MULTI-PRONG SEARCHES FOR LIGHT DARK MATTER

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VLDM WORKSHOP, MARCH 29, 2023

ASK ME ABOUT --

Description	Experiment	Mass
Spin-mass interaction mediated by QCD axion	ARIADNE	$10^{-6} - 10^{-3}$ eV
GWs from bosons created via BH superradiance	LSD	$10^{-11} - 10^{-10}$ eV
Dilaton DM using auxiliary channels in GW detectors	LIGO	$10^{-13} - 10^{-11}\ eV$
GWs from light and ultralight primordial blackholes	LIGO + LSD	$10^{-10} - 10^{-1} M_{\odot}$

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TODAY’S MENU


ADVANCED LIGO, LISA, AND COSMIC EXPLORER AS DARK MATTER TRANSDUCERS
Arxiv:2210.17487
Collaboration with Evan Hall
sesame/DigitalVision Vectors/Getty
Nancy Aggarwal, Northwestern University
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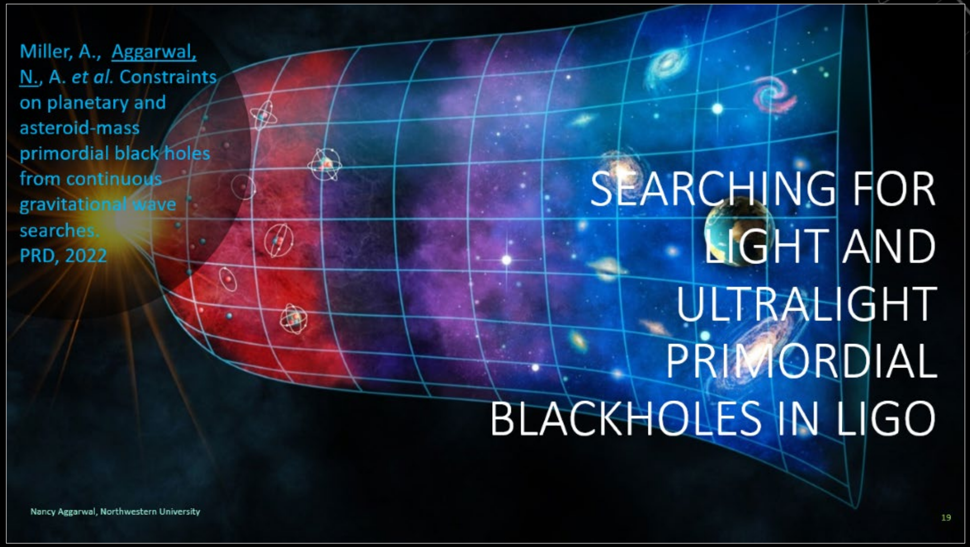
Miller, A., Aggarwal, N., A. et al. Constraints on planetary and asteroid-mass primordial black holes from continuous gravitational wave searches. PRD, 2022
SEARCHING FOR LIGHT AND ULTRALIGHT PRIMORDIAL BLACKHOLES IN LIGO
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ADVANCED LIGO, LISA, AND COSMIC EXPLORER AS DARK MATTER TRANSDUCERS

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Collaboration with Evan Hall

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THE CANDIDATE SIGNAL

- Scalar coupling to SM Lagrangian:

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

- Modulates \alpha and mass of electron:

$$\frac{\Delta\alpha(t)}{\alpha} = A_e \cos\left(\Omega_{\rm DM} t\right)$$

$$\frac{\Delta m_e(t)}{m_e} = A_{m_e} \cos\left(\Omega_{\rm DM} t\right)$$

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

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

IMPACT ON SOLID OBJECTS

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

(due to change in Bohr radius and bond lengths)

IMPACT ON GW DETECTORS

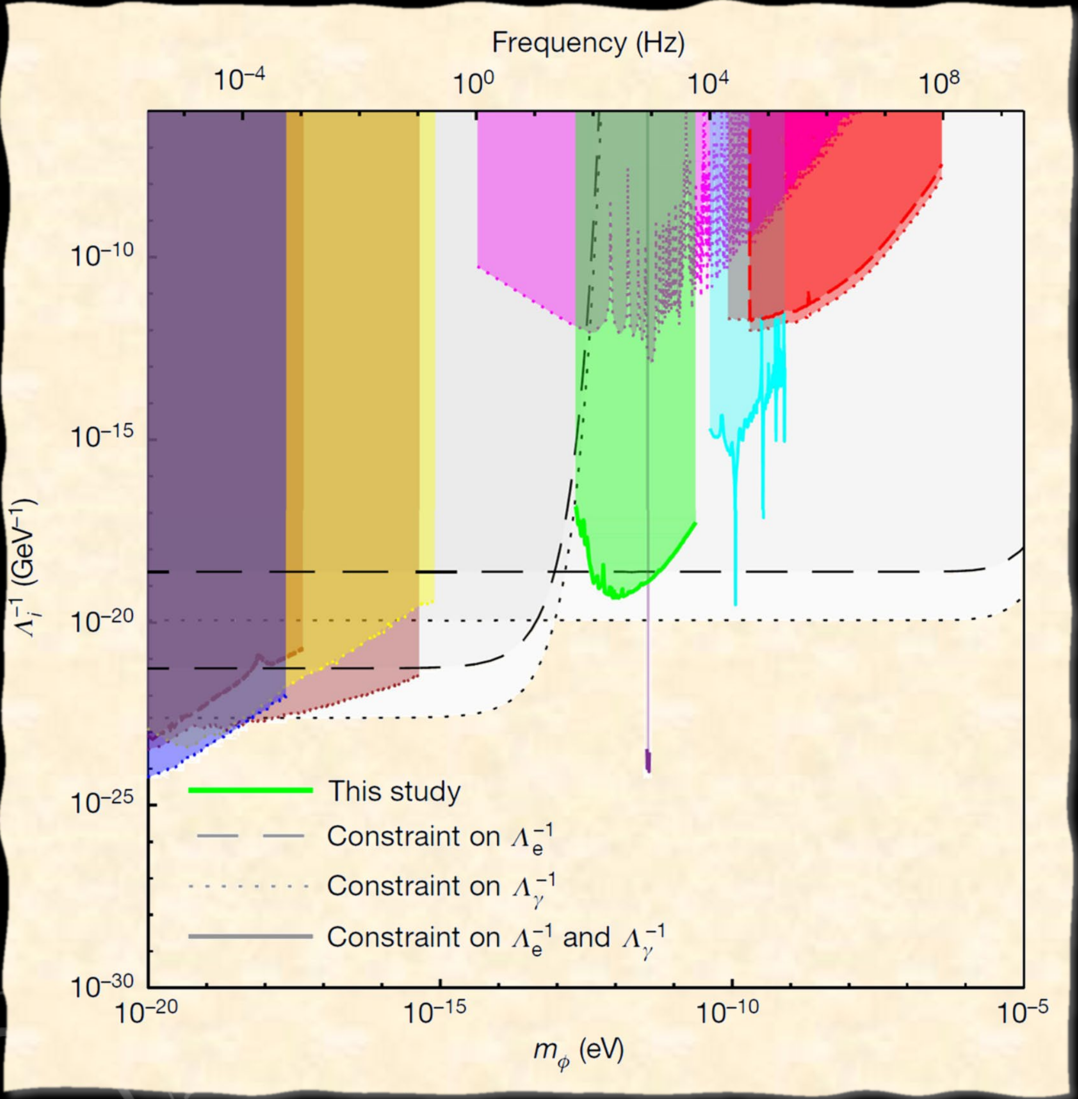
$$h_{\mathrm{DM}}(t) = -\left(\frac{\Delta\alpha(t)}{\alpha} + \frac{\Delta m_e(t)}{m_e}\right)$$

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

A. Modulation of thickness of beamsplitter
   - Can be measured at dark port of Michelson (shown in GEO600)
   - $h_{DM(t)} = \mathcal{G}_{arm} \frac{L_{arm}}{l_{BS}} h_{GW(t)}$

B. Modulation of length of solid reference cavity
   - Can be measured by comparing frequency fluctuations of reference cavities w.r.t. suspended cavities – typically one of the auxiliary channels of a GW detector

GEO600 MEASUREMENT



- Modulation of thickness of beam-splitter can be determined from dark port of Michelson (aka GW channel): $h_{DM(t)} = \mathcal{G}_{arm} \frac{L_{arm}}{l_{BS}} h_{GW(t)}$
- Use variable-binwidth FFTs, identify(+reject) peaks, convert the rest into upper limits

$$\sqrt{\frac{\hbar c^5}{G}}\frac{1}{\Lambda_i} = \sqrt{4\pi}\, d_i$$

Vermeulen, S.M., Relton, P., Grote, H. *et al.* Direct limits for scalar field dark matter from a gravitational-wave detector. *Nature* **600**, 424–428 (2021).

THIS WORK

Advanced LIGO, LISA, and Cosmic Explorer as dark matter transducers

Arxiv:2210.17487

- Modulation of thickness of beamsplitter
  - Can be measured at dark port of Michelson
- Modulation of length of solid reference cavity
  - Can be measured by comparing frequency fluctuations of reference cavities w.r.t. suspended cavities using auxiliary channel in LIGO

WHERE IS THE REFERENCE CAVITY?

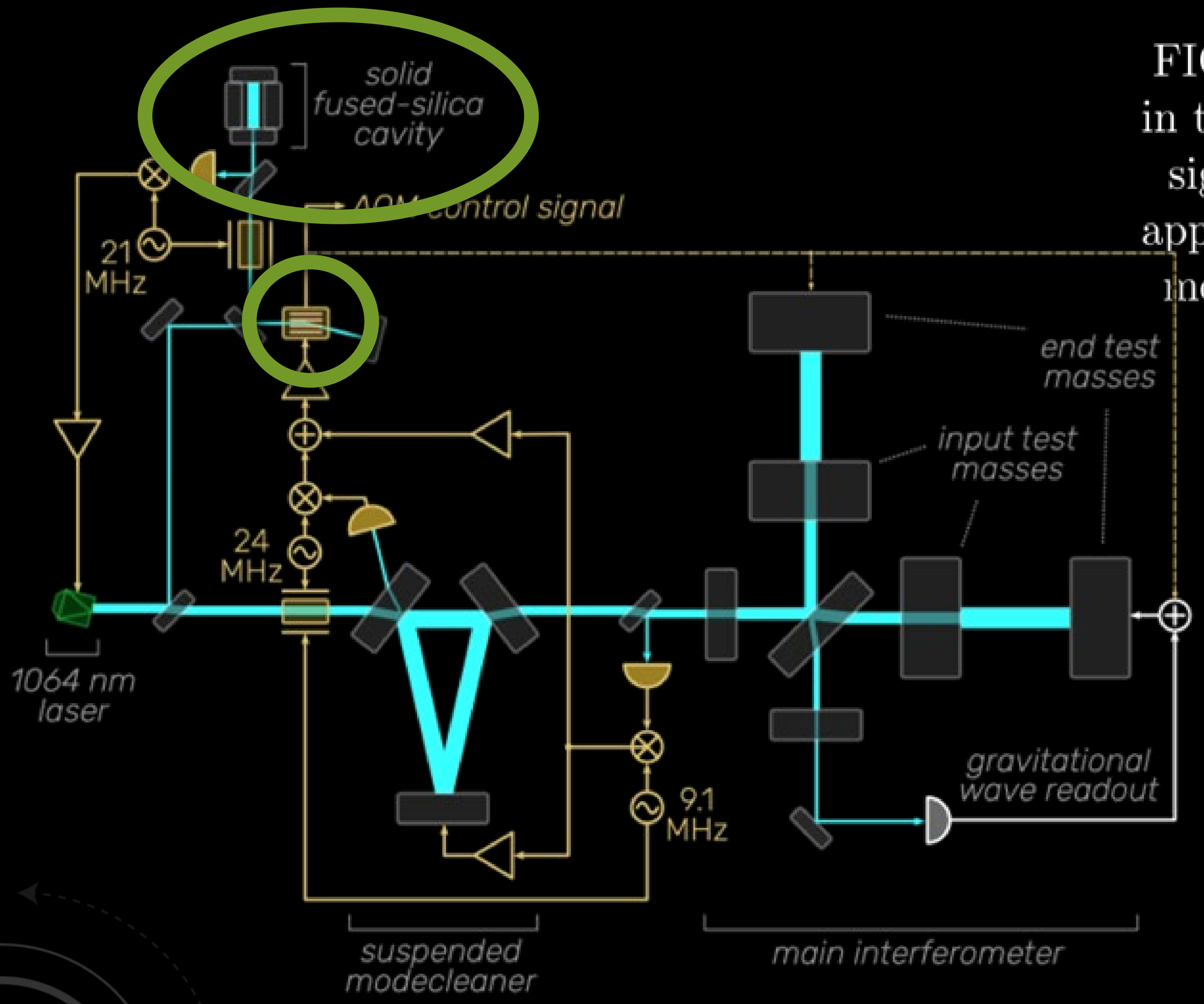
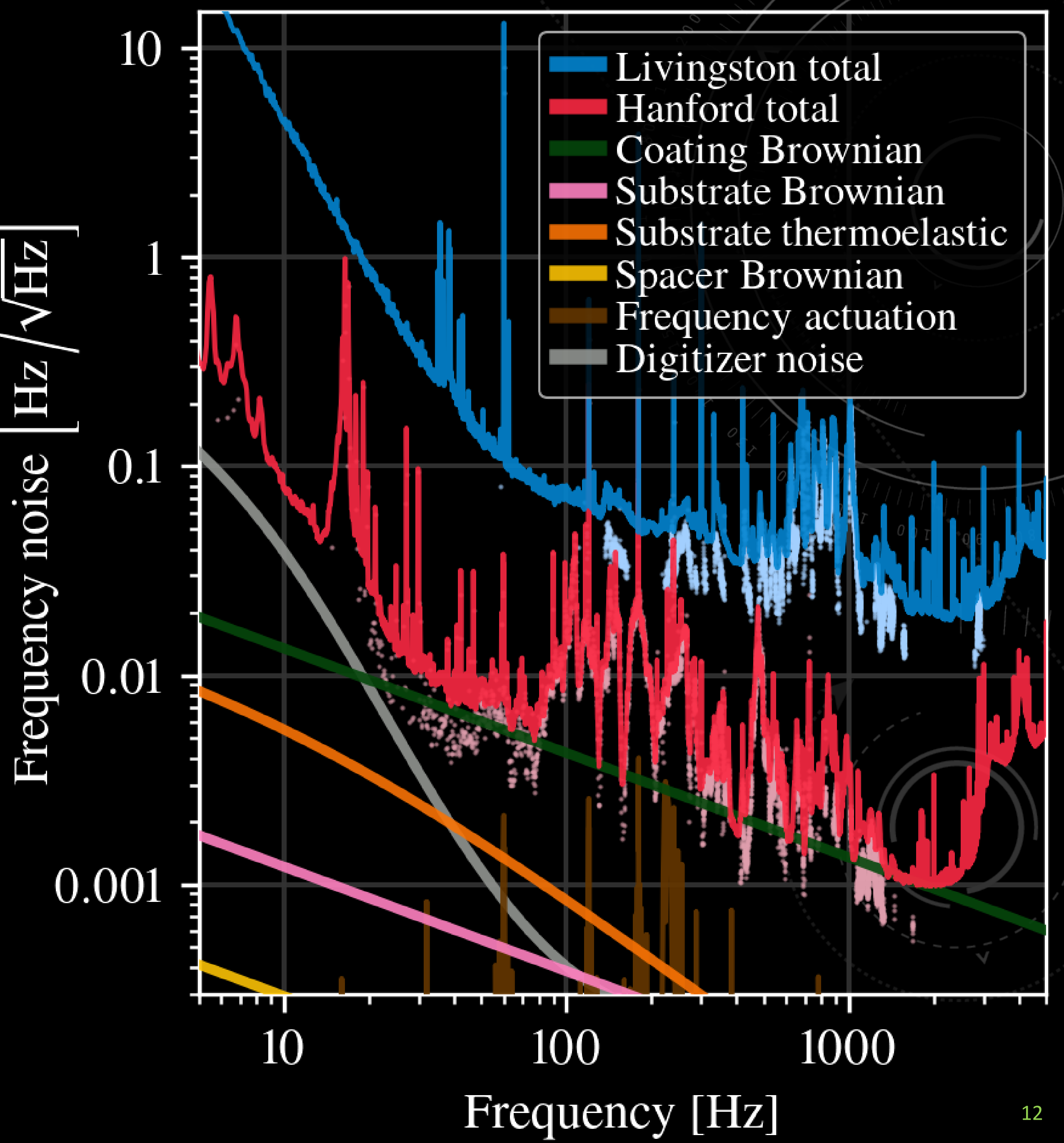


FIG. 1: Advanced LIGO frequency stabilization. Noise in the solid cavity, including noise from any dark matter signal that changes the length of the solid cavity, will appear on the control signal applied to the acousto-optic modulator (AOM). The various noise contributions to this control signal are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

Relative frequency shifts will show up in this auxiliary channel

NOISES IN THE RELEVANT AUXILIARY CHANNEL (AS OF OCT 2022)

- LHO reaches thermal limit at some frequencies
- LLO needs to be improved, potentially by improving couplings with laser table vibration
- LHO and LLO can be cross-correlated to obtain upper limits on DM couplings



REFERENCE CAVITY AND GW DETECTOR PARAMETERS

TABLE I: Parameters deciding thermal noise in solid reference cavities. The current reference cavity parameters are as-built [39]. "Upgraded" parameters are proposed with a modest, achievable upgrade.

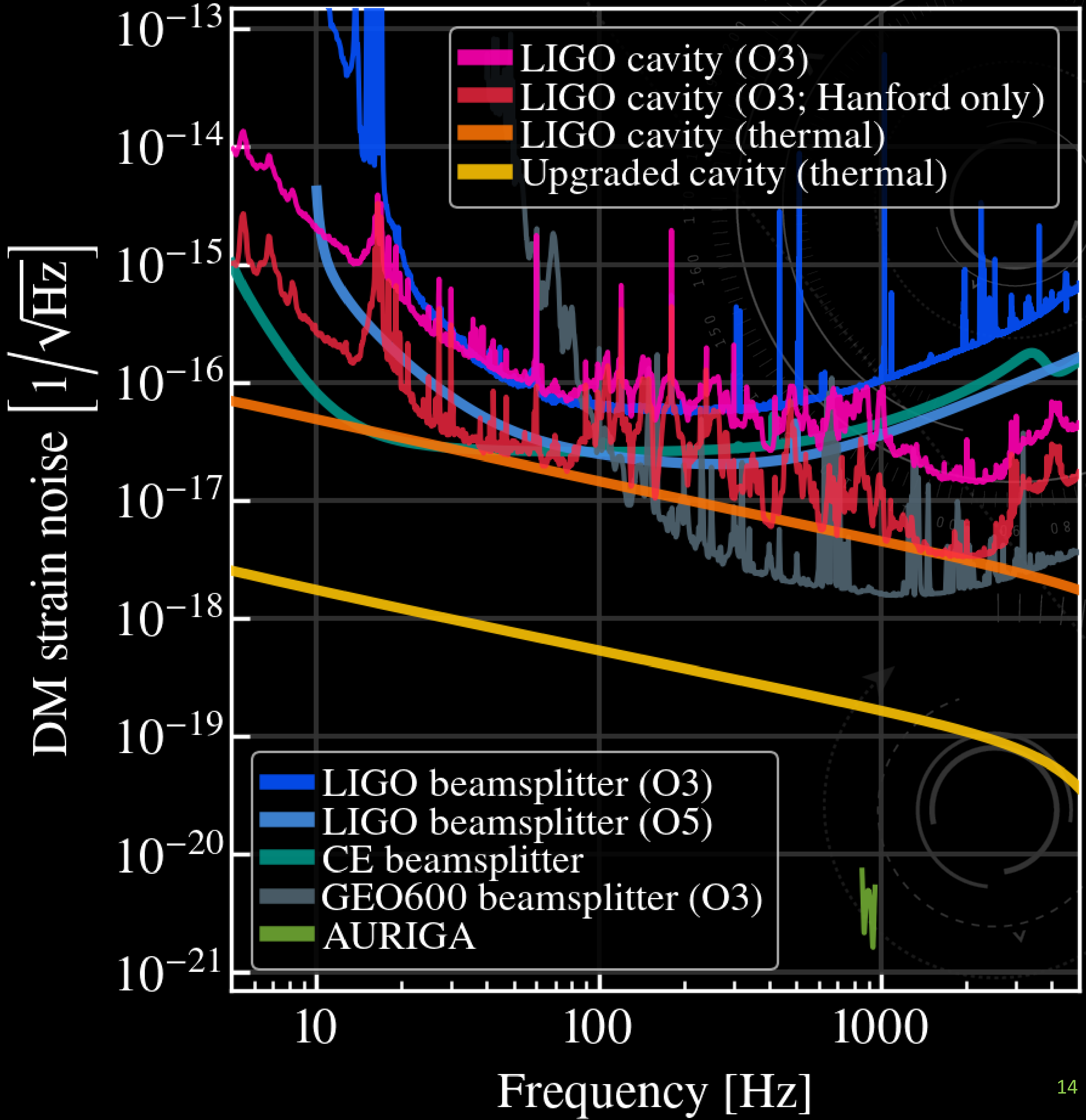
Cavity parameter	Symbol	Current	Upgraded
Length [cm]	$L_{\rm rc}$	20.3	30.0
Beam size [mm]	w	0.29	3.0
Coating loss	ϕ	4.4×10^{-4}	2.2×10^{-4}
Substrate/spacer loss	$\phi_{\rm s}$	10^{-7}	10^{-7}
Coating thickness [μm]	d	4.5	4.5
Wavelength [nm]	λ_0	1064	1064
Temperature [K]	T	300	300
Young modulus [GPa]	E	72	72
Poisson ratio	σ	0.17	0.17
Input power [mW]	$P_{\rm rc}$	10	10
Finesse	$\mathcal{F}_{\rm rc}$	10^4	10^4

TABLE II: Parameters for scalar-field dark matter detection using the beamsplitters of laser interferometric gravitational-wave detectors. The thickness given here is the physical thickness of the beamsplitter, not its effective optical thickness.

	GEO600	LIGO	CE
Beamsplitter thickness [cm]	8	6	6
Arm length [km]	1.2	4	40
Arm gain	1	280	280

EFFECTIVE DM STRAIN NOISE (AS OF OCT 2022)

- LHO and LLO reference cavity cross-correlated (magenta)
- GEO (gray)
- Magenta is better than gray below ~ 100 Hz
- If operated at thermal noise limit, current cavities (orange) are better than O5 and CE beamsplitter, and better than GEO below 100 Hz



FROM STRAIN NOISE TO PROJECTED LIMITS

From noise to DM strain limit:

$$\mathfrak{h}_{\mathrm{DM}} \leq \frac{\sqrt{\rho\, S(\Omega_{\mathrm{DM}})}}{(T\tau_{\mathrm{DM}})^{1/4}}$$

ρ = threshold amplitude SNR (assumed 3)

$S(\Omega_{DM})$ = DM strain noise psd (from cross-correlation or single detector)

T = integration time (assumed 1000 h for ground-based)

τ = DM coherence time (~10^6 cycles)

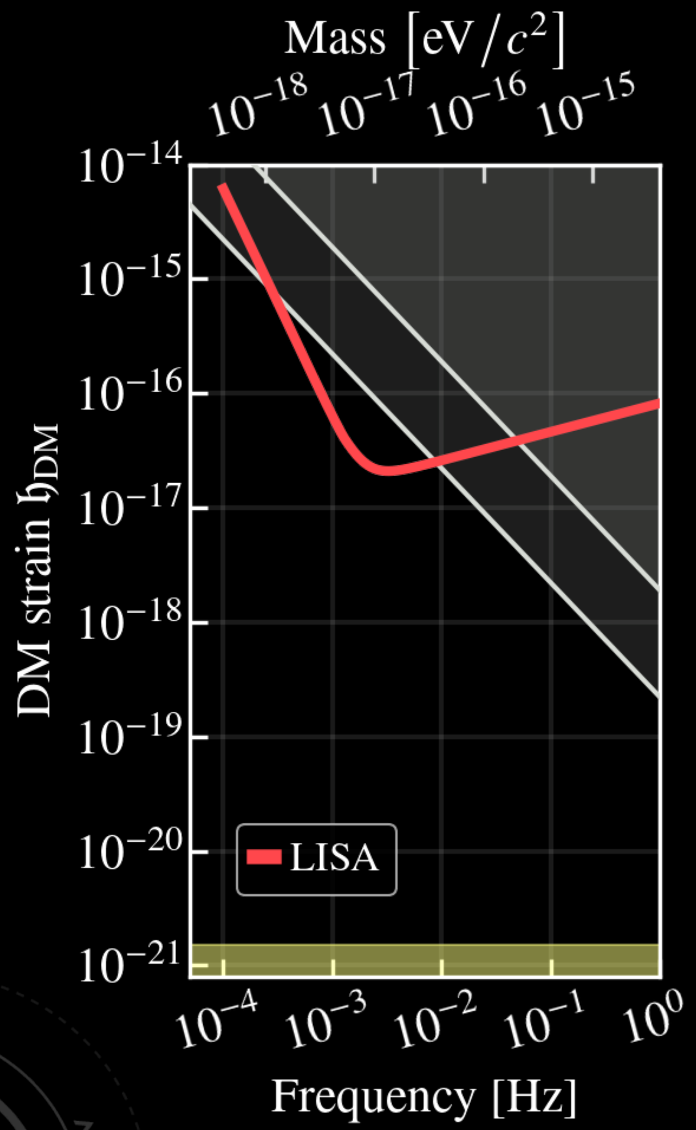
From DM strain limit to DM couping:

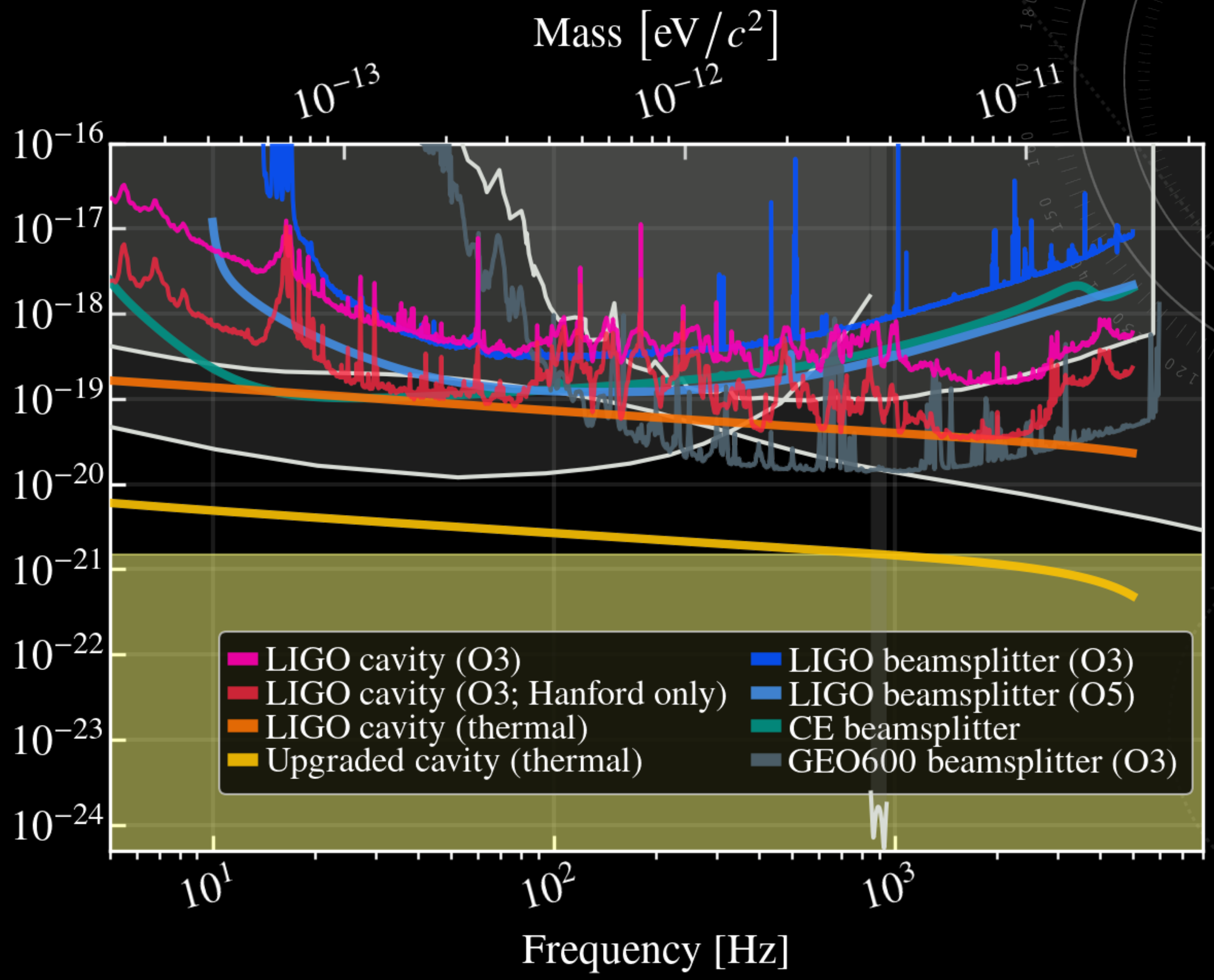
$$A_i \sim d_i \sqrt{8\pi\rho_{\mathrm{DM}} G}\, \frac{\hbar}{m_{\mathrm{DM}} c^3}$$

A_i = strain amplitude limit

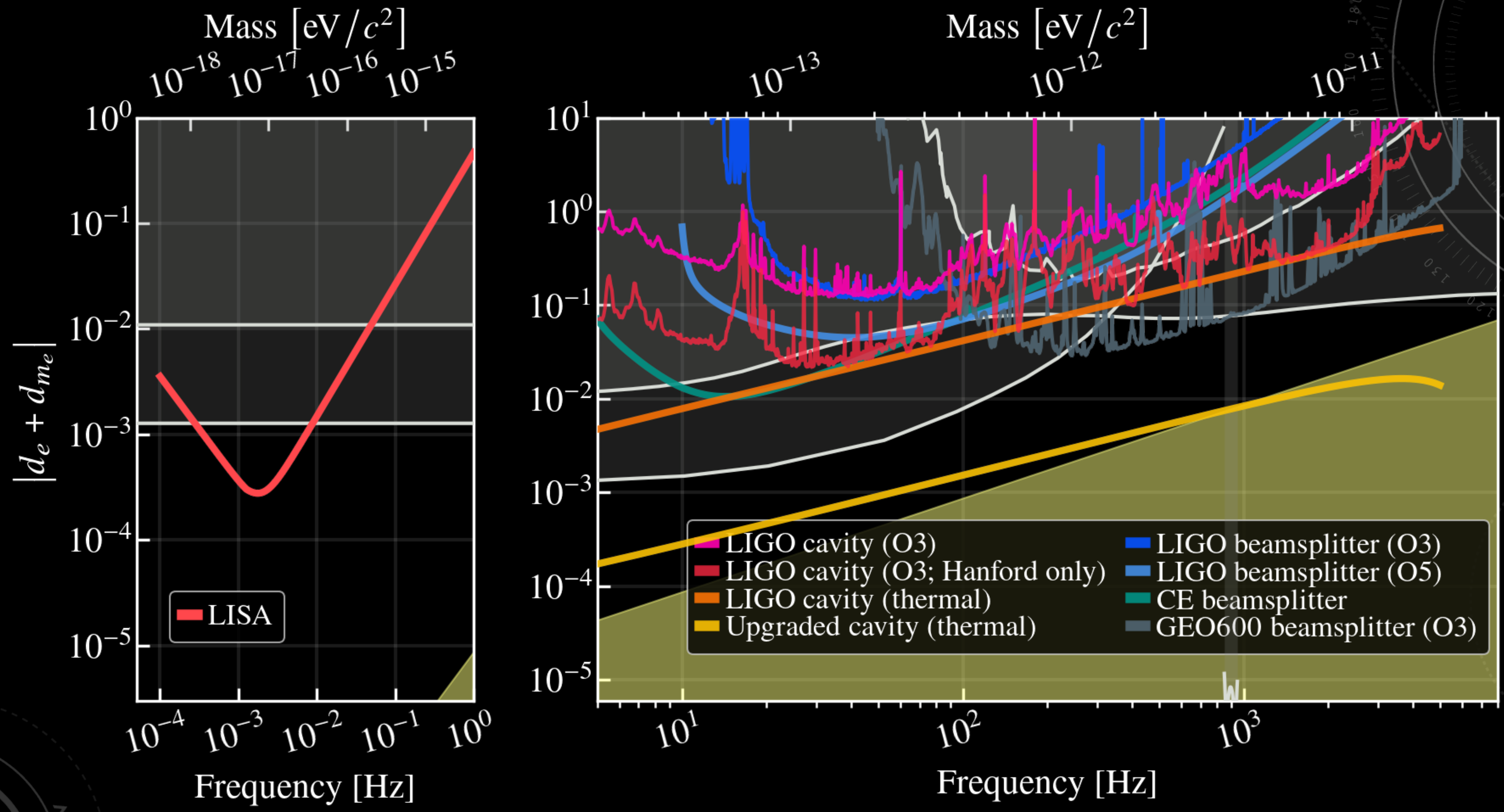
d_i= coupling limit

PROJECTED UPPER LIMITS (STRAIN)



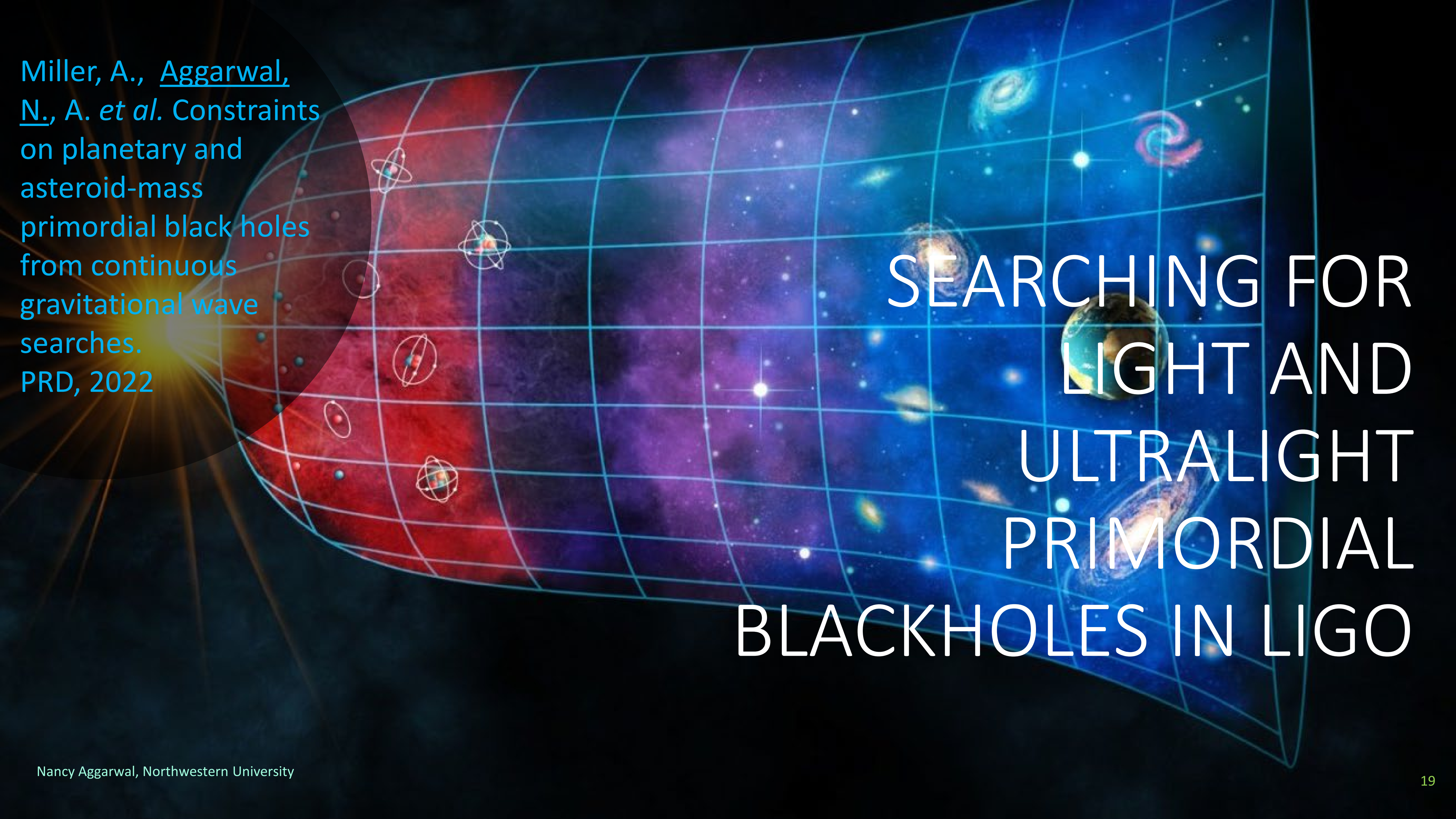


PROJECTED UPPER LIMITS (COUPLING)



PART1: ULTRALIGHT SCALAR DM: SUMMARY/OUTLOOK

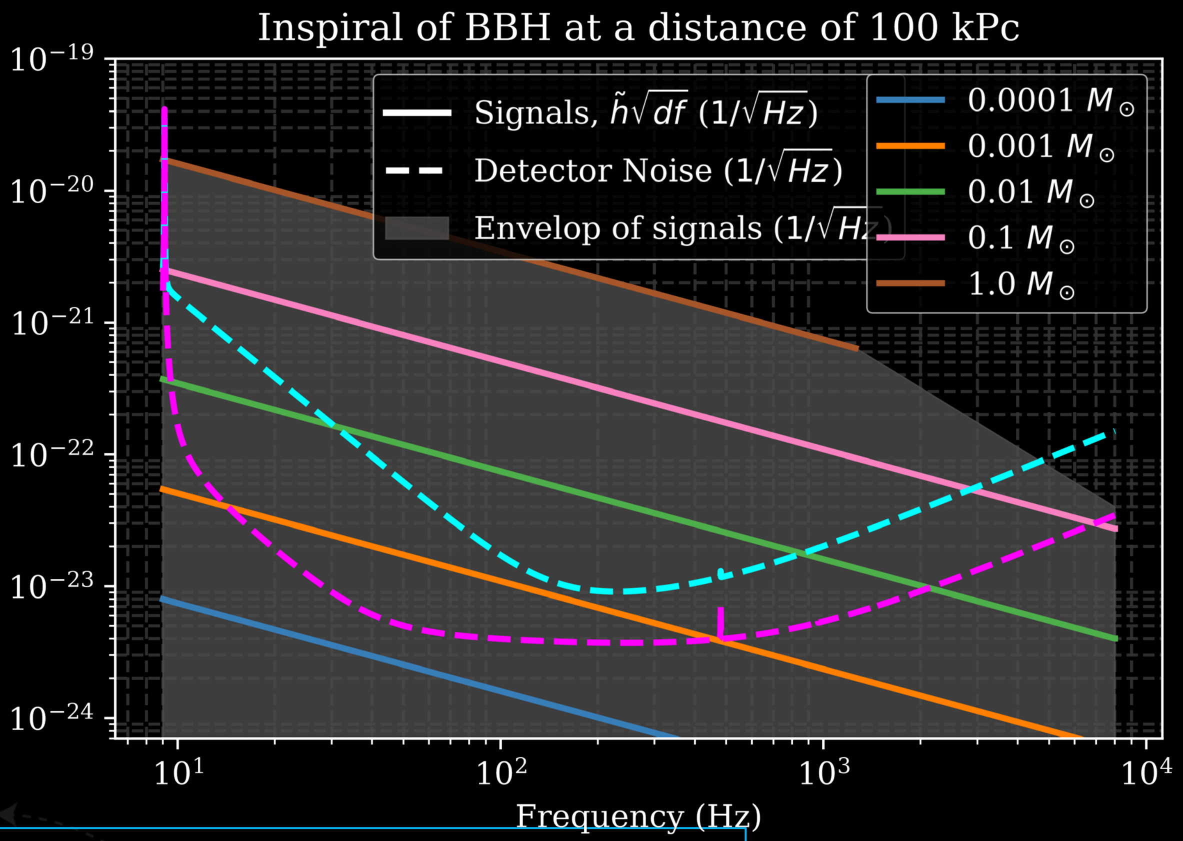
- Competitive limits can be set by analysing O3 data even with the higher noise in LLO
    - Competitive with GEO600 at low frequencies
- Technical noise could be improved in O4 now that there is a compelling science case
- Longer length FFTs maybe used to optimize SNR at low-frequencies
- In the long term,
    - CE BS will set better limits than LIGO beamsplitter
    - there is motivation to swap the refcav with a lower noise cavity, which will set better limits than CE, even with LIGO suspended cavities to probe into the natural d parameter space

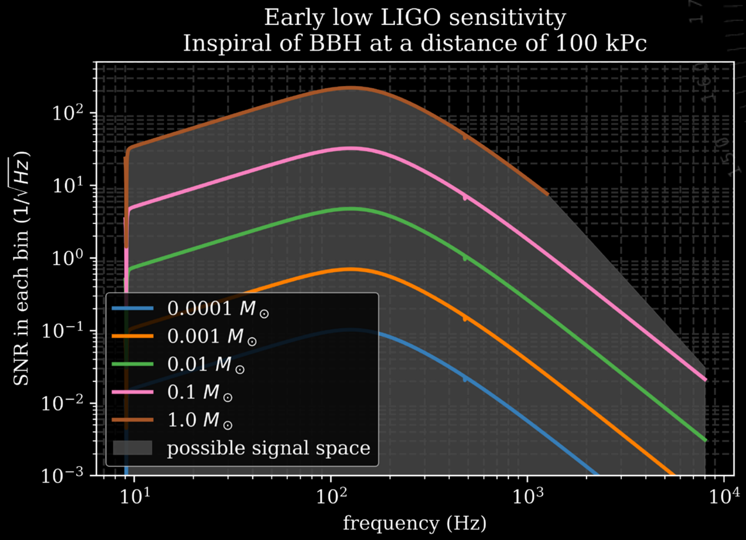


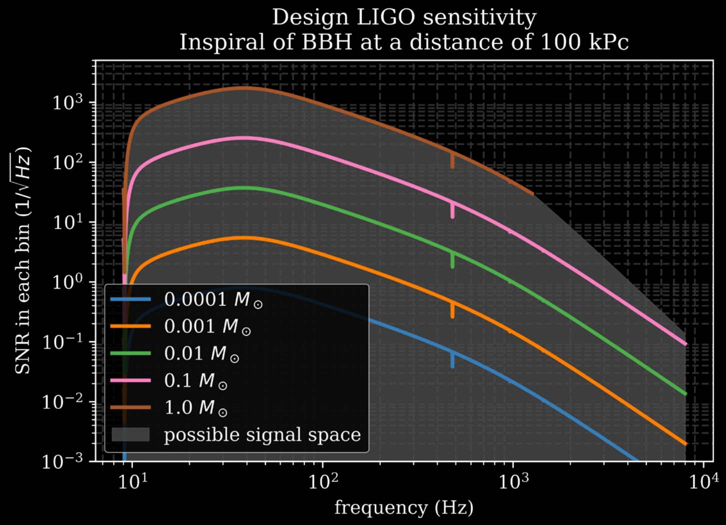
Miller, A., Aggarwal, N., A. *et al.* Constraints on planetary and asteroid-mass primordial black holes from continuous gravitational wave searches. PRD, 2022

SEARCHING FOR LIGHT AND ULTRALIGHT PRIMORDIAL BLACKHOLES IN LIGO

PBH MERGER STRAIN COMPARED TO LIGO NOISE

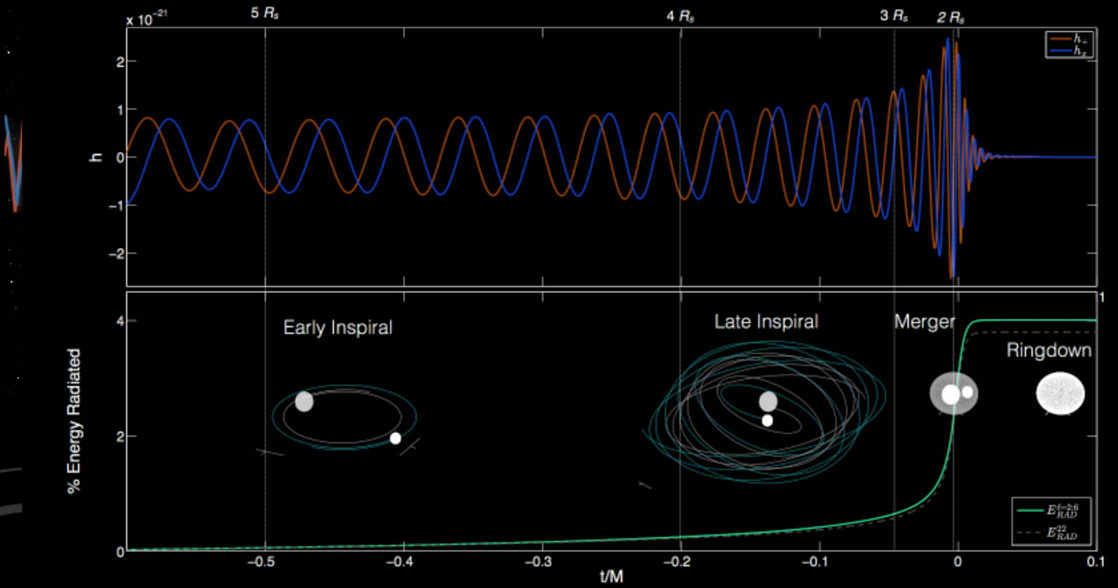






Preliminary: Aggarwal et al. (see LIGO T2000423)

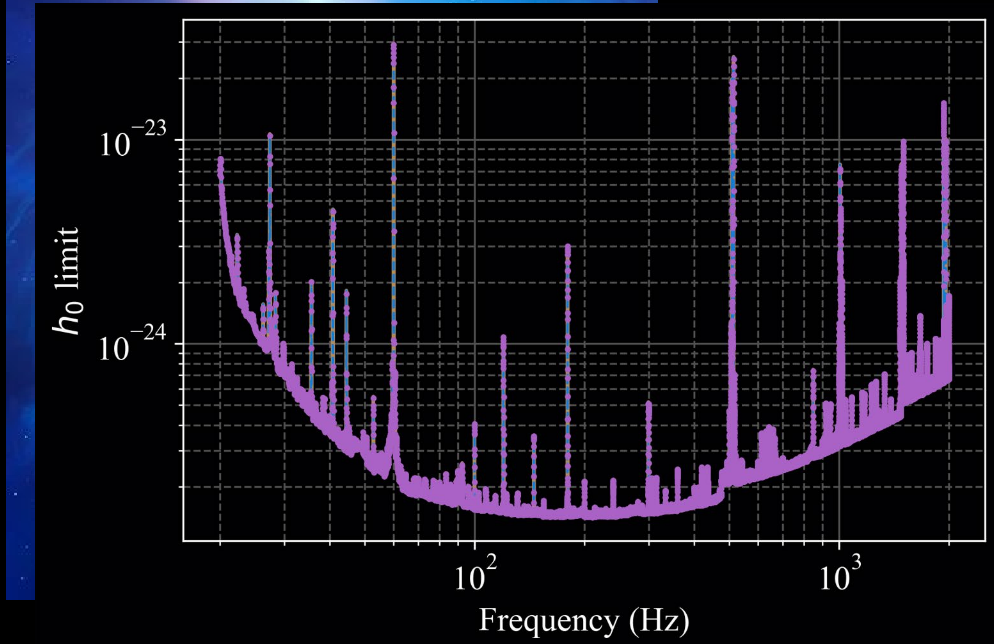
CBC VS CW SEARCHES



Monochromatic GW

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

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



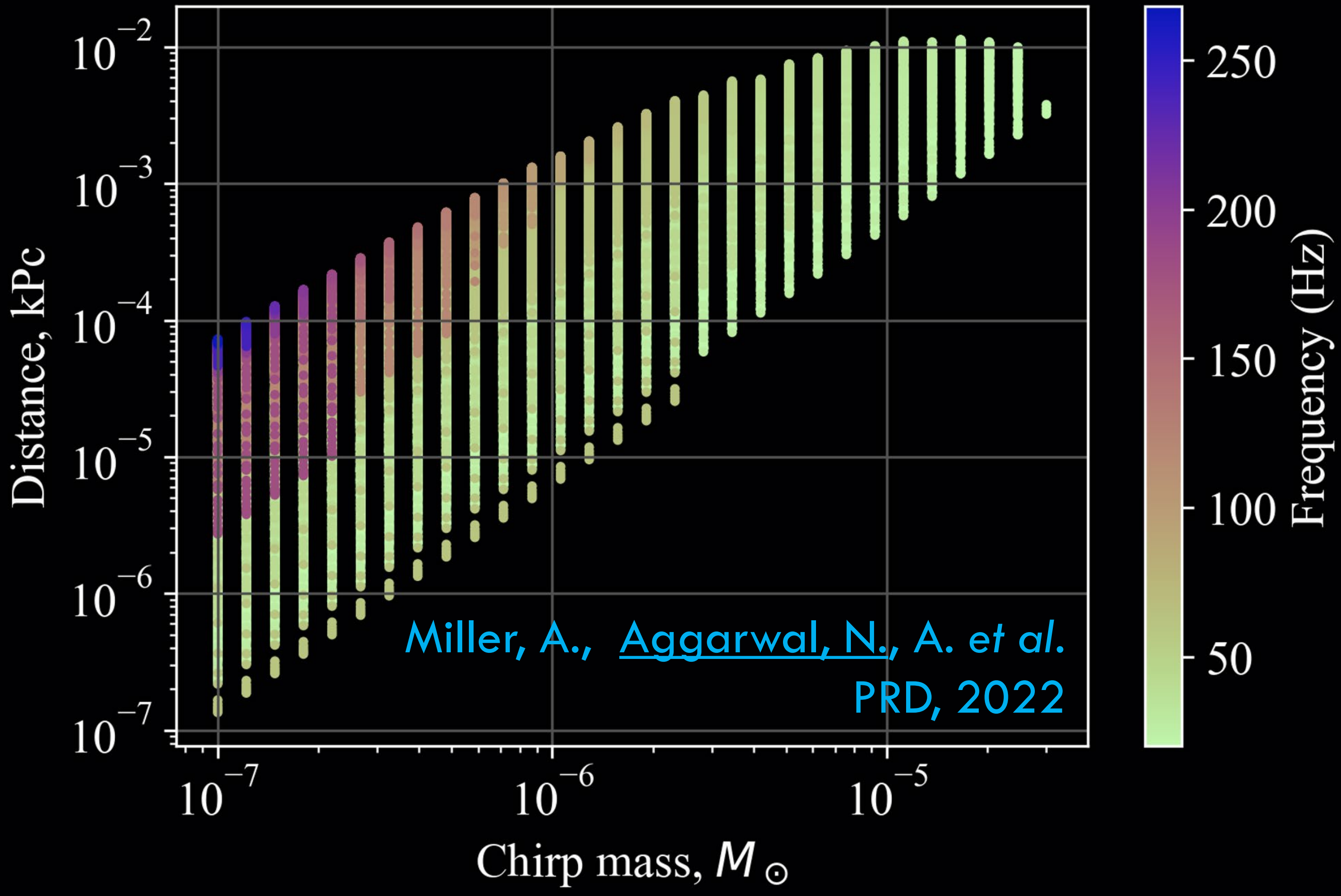
DISTANCE LIMIT FOR M_C AND f_{GW}

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

CW constraints:

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

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



EXCLUSION W/ LIGO

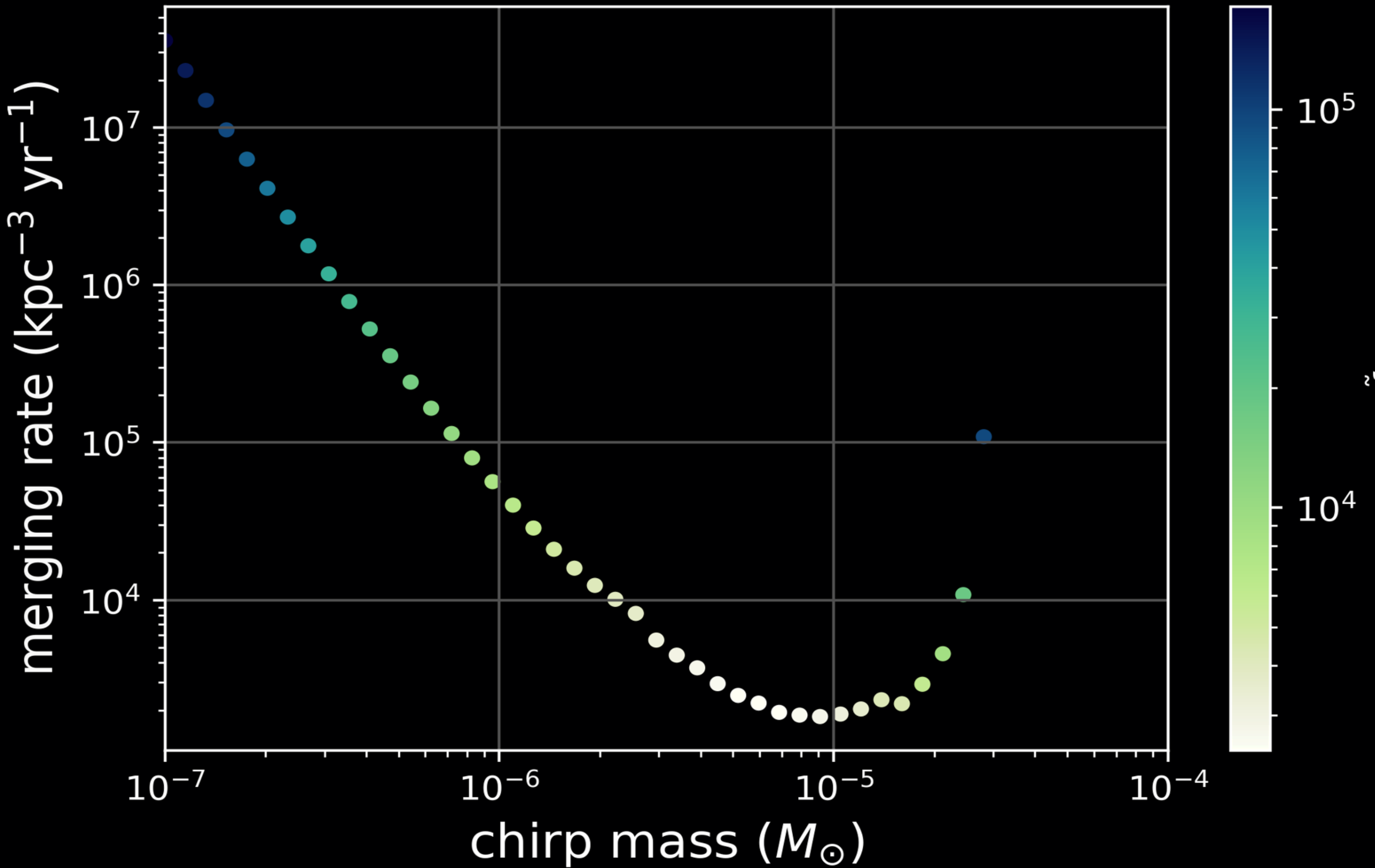
$$N_{\rm bin}(f) \simeq \frac{4}{3}\pi d(f)^3 RT,$$

$$T = \max(T_{obs}, \Delta T)$$

$$N_{\rm bin}^{\rm tot} = \sum_i N_{\rm bin}(f_i)$$

$$R = 1.04 \times 10^{-6}\,{\rm kpc}^{-3}{\rm yr}^{-1} f_{\rm sup} f(m_{\rm PBH})^2 \left(\frac{m_{\rm PBH}}{M_\odot}\right)^{-32/37} (f_{\rm PBH})^{53/37}.$$

$$\tilde{f}^{53/37} \equiv f_{\rm sup} f(m_1) f(m_2) f_{\rm PBH}^{53/37}$$

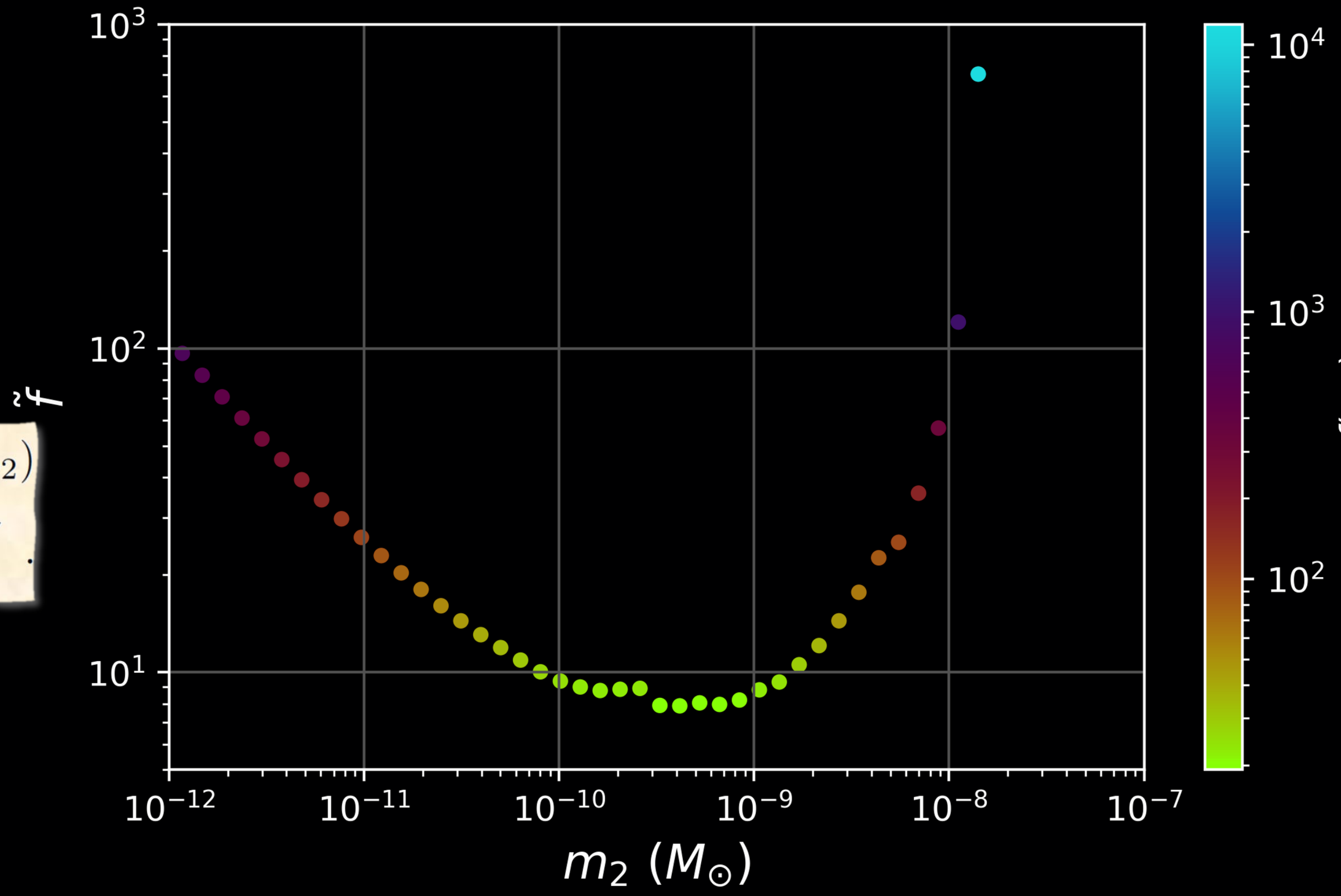


CONSTRAINTS WITH ASYMMETRIC MASS RATIO

$m_1 = 2.5\ M_{\odot}$

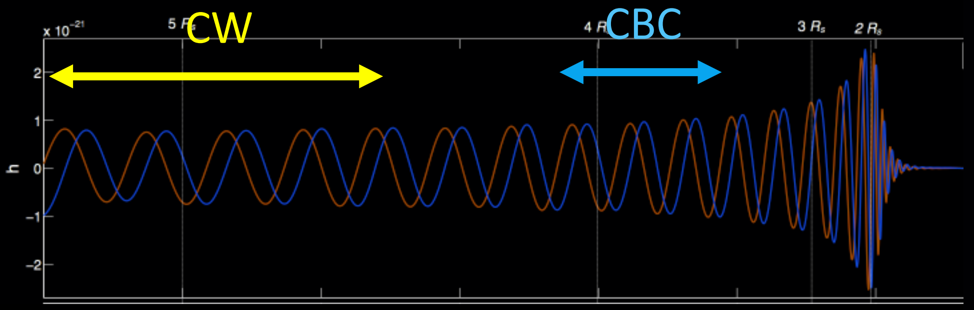
$$R = 5.28 \times 10^{-7}\,\mathrm{kpc}^{-3}\mathrm{yr}^{-1} f_{\mathrm{sup}} f(m_1) f(m_2) \left(\frac{m_1}{M_\odot}\right)^{-32/37} \left(\frac{m_2}{m_1}\right)^{-34/37} (f_{\mathrm{PBH}})^{53/37}.$$

For $f(m_2)$:
$f(m_1) \approx f_{PBH} \approx 1$

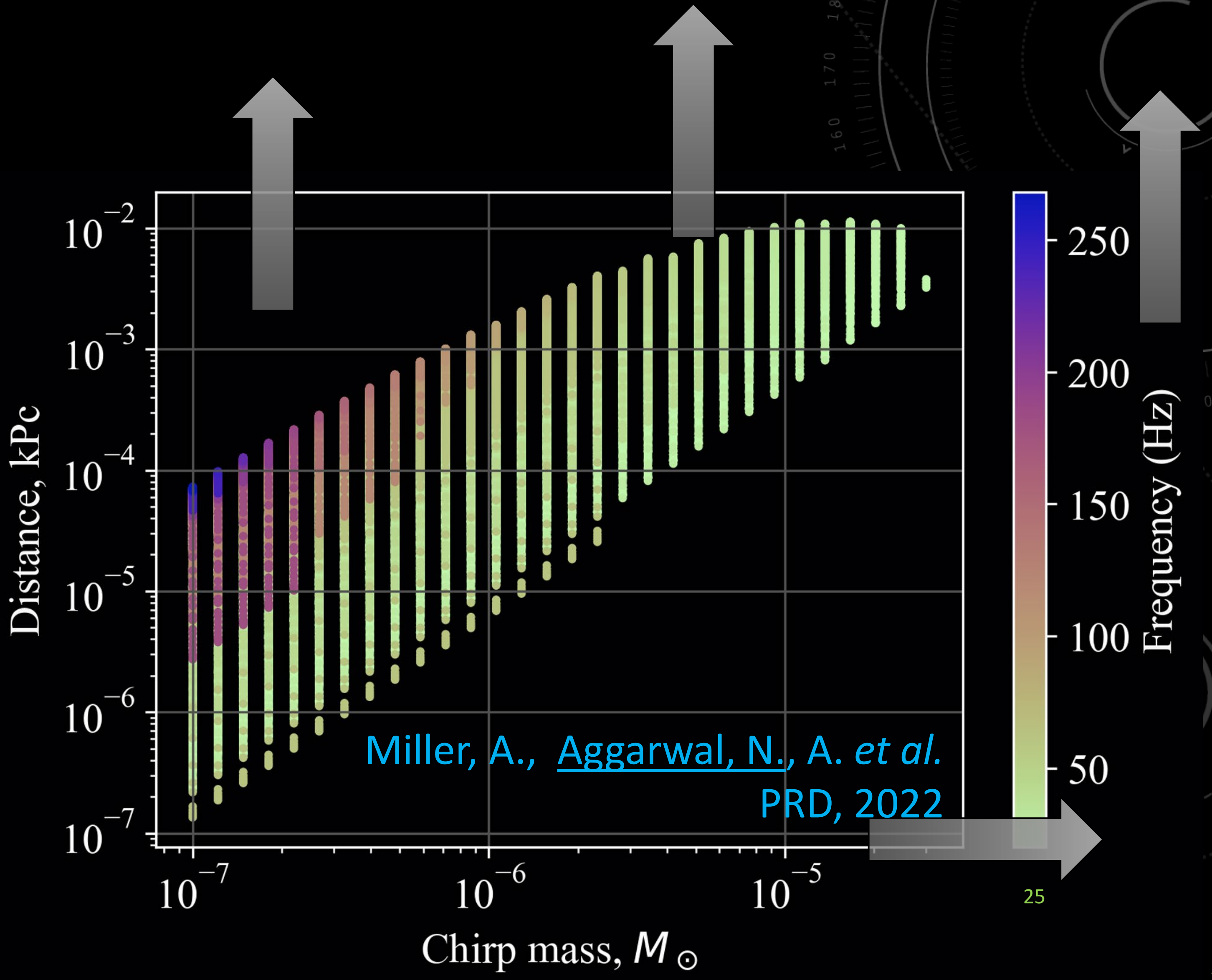


IMPROVED UPPER LIMITS ON PBHS

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



PART2: PBH IN LIGO: SUMMARY/OUTLOOK

1. Method to interpret continuous-wave constraints from LIGO into constraints for primordial blackholes
2. Current CW searches are designed for pulsars, so limited to linear frequency evolution and small f-dot
3. Work ongoing to extend CW searches to higher spin-ups
4. Work ongoing to place constraints on the higher-frequency part using matched-filtering searches
5. Work ongoing to combine CBC and CW constraints

THANK YOU

ALSO SEE ARXIV 2011.12617, 2010.13157 FOR OTHER DARK MATTER PROJECTS

SPARE SLIDES

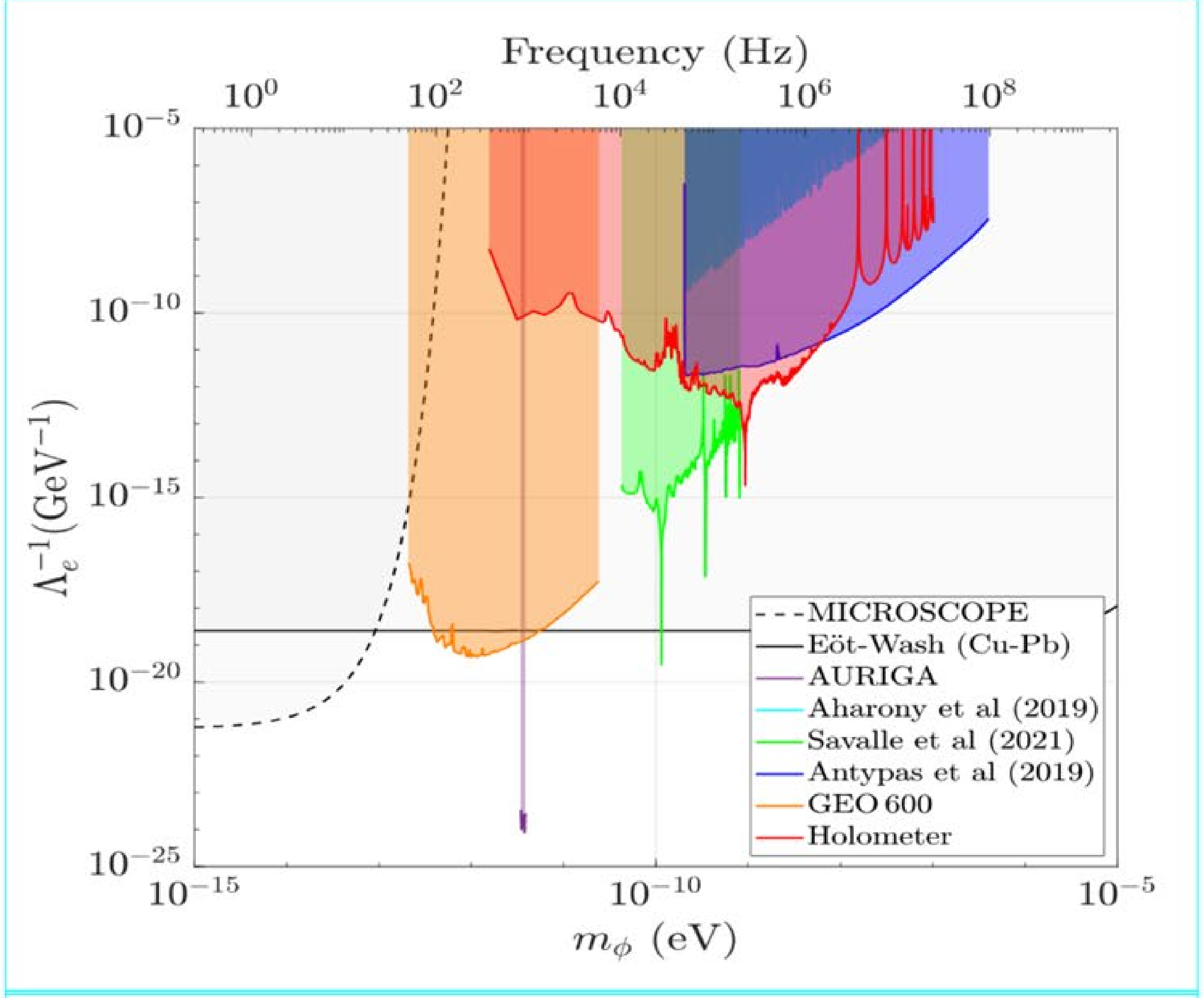
PART1: DILATON DM: OUTLINE

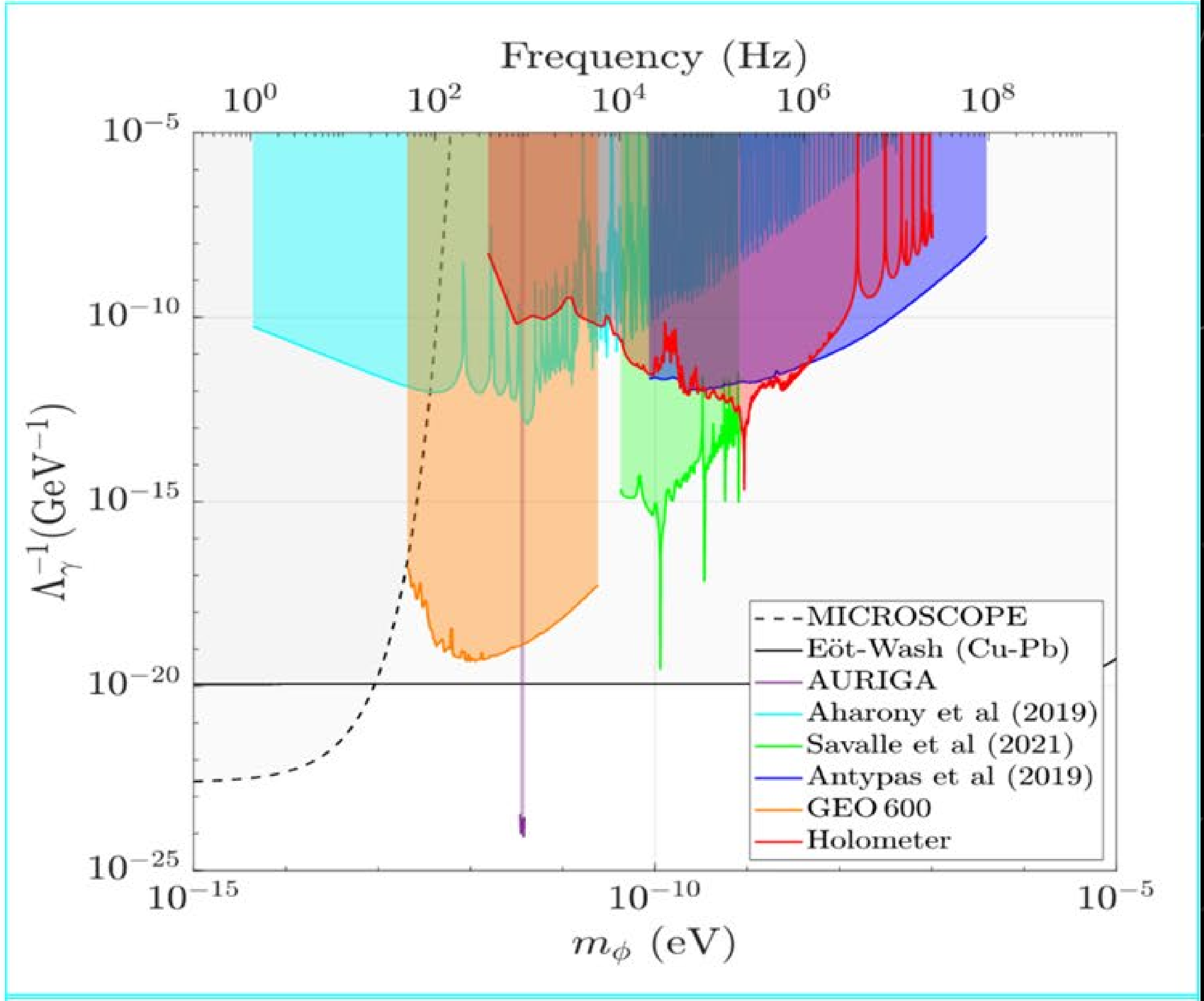
1. The candidate signal
2. Previous limits
3. Our method using auxiliary channel in LIGO
4. Possible limits from LIGO's third observing run
5. Performance with lowering noise in current system, upgraded system, LISA
6. Possible limits from using normal GW channel in O3, O4, O5, CE

COMPARING GEO VS LIGO BEAMSPLITTER

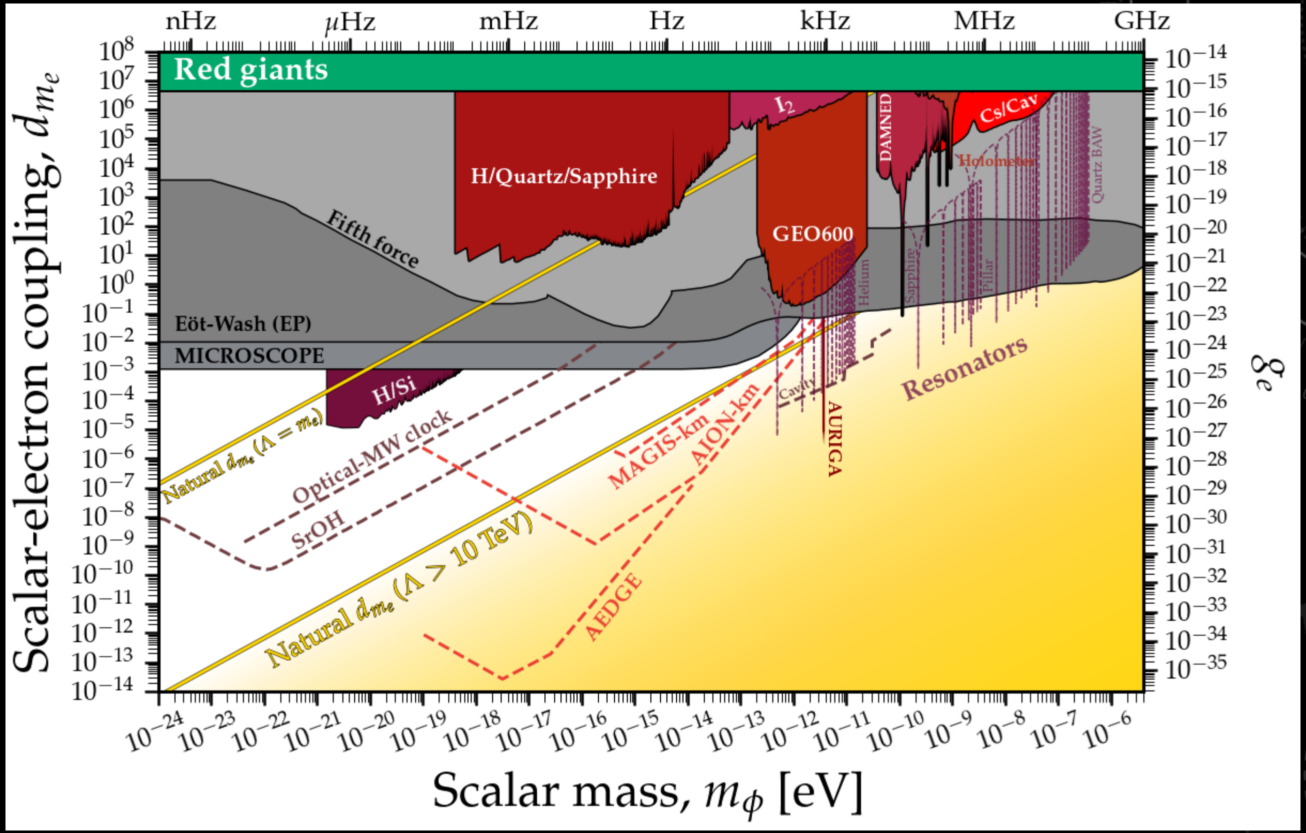
- $h_{DM(t)} = \mathcal{G}_{arm} \frac{L_{arm}}{l_{BS}} \; h_{GW(t)}$
- LIGO has better h_GW, but GEO has no arm cavities, and thicker beam splitter

HOLOMETER (2108.04746)





BROADER LANDSCAPE (GITHUB:CAJOHARE/AXIONLIMITS)



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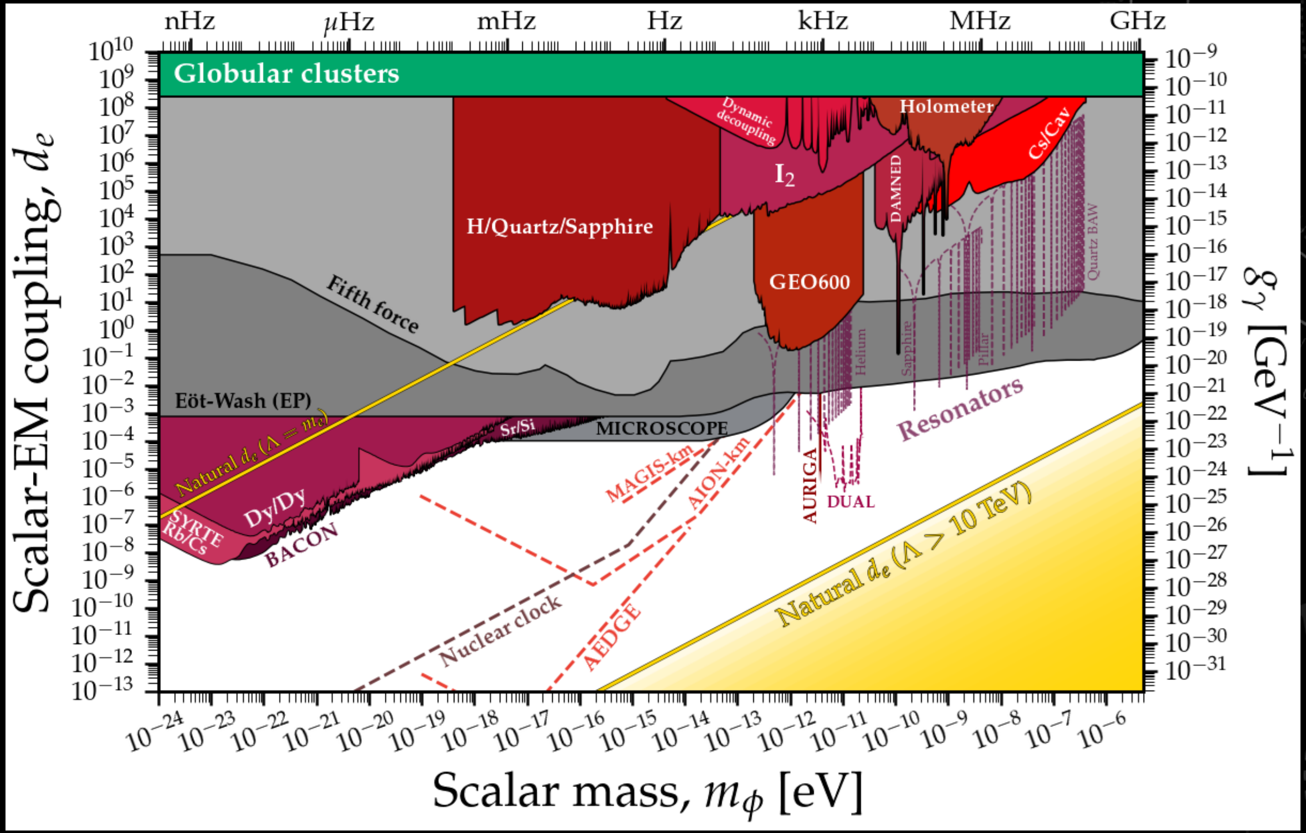
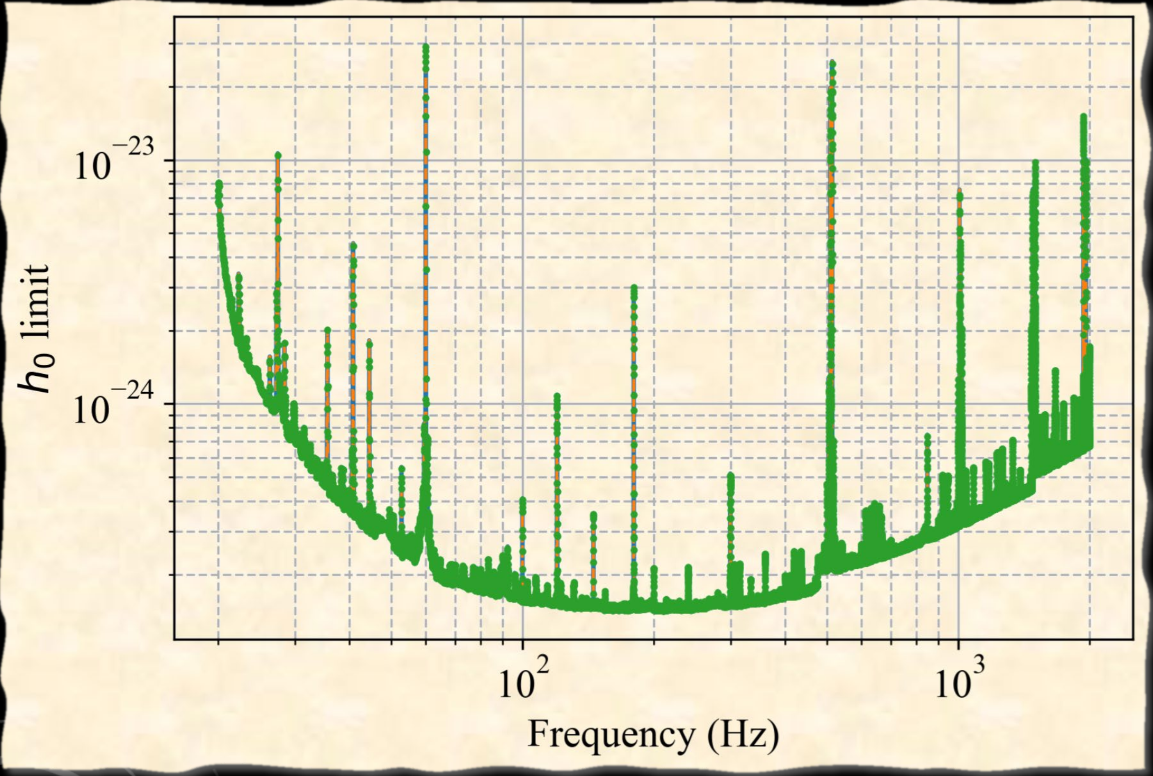
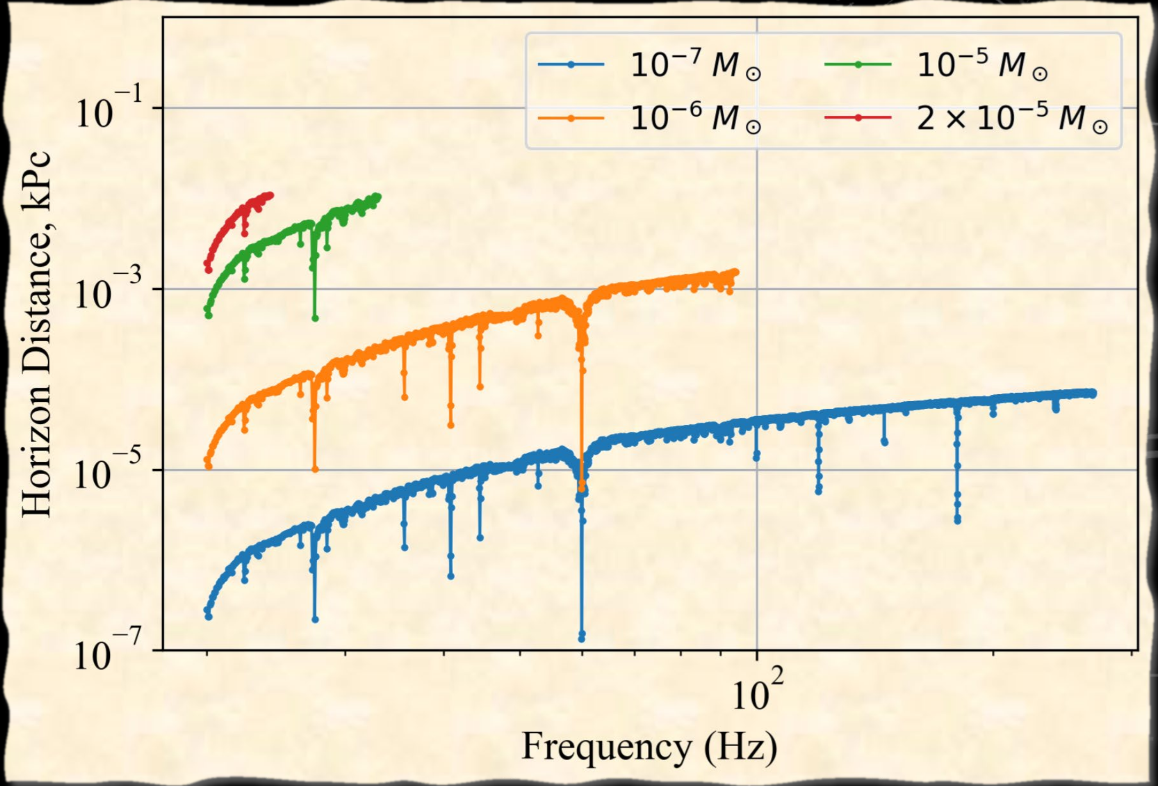


CW SEARCH CONSTRAINTS

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

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



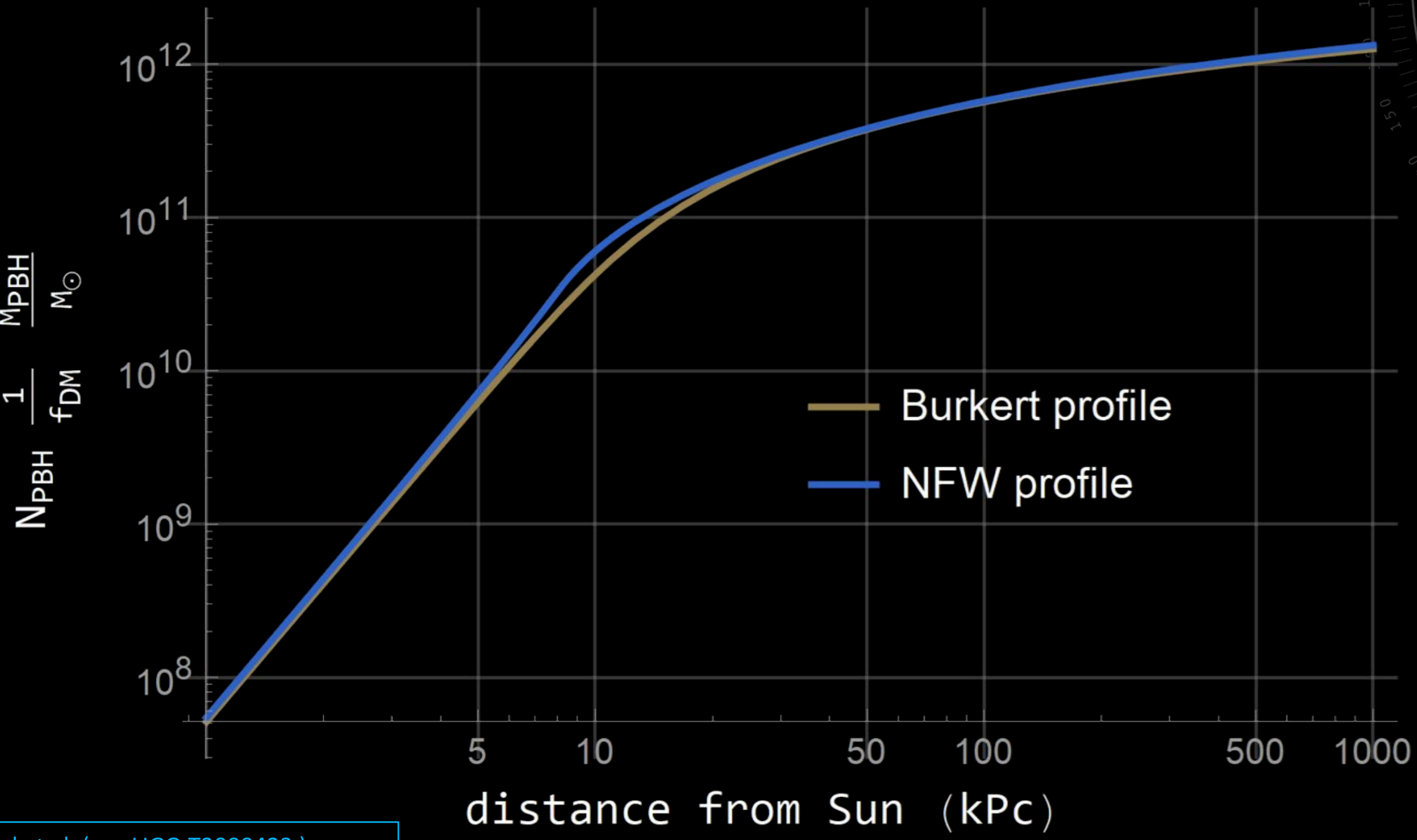


MERGER RATE FULL EXPRESSION

$$R^{\cos}_{\rm prim} \approx \frac{1.6\times 10^{6}}{\rm Gpc^3 yr} f_{\rm sup} f_{\rm PBH}^{53/37} \left(\frac{m_1+m_2}{M_\odot}\right)^{-32/37} \times \left[\frac{m_1 m_2}{(m_1+m_2)^2}\right]^{-34/37} f(m_1) f(m_2)\ ,$$

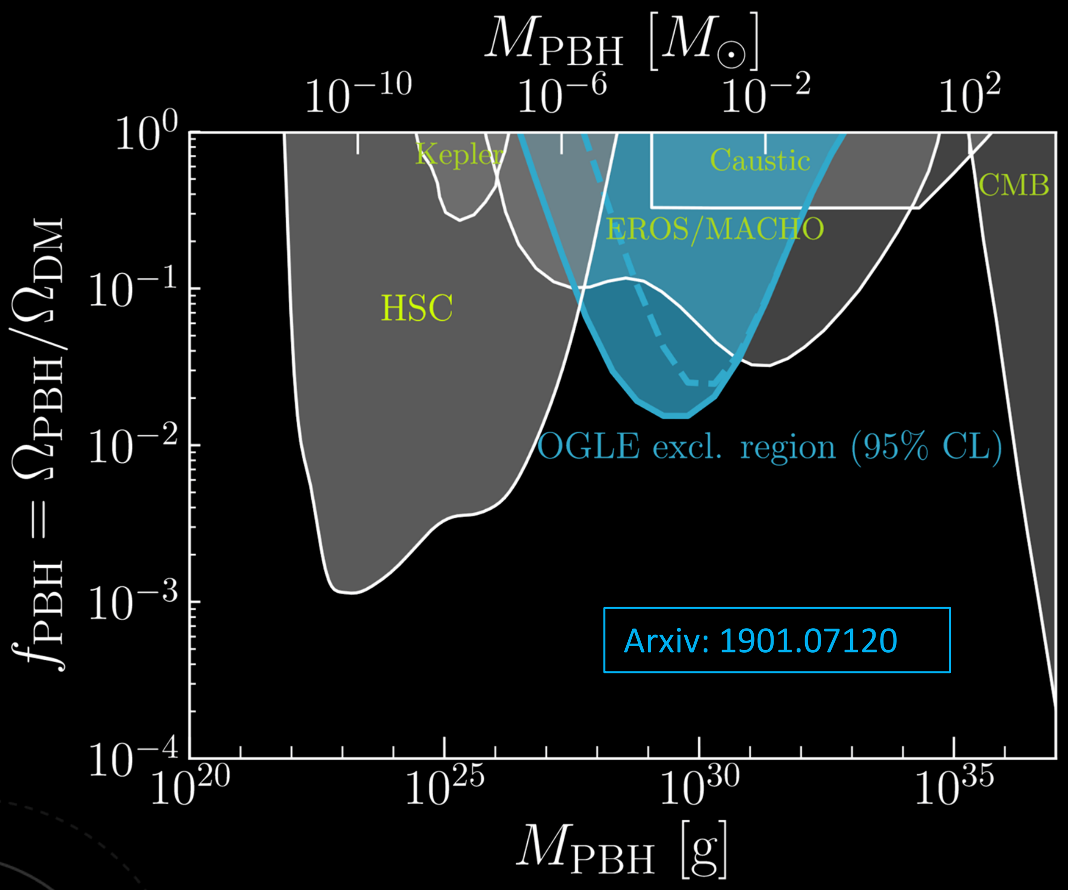
$$R = 3.3\times 10^{5} R^{\cos}_{\rm prim}$$

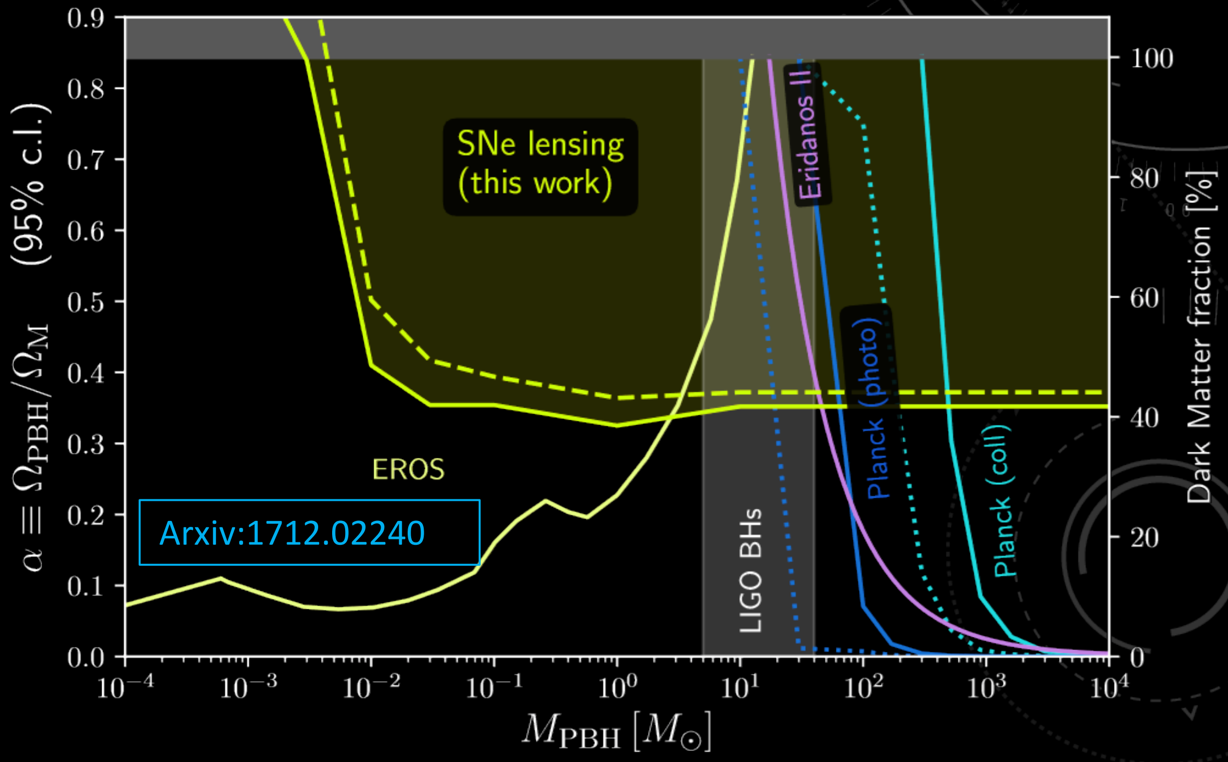
NUMBER OF PBHS IN THE MILKY WAY



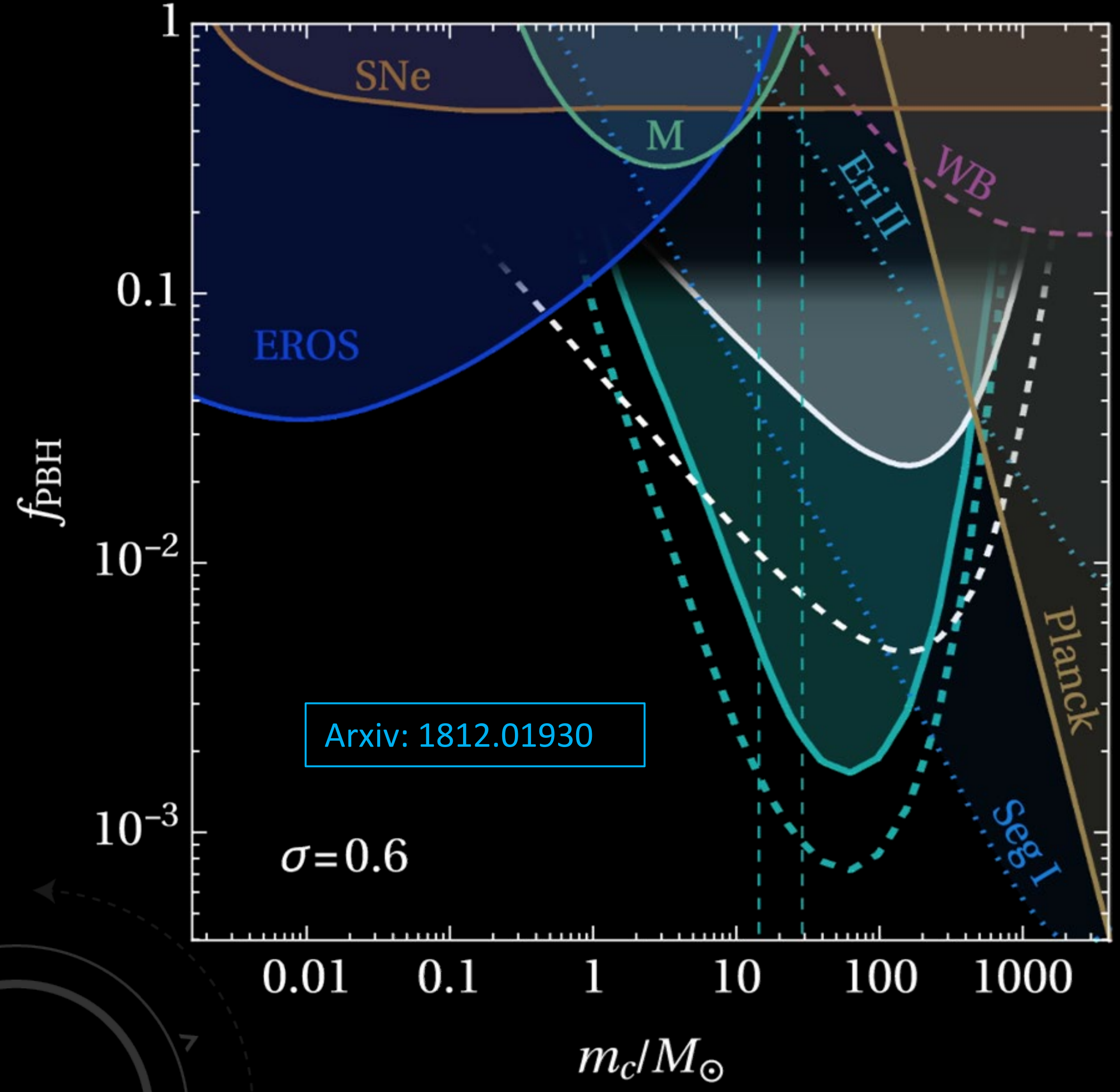
Preliminary: Aggarwal et al. (see LIGO T2000423)

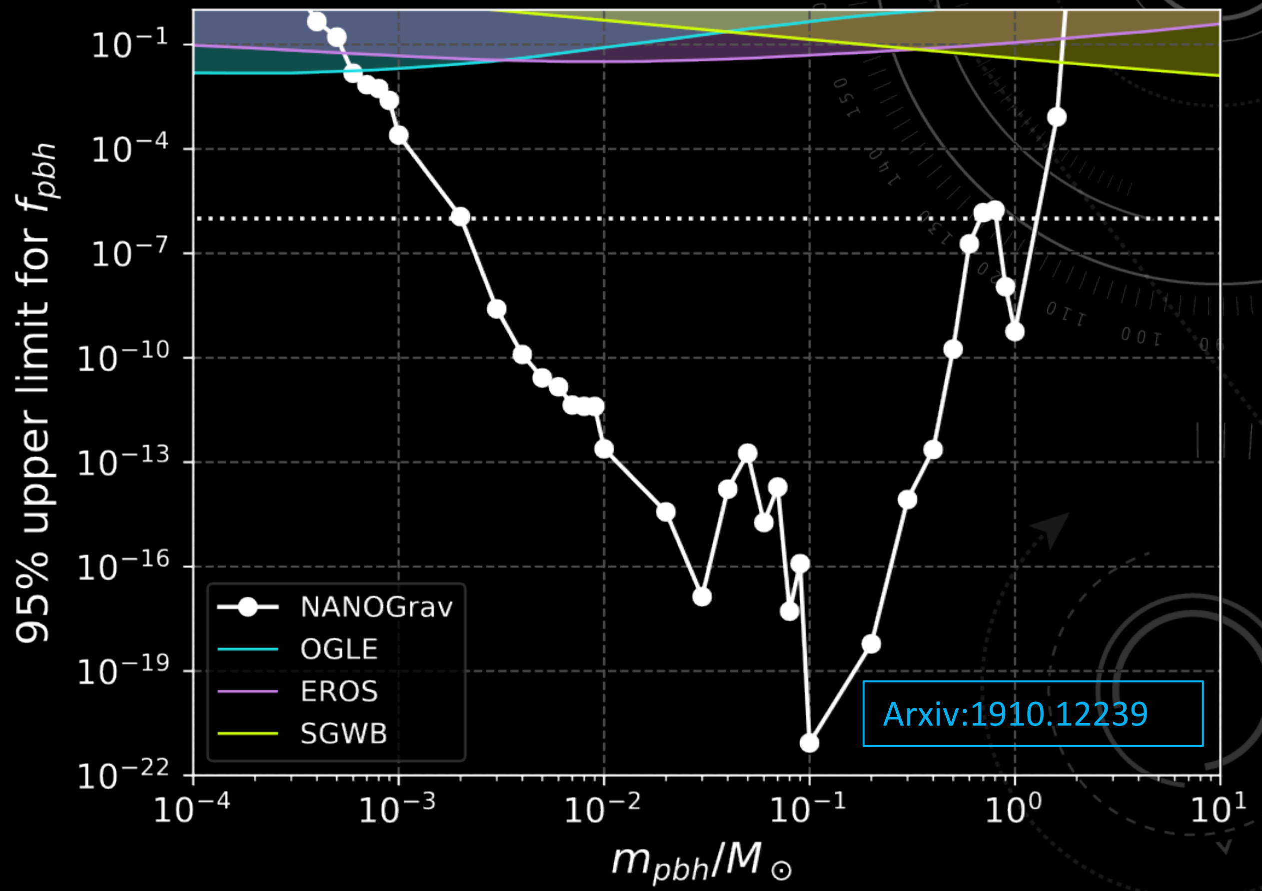
MICROLENSING AND SN LIMITS ON PBHS

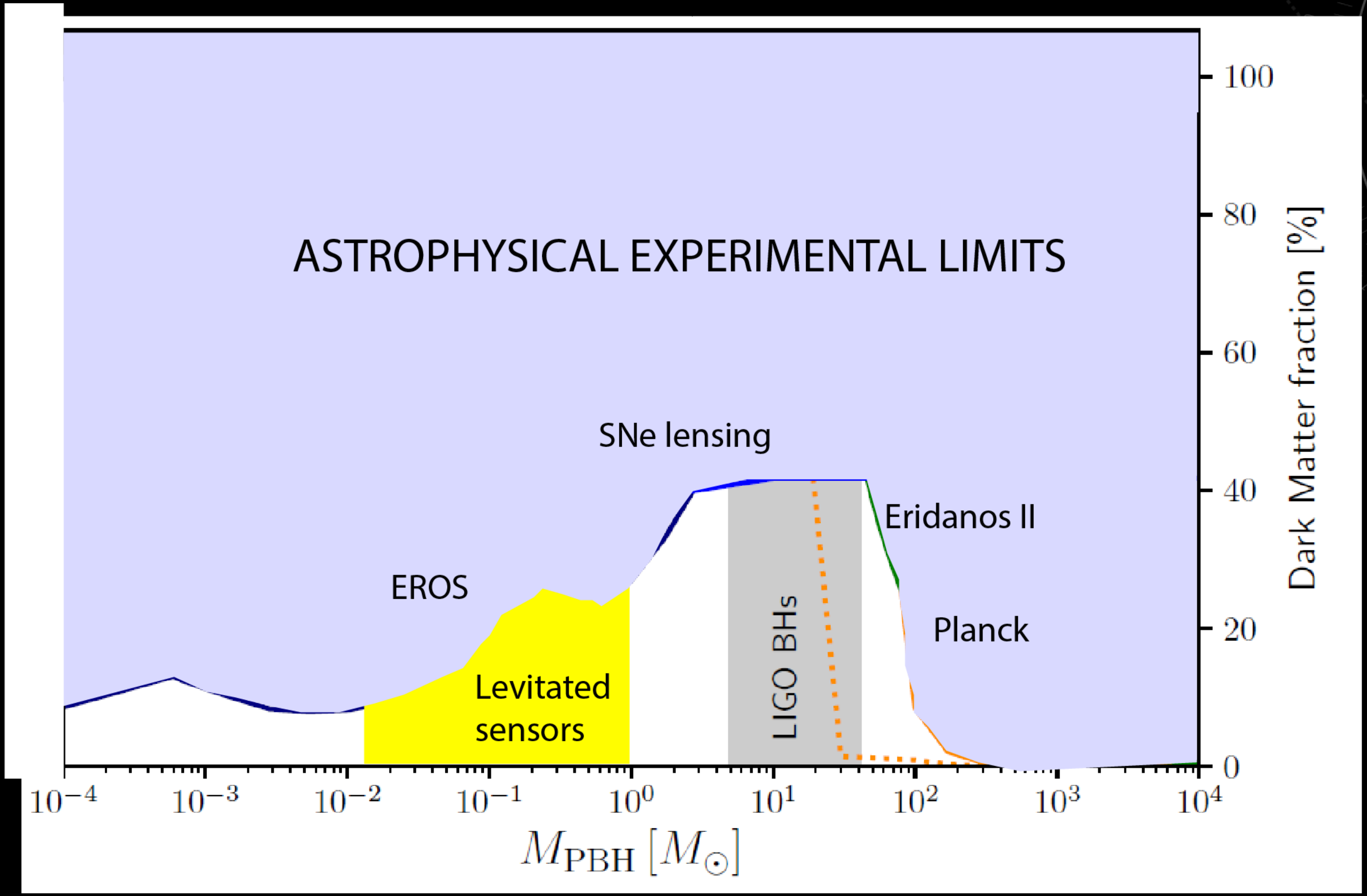




LIMITS ON PBHS USING GWS

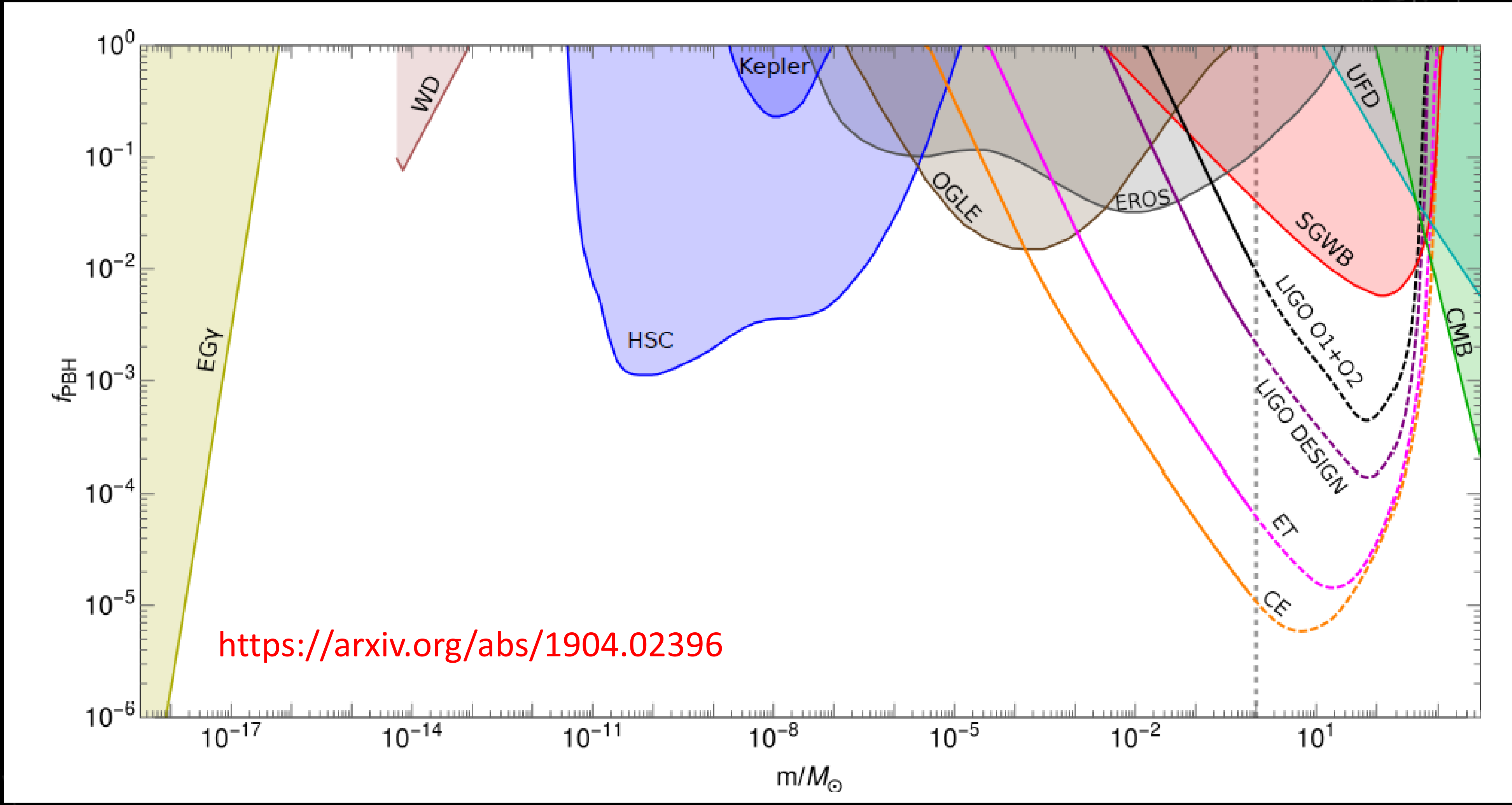


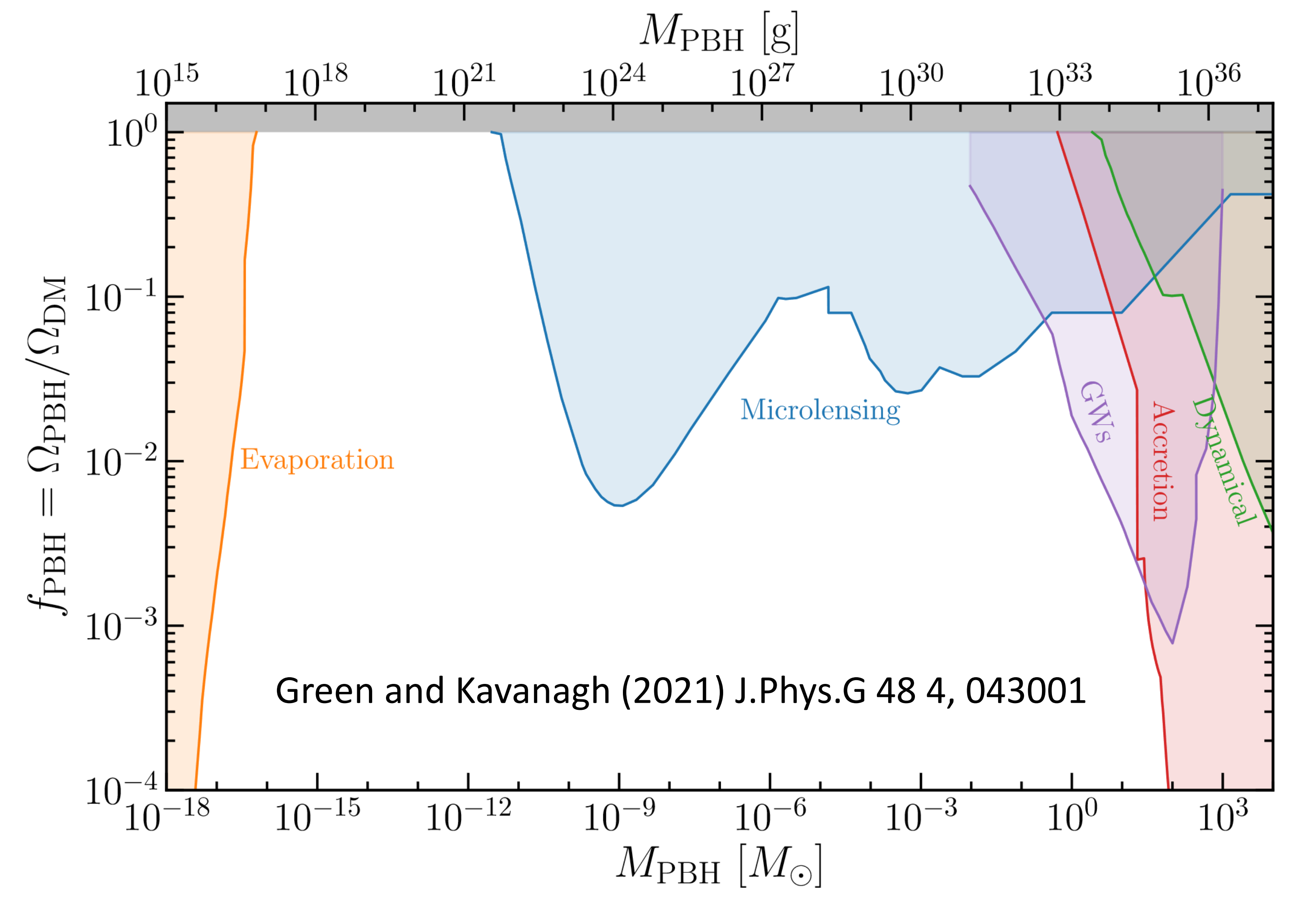




ASTROPHYSICAL EXPERIMENTAL LIMITS
SNe lensing
Eridanos II
EROS
Planck
Levitated sensors
LIGO BHs
100
80
60
40
20
0
Dark Matter fraction [%]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
M_{PBH} [$M_{\odot}$]

DISTINGUISHING PBHS FROM ASTROPHYSICAL BHS BY EINSTEIN TELESCOPE AND COSMIC EXPLORER





Green and Kavanagh (2021) J.Phys.G 48 4, 043001