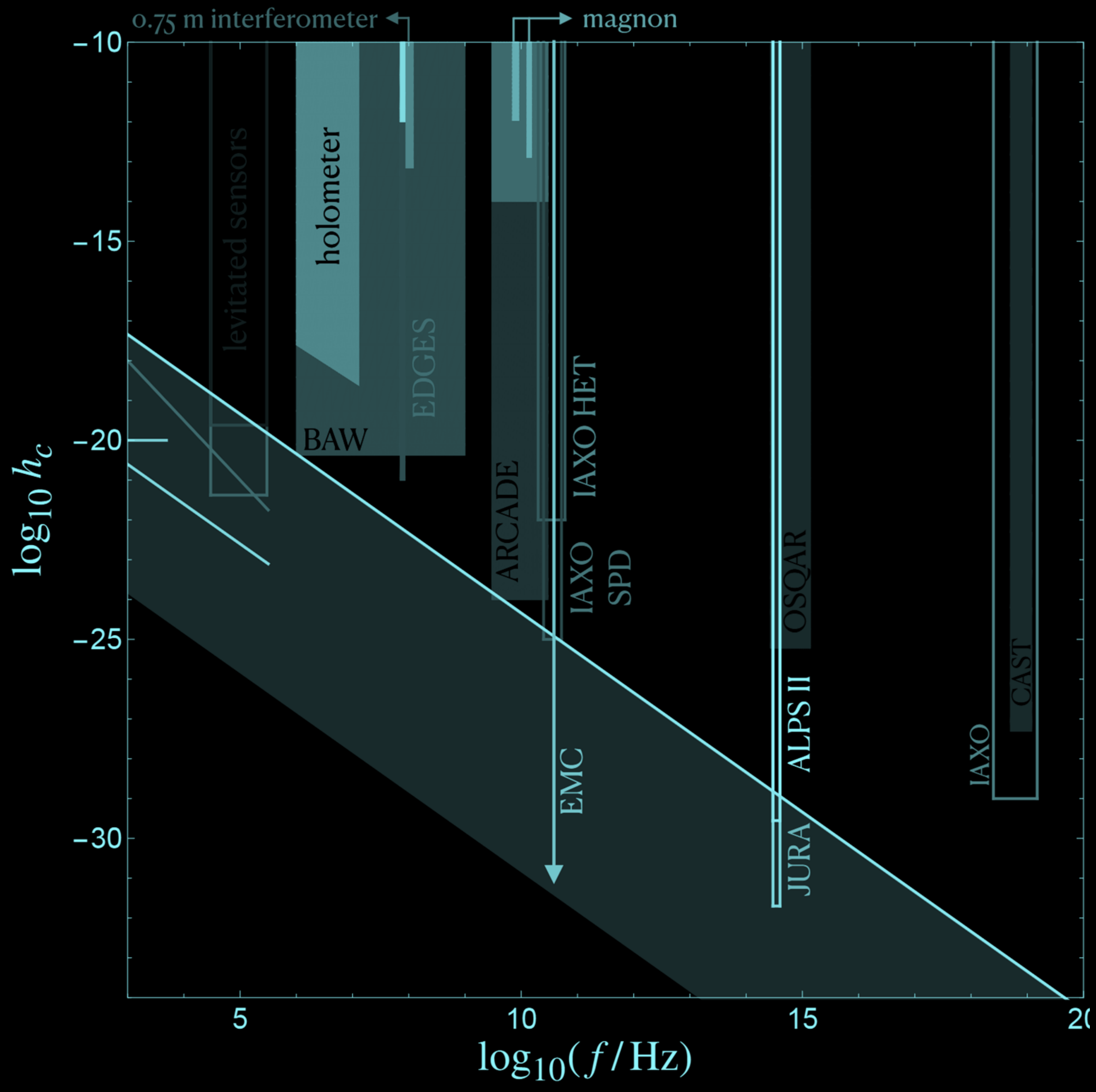
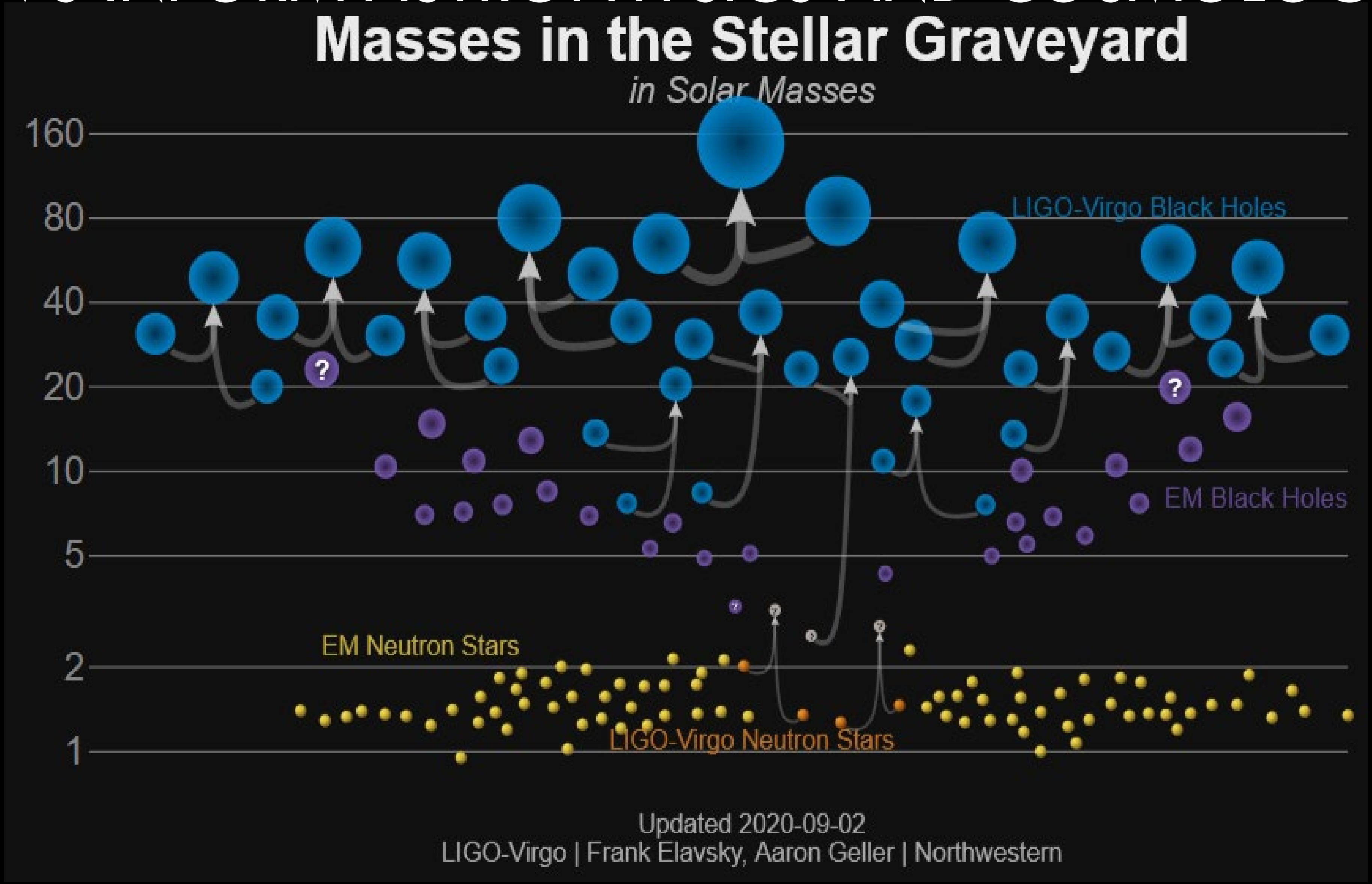


ULTRA-HIGH FREQUENCY GRAVITATIONAL WAVE INITIATIVE

GWS INFORM ASTROPHYSICS AND COSMOLOGY



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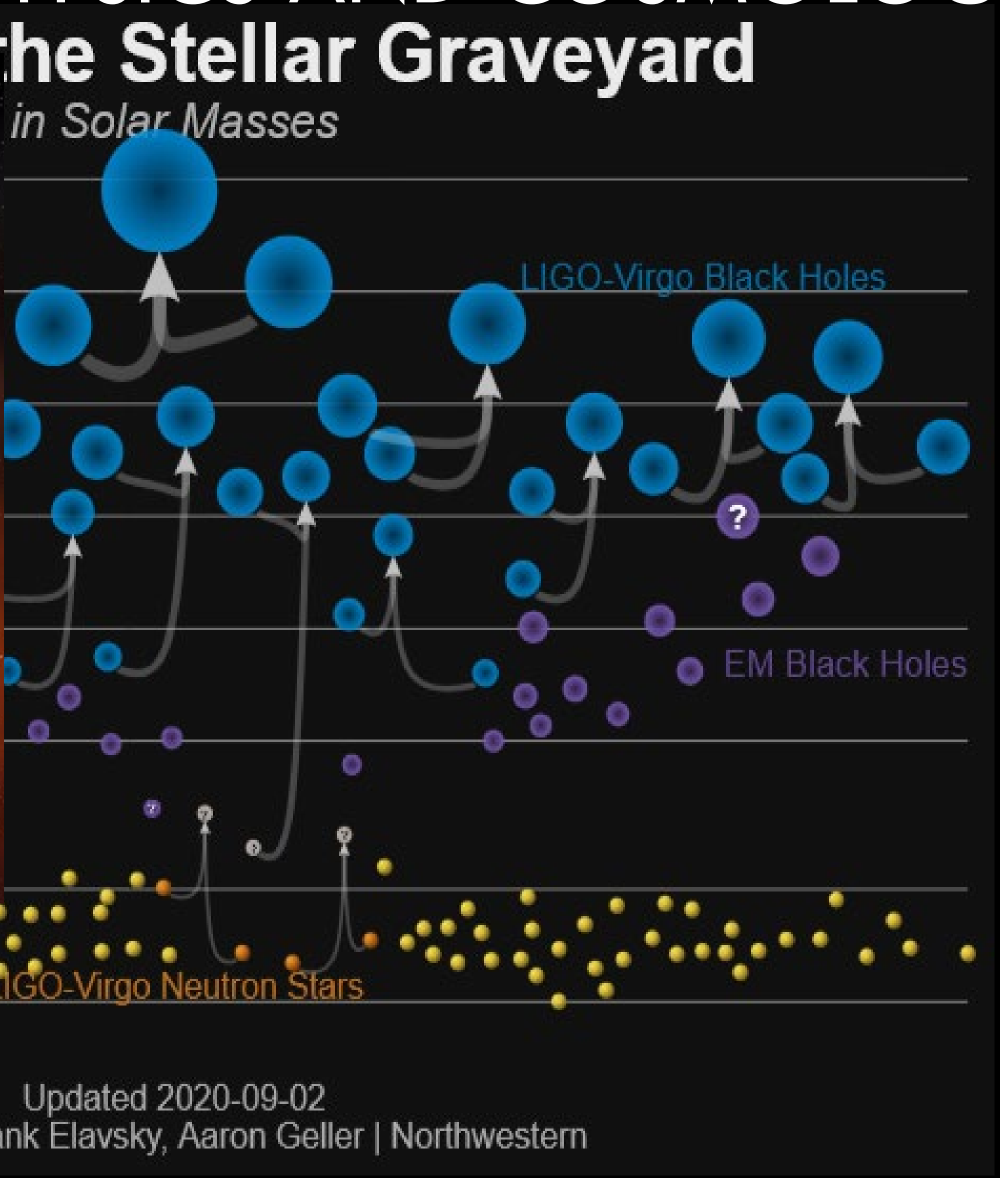

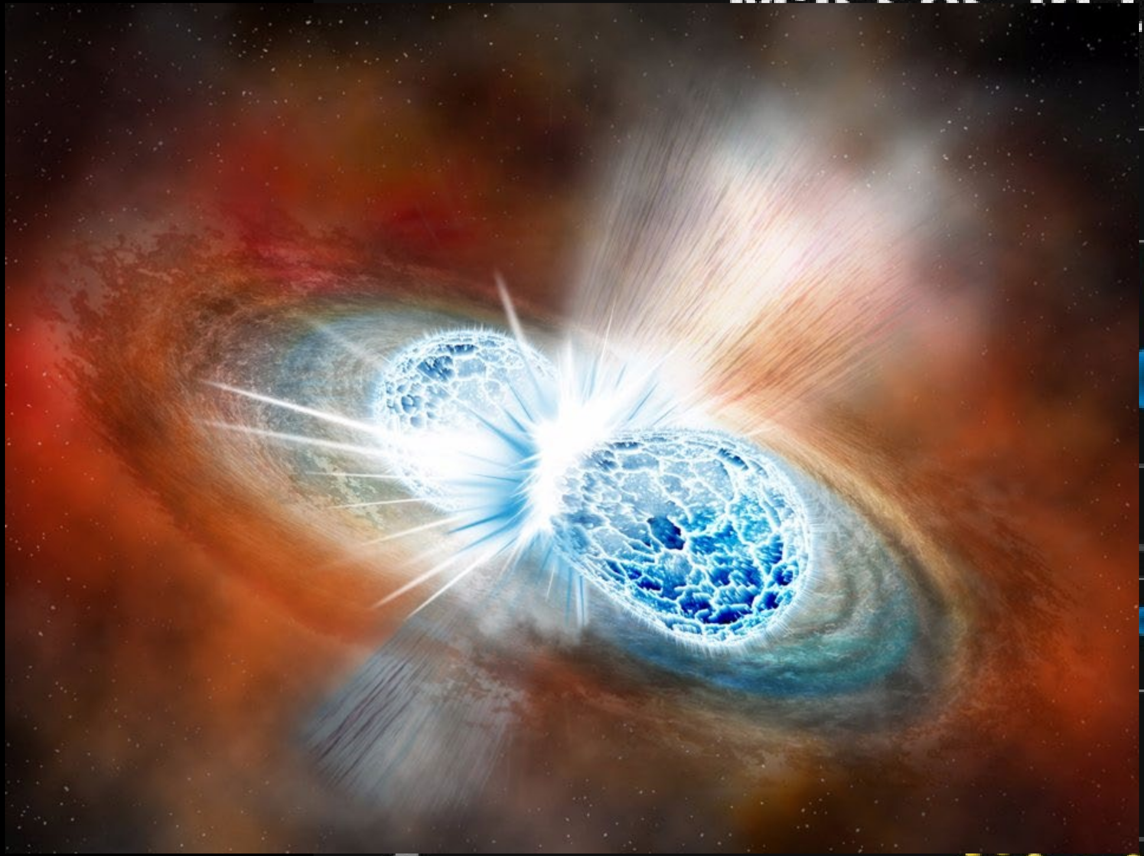

Biggish bang: artist's impression of a neutron-star merger (Courtesy: NASA)

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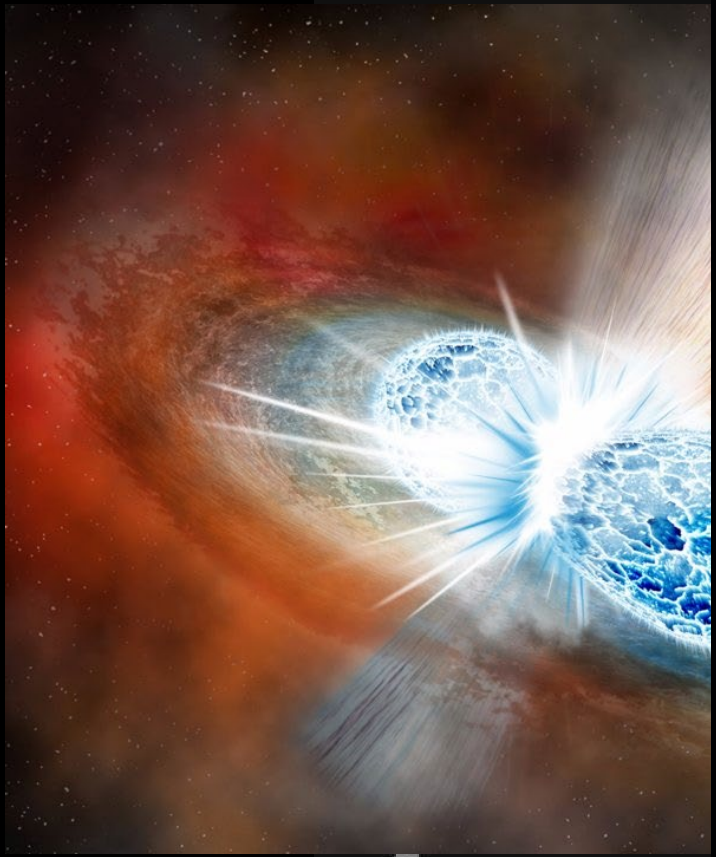

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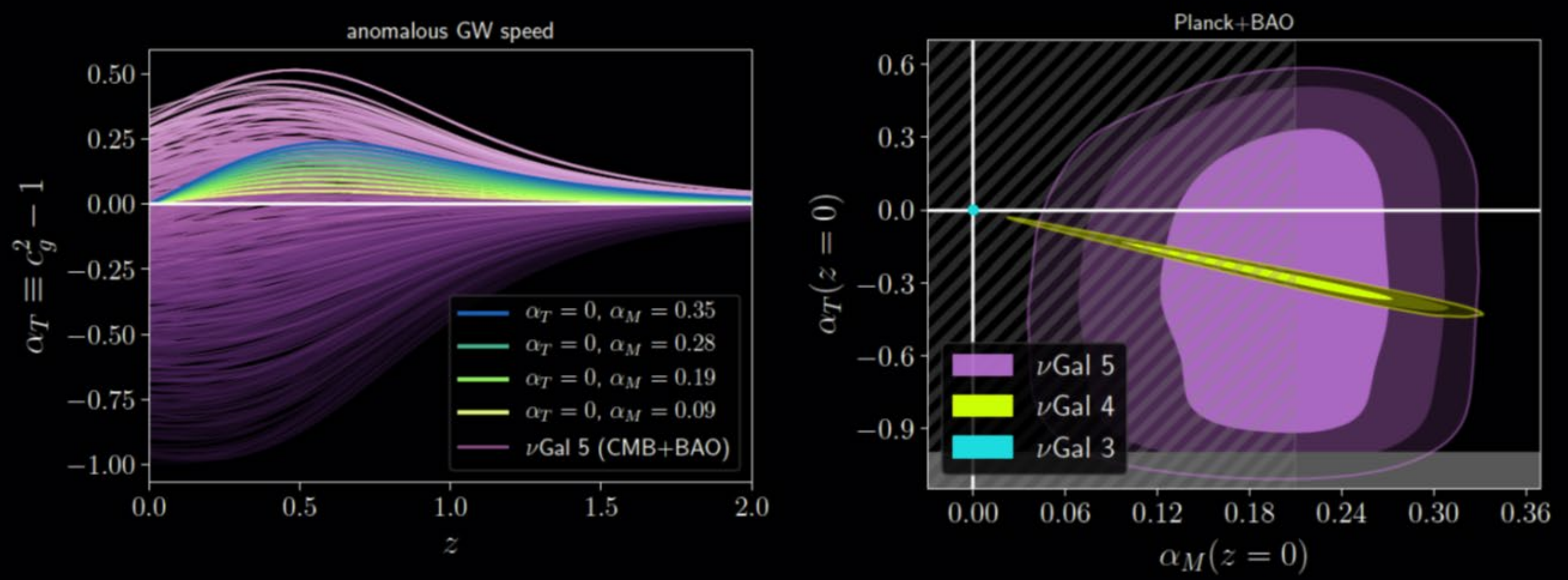
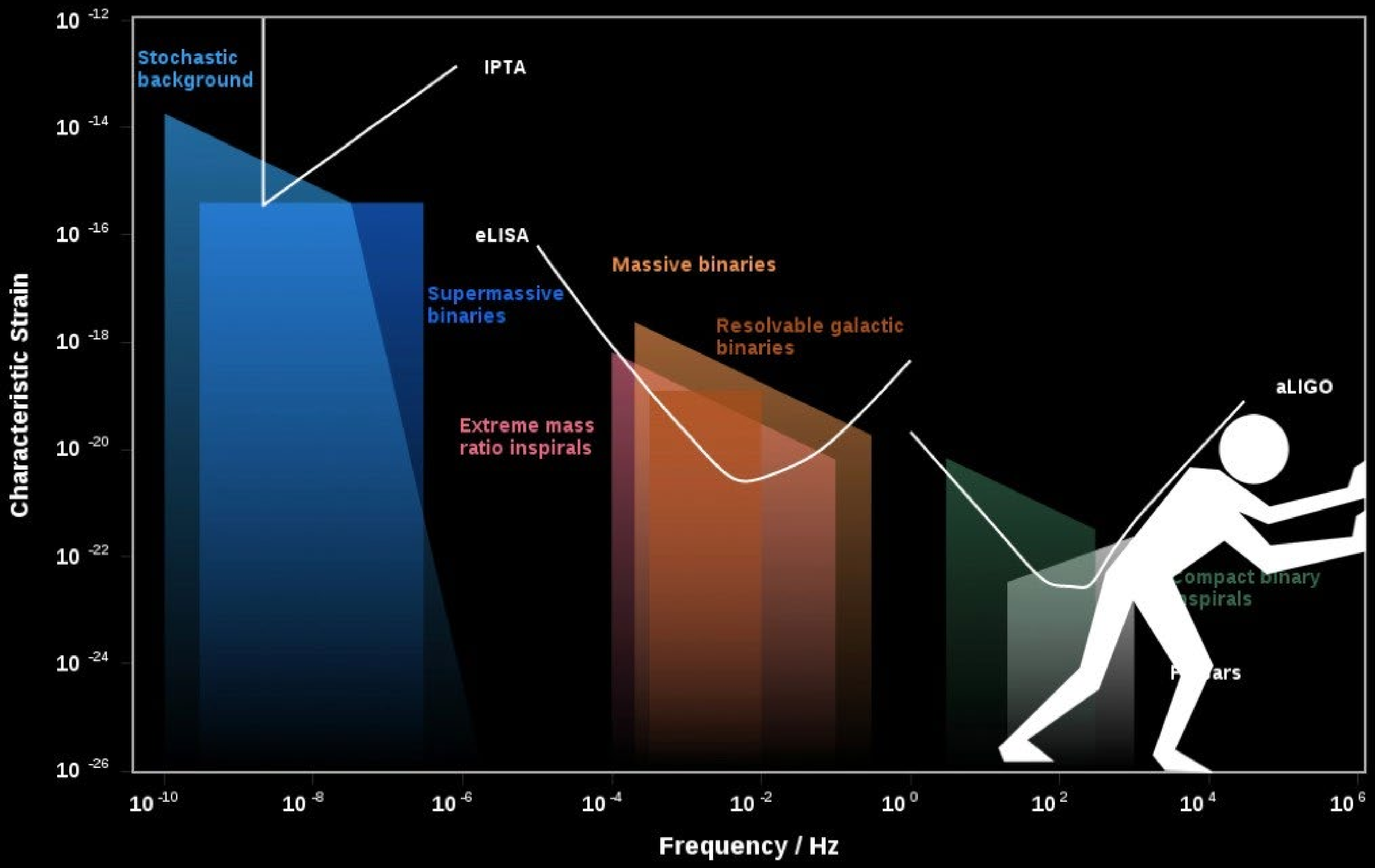


FIG. 1: **Left:** time evolution of the tensor speed excess α_T as a function of redshift for 300 different realizations of viable quintic Galileon cosmologies. Only quintic fine tuned cases (colored) predict $\alpha_T(z=0) \approx 0$. **Right:** 1, 2 and 3σ confidence regions of the parameter space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

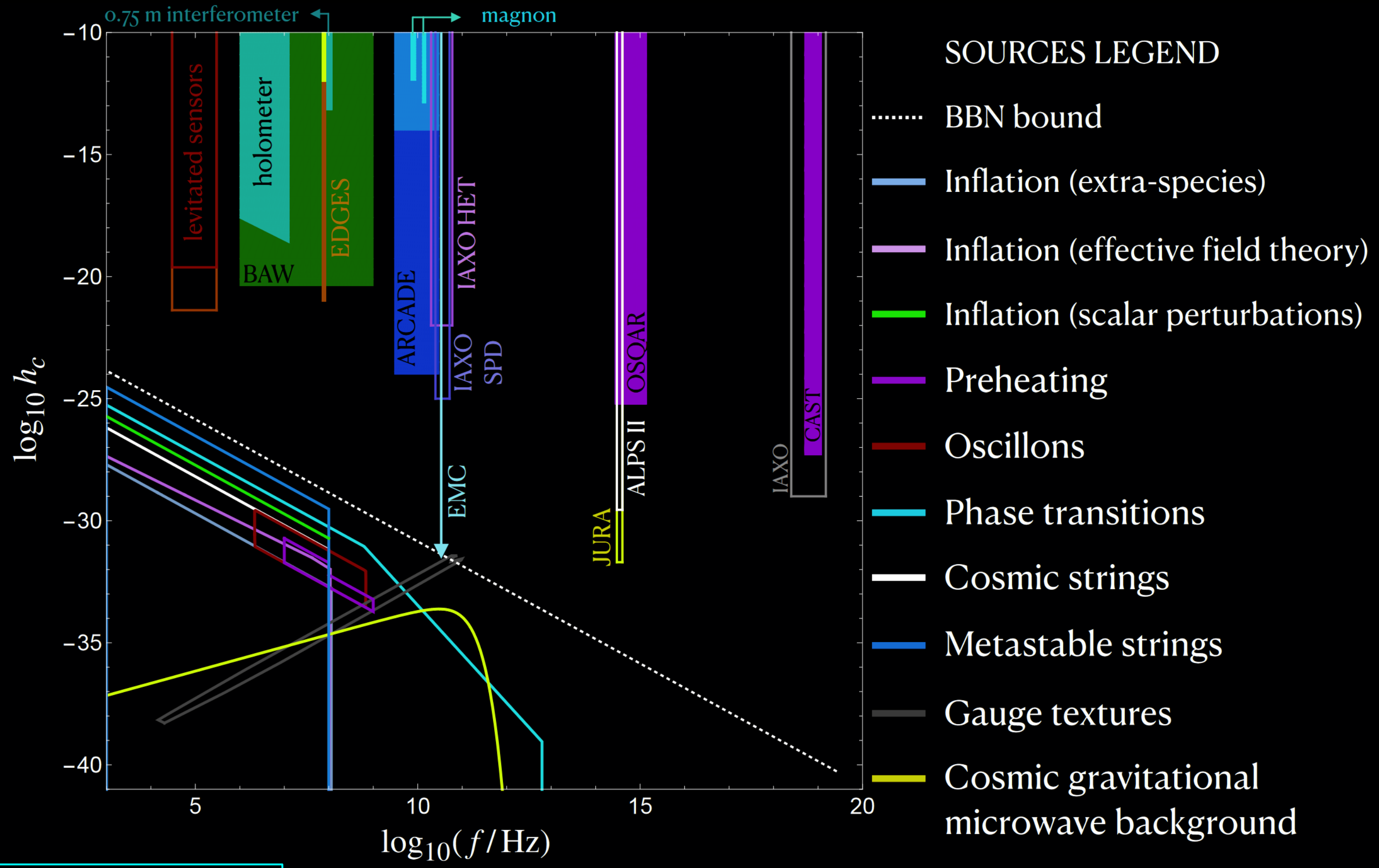
GWS ABOVE THE AUDIO BAND?



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

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

NUMEROUS INTERESTING SOURCES & PROMISING TECHS!!!



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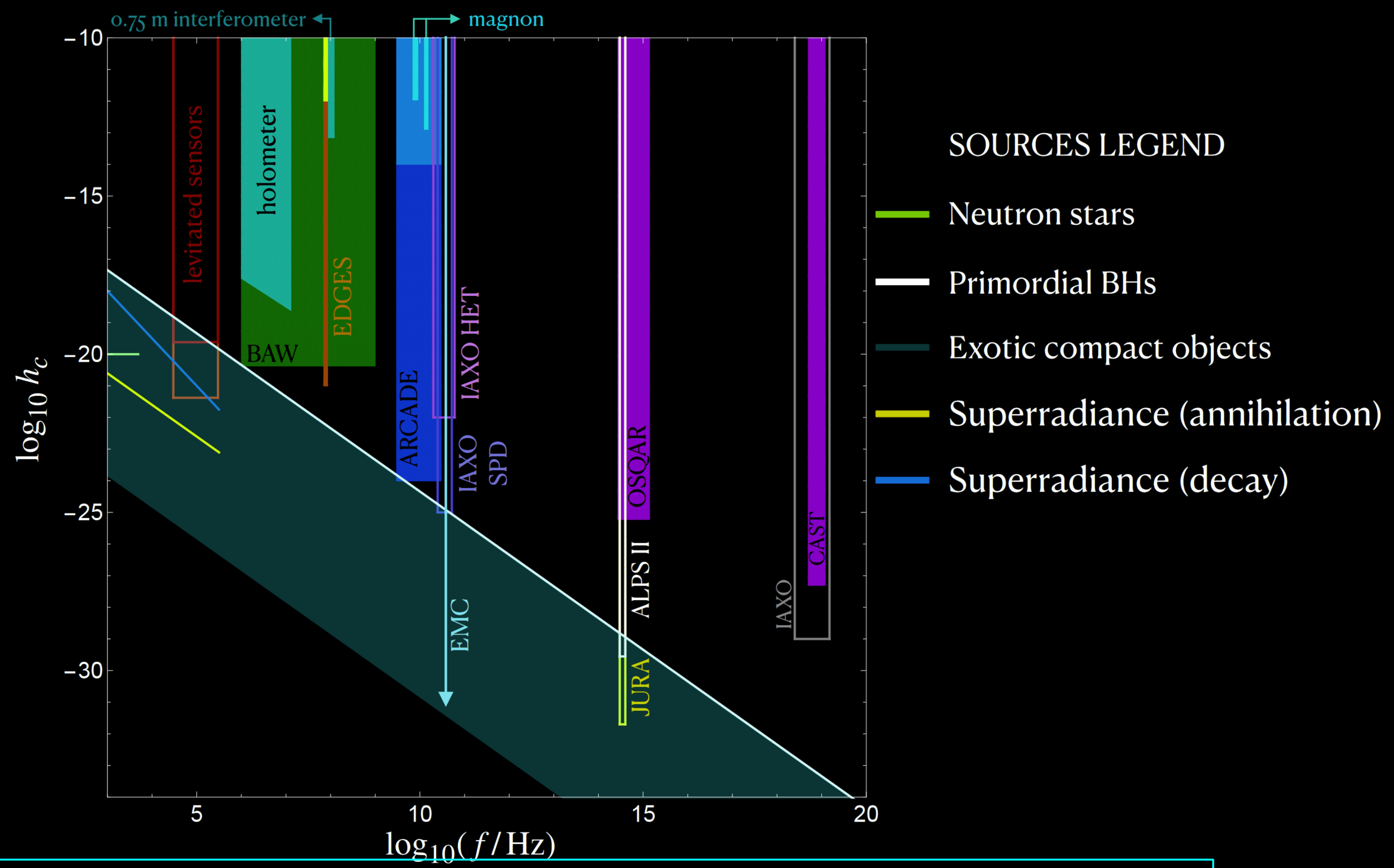

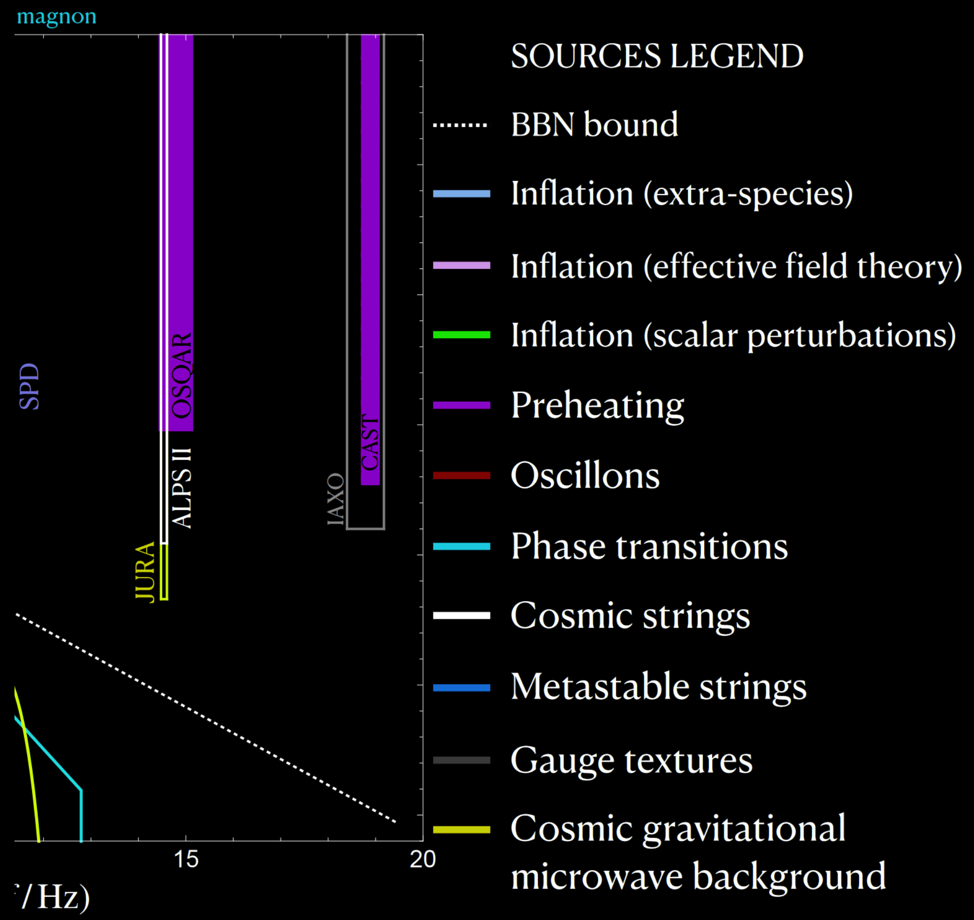

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THANKS!

Collaborators

- Northwestern University: Andrew Geraci, Vicky Kalogera, Shane Larson, George Winstone, Aaron Wang, Shelby Klomp, Chloe Lohmeyer, Lucas Stanley, many others
- Indiana University: Mike Snow and many others
- PTB: Jens Voigt, Wolfgang Killian, Sylvia Guttenberg
- Stanford University: Aharon Kapitulnik, Alan Fang
- UIUC: Josh Long
- Caltech: Andrew Laeuger
- MIT: Nergis Mavalvala, Evan Hall, Swadha Pandey, Bobby Lanza
- LSU: Thomas Corbitt, Jon Cripe Torrey Cullen
- Nikhef: Andrew Miller
- Georgia Tech: Surabhi Sachdev
- CAPP: Yannis Semeridis, Yun Shin