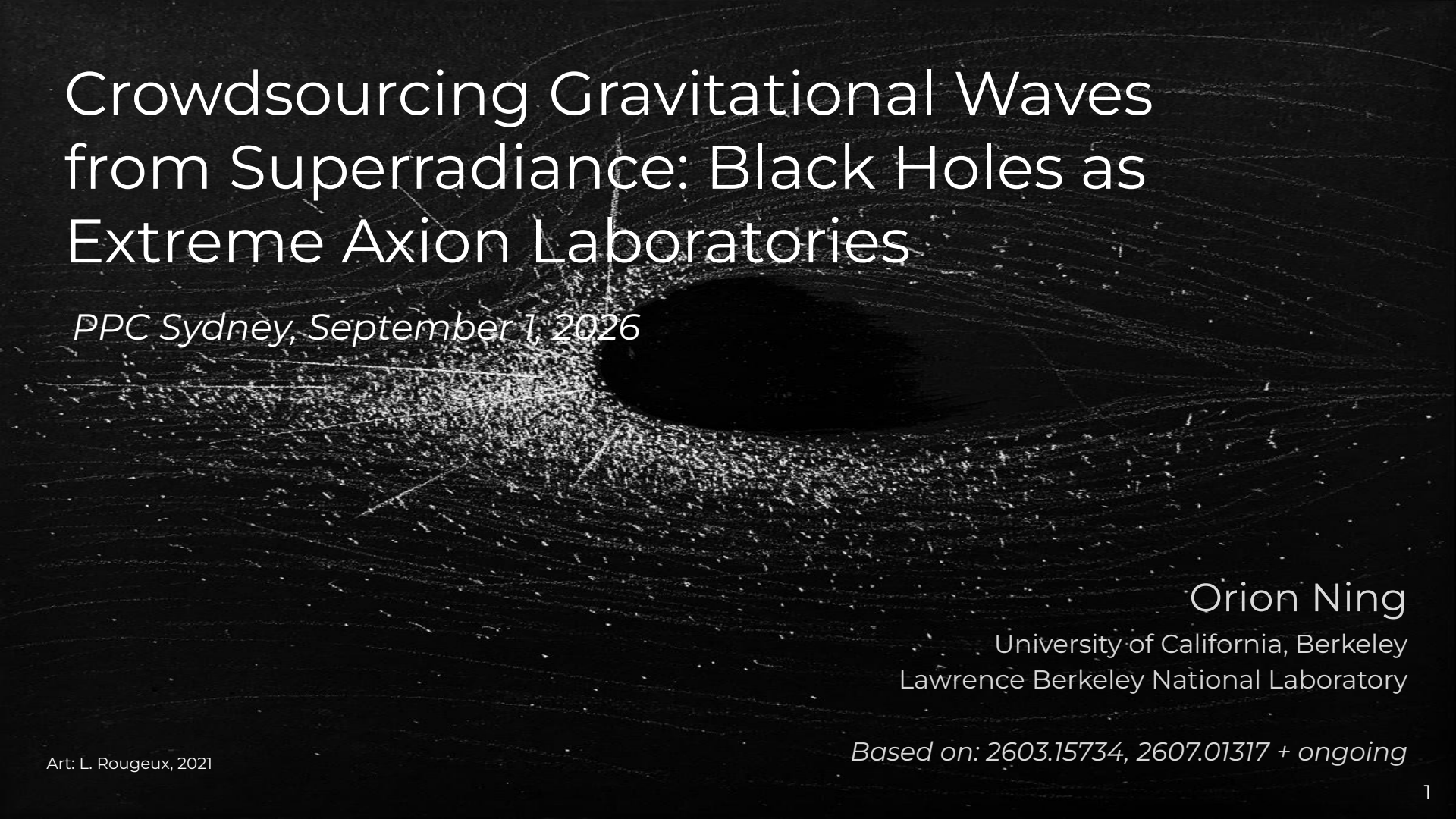




Crowdsourcing Gravitational Waves from Superradiance: Black Holes as Extreme Axion Laboratories

PPC Sydney, September 1, 2026

Orion Ning

University of California, Berkeley
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Key Highlights

I. *Superradiance* of Axions

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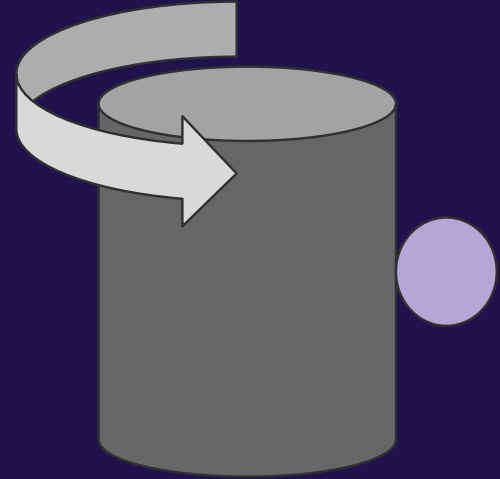
- I. *Superradiance of Axions*
- II. *Axion-Induced GW Signals from BH Populations*
 - A. Prospects for Future GW Observatories

Key Highlights

- I. *Superradiance of Axions*
- II. *Axion-Induced GW Signals from BH Populations*
 - A. Prospects for Future GW Observatories
- III. Extensions: More Superradiance Paths

Black Hole Superradiance

- *Superradiance*: Bosonic Scalars can form bound states that induce perturbations and build up an exponential cloud that extracts the spin of Kerr BHs (see, e.g. Arvanitaki, Dubovsky 1004.3558)
- Wave analog of *Penrose process*: scattering off BH can extract energy from the BH



Solving the EOM for the axion in the Kerr metric leads to solutions for the ‘Gravitational Atom’

$$\Phi = e^{-i\omega t} e^{im\phi} S_{lm}(\theta) R_{nl}(r)$$
$$\alpha \equiv M\mu$$

Characterized by ‘hydrogenic’ mode numbers, $[n, l, m]$ and a ‘gravitational coupling’ α

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Superradiance Conditions:

$$\omega_I > 0 \rightarrow \omega_R \sim \mu < \frac{m\chi}{2M\bar{r}_+}$$

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Superradiance Conditions:

$$\omega_I > 0 \rightarrow \omega_R \sim \mu < \frac{m\chi}{2M\bar{r}_+}$$

High spin ✓
High m ✓*
Larger $\mu \rightarrow$ Smaller
M (and vice versa)

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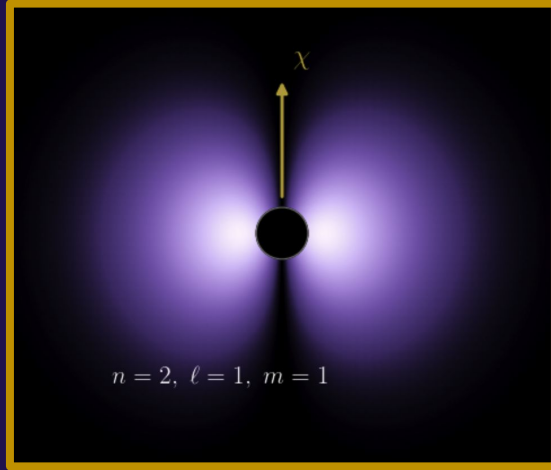
→ Estimated SR
Sensitivity:

$$\mu \lesssim m \times 7 \times 10^{-12} \text{ eV} \left(\frac{10 M_{\odot}}{M} \right)$$

Superradiance gives observational signatures, an example

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$$\mu = 1 \times 10^{-12} \text{ eV}$$



1. Initial BH and $m=1$ SR
cloud growth

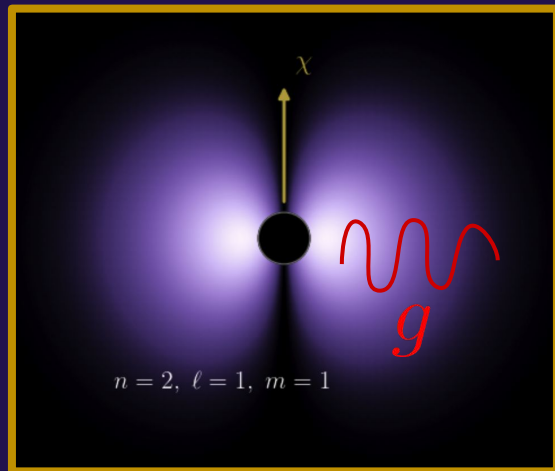
$$M_i = 10 M_{\odot}$$

$$\chi_i = 0.9$$

$$\tau_c \approx 200 \text{ yr}$$

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2. Spin down and GW emission

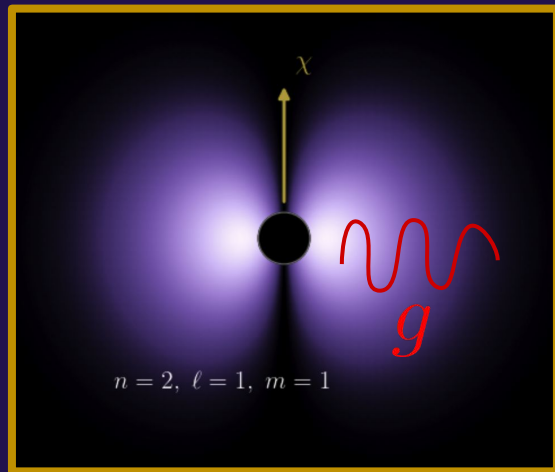
$$M_f = 9.5 M_{\odot}$$

$$\chi_f = 0.27$$

$$\tau_h \approx 2 \times 10^8 \text{ yr}$$

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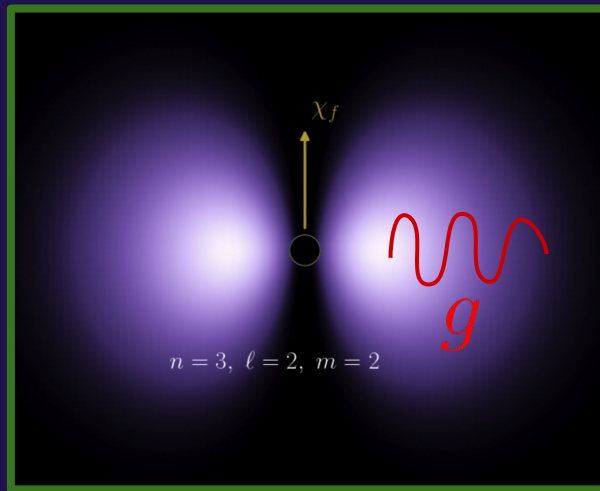
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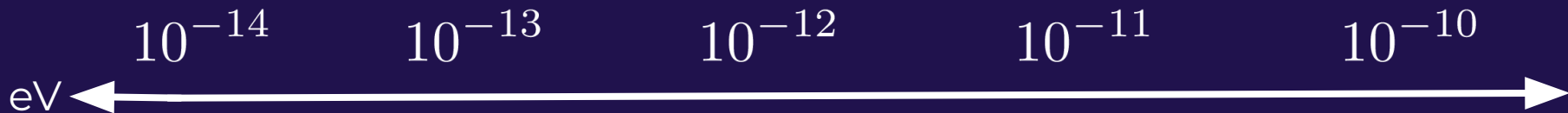
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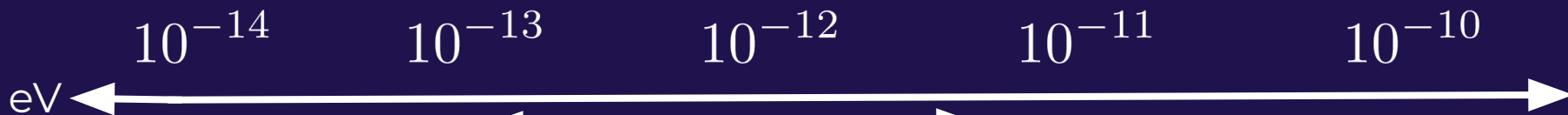


3. If applicable, next $m=2$ mode begins growing, and then emission again etc.

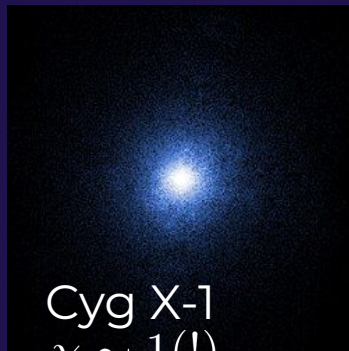
Current SR Lore (mostly spin-down of single BHs)



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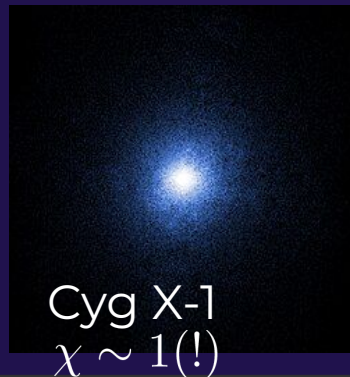
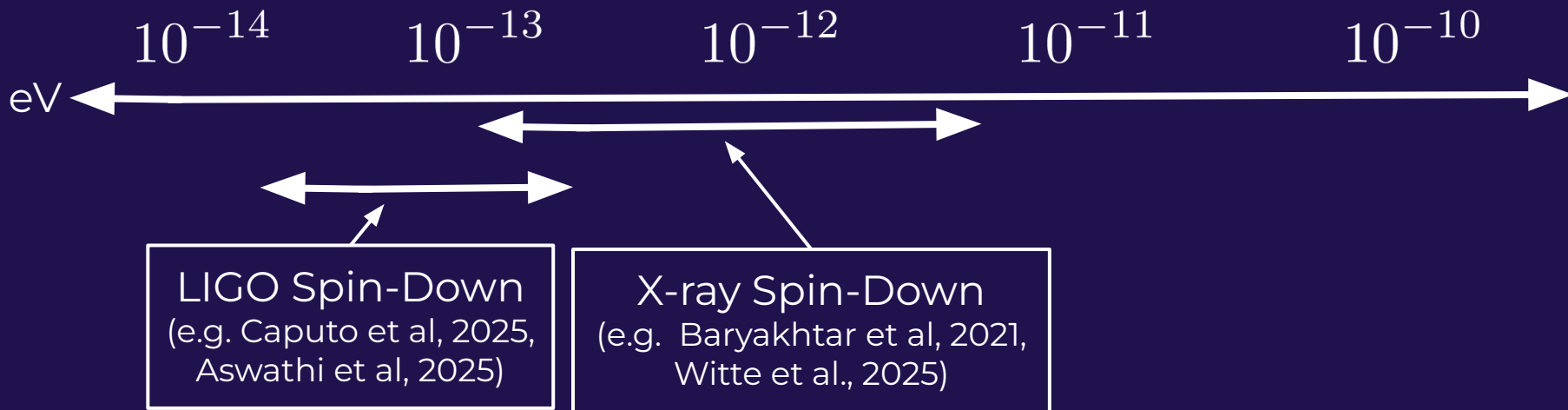


X-ray Spin-Down
(e.g. Baryakhtar et al, 2021,
Witte et al., 2025)

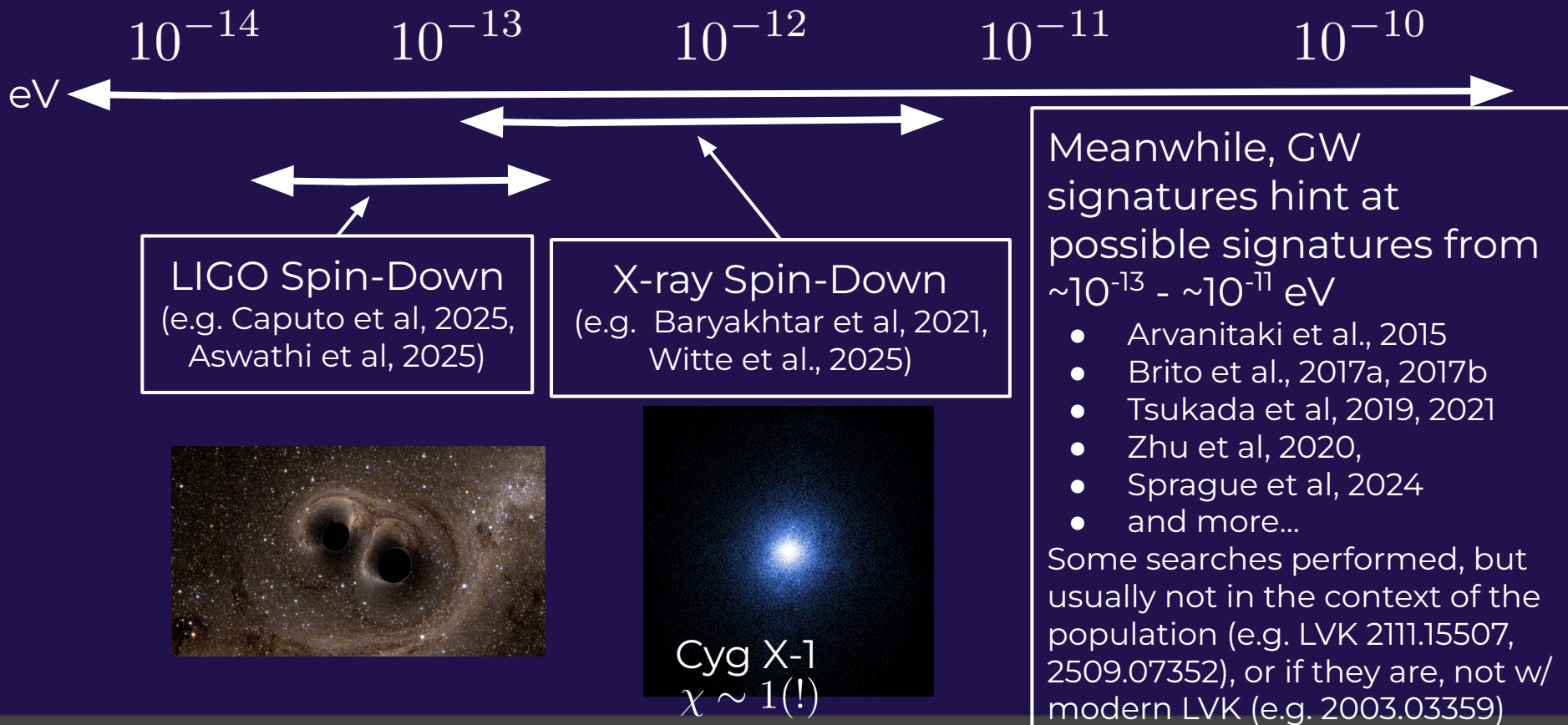


Cyg X-1
 $\chi \sim 1(!)$

Current SR Lore (mostly spin-down of single BHs)



Current SR Lore (mostly spin-down of single BHs)

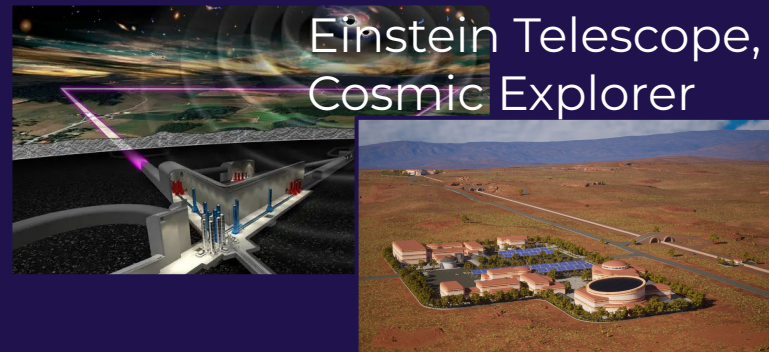


Our focus: Axion-Induced GW Signals *from BH populations*

S. Ellis, ON, N. Rodd, J. Schütte-Engel, 2603.15734

Our emphasis on the GW signal from

1. Galactic Resolvable Signals
2. The Extragalactic Stochastic Background



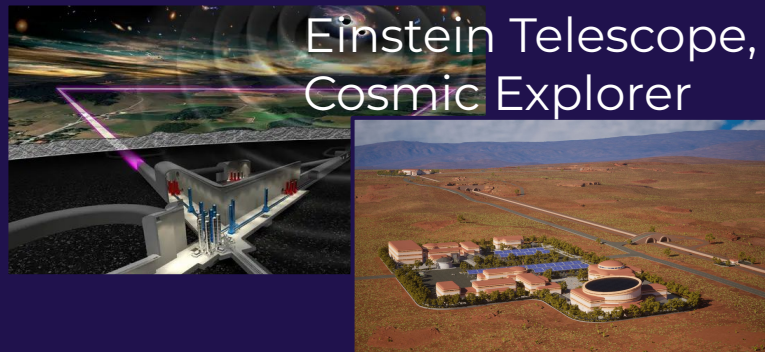
Einstein Telescope,
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Two key pieces of motivation:

1. Past searches often rely on serious systematic uncertainties from singular X-ray BBH observations
2. Rich current and upcoming data from LVK and 3rd Gen. GW Observatories

Emphasis on astrophysical systematics and uncertainties, and projections for axion exclusion

Galactic Resolvable Signals

Stellar Mass BHs $\rightarrow$ we see $O(10)$ - $O(100)$ of them in galaxy, but expect $O(10^8)$!

Fiducial Model (which we vary):

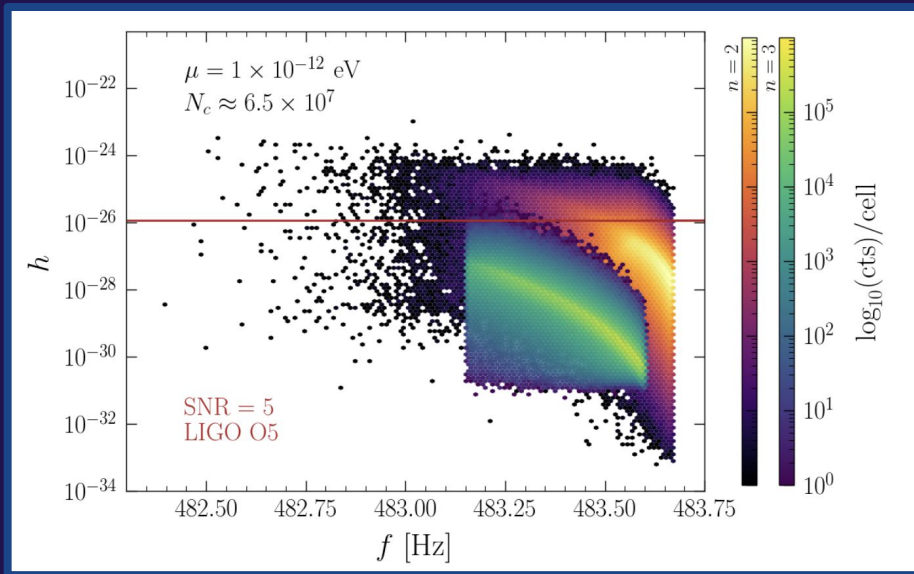
- Mass Dist.: Salpeter-like restricted to 5-20 solar masses
- Spin Dist.: Uniform from 0 to 1
- Spatial Dist.: Follows mass density profile for thin/thick disk and bulge
- Age Dist.: Follows Milky Way SFH



Our Procedure:

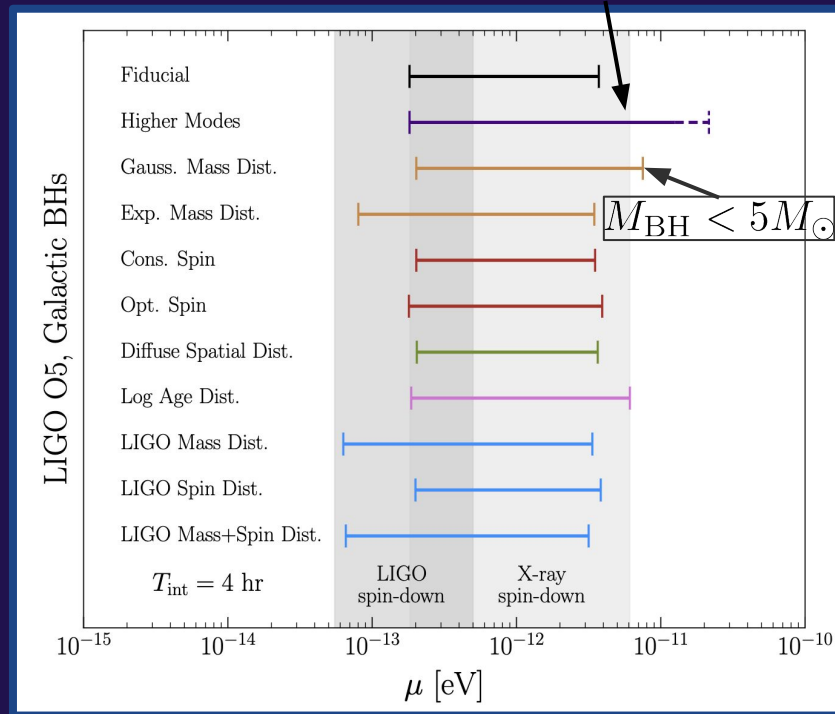
- Loop through all simulated BHs
- check for SR, compute GW signal (monochromatic!)
- calculate SNR under assumed null observation $\rightarrow$ projections for axion mass sensitivity

Results



MW BH Population GW Signals

higher modes reach heavier axions



by default: only first SR mode $m=1$

Extragalactic Stochastic Signal

The stochastic signal from all BHs in the universe

Calculate GW bkg from a variety of initial inputs:

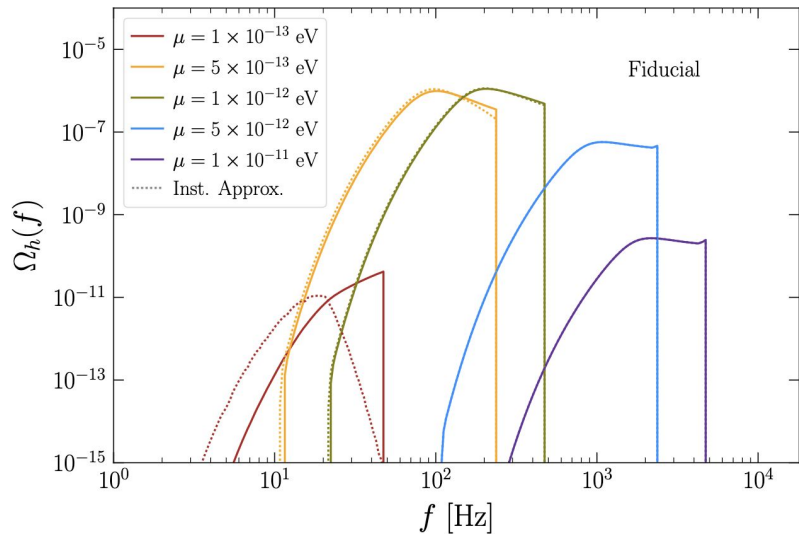
- Stellar SFR: Follows from galaxy LFs
- Stellar IMF: Salpeter IMF
- Stellar-BH Relation: Metallicity and Redshift Dependent
- Spin Dist: Uniform from 0 to 1
- Non-instantaneous SR emission (contrast with Phinney 2001)



Our Procedure:

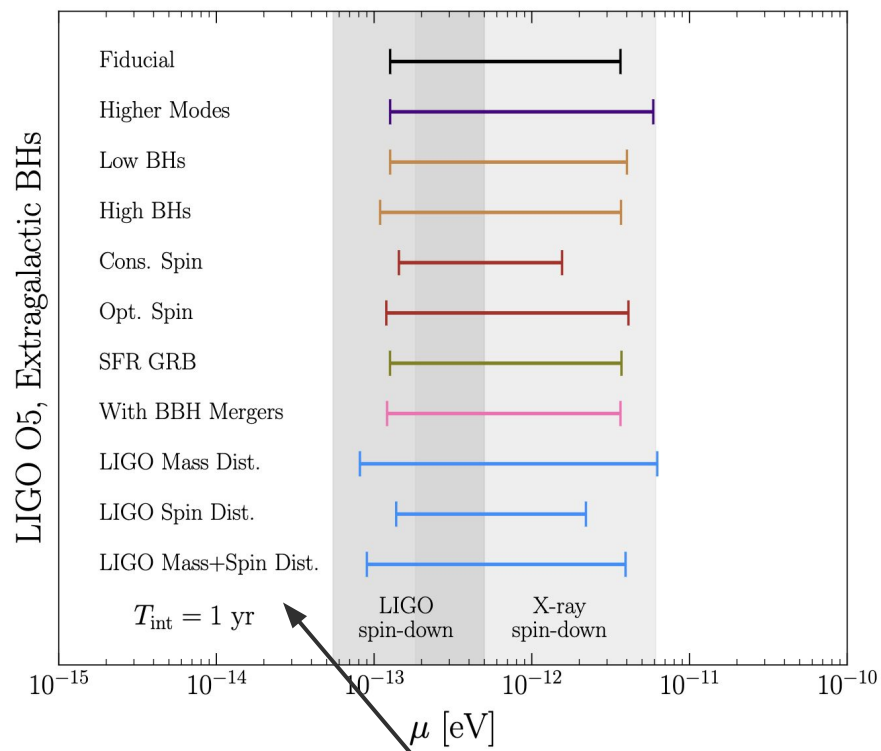
- Begin with stellar info, compute BH formation rate
- Integrate over masses, spins, redshifts, etc., determine SR and compute GW density
- calculate SNR for stochastic GW density $\rightarrow$ projections for axion mass sensitivity

Results



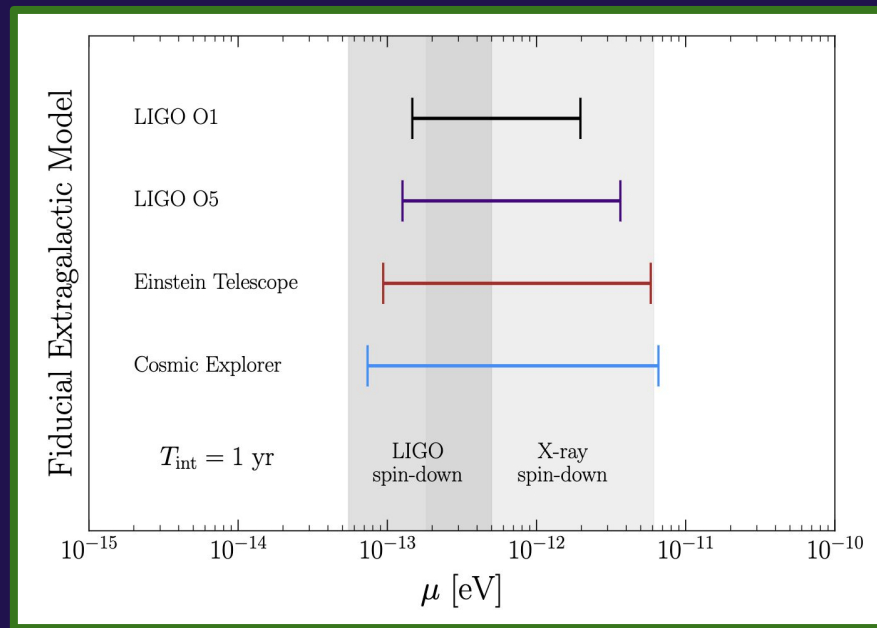
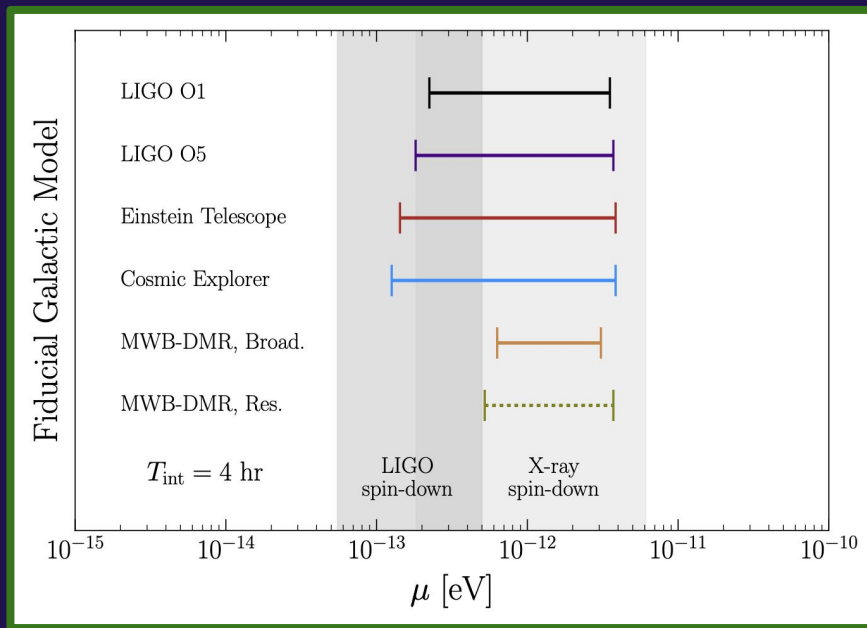
EG BHs Stochastic GW Density

by default: only first SR mode $m=1$

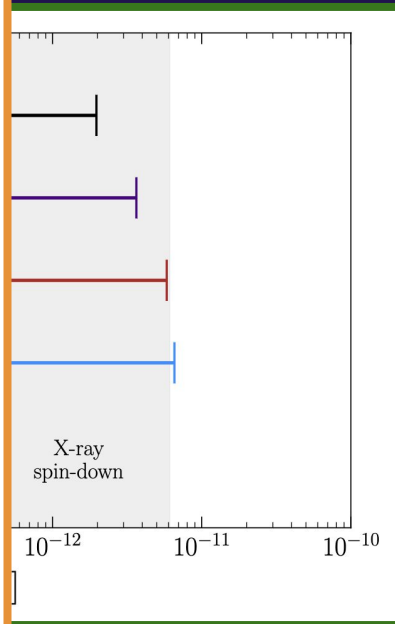
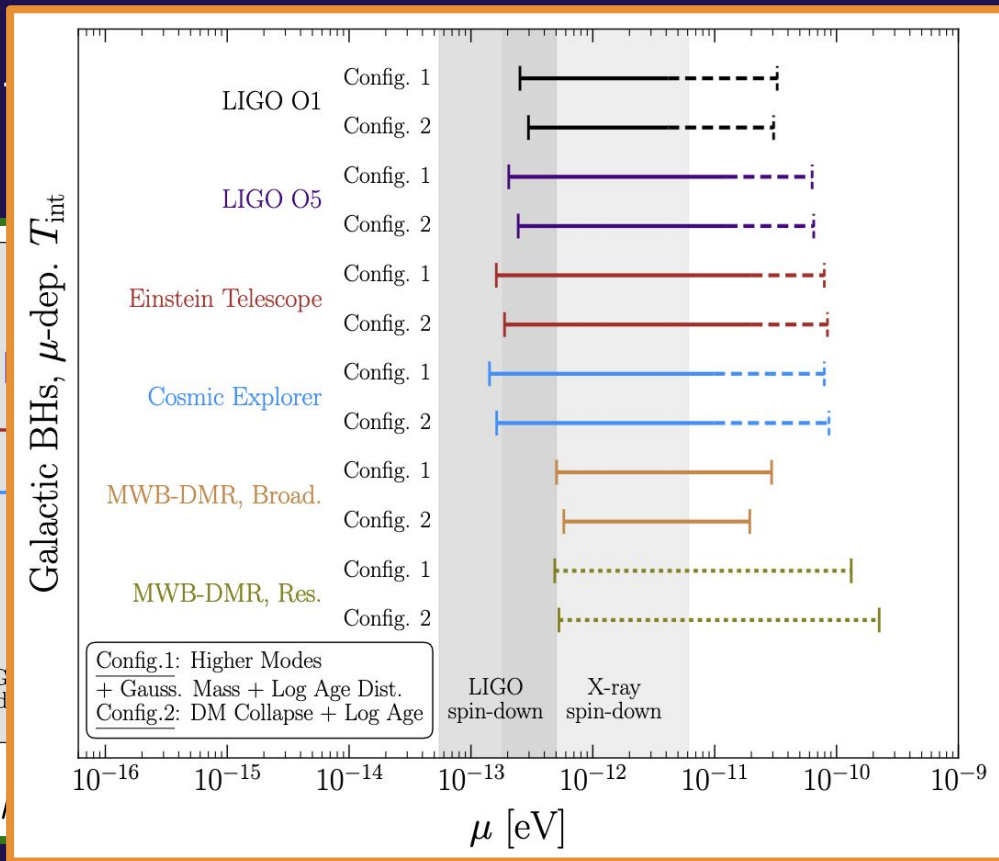
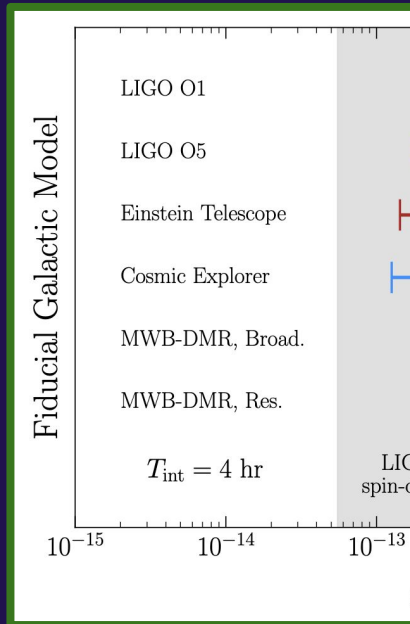


inspired by LIGO GWTC parameter estimates

Projections for 3rd Gen. GW Observatories



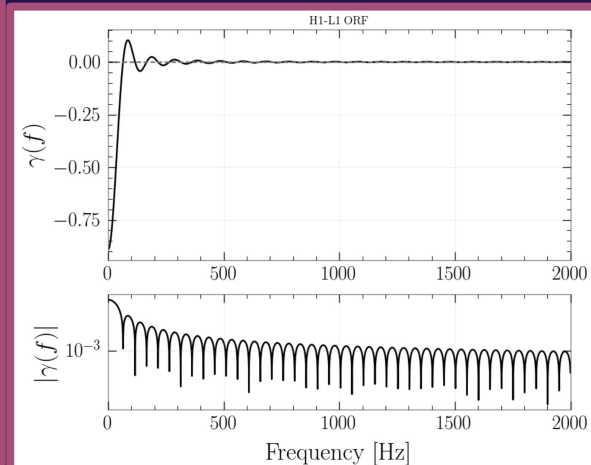
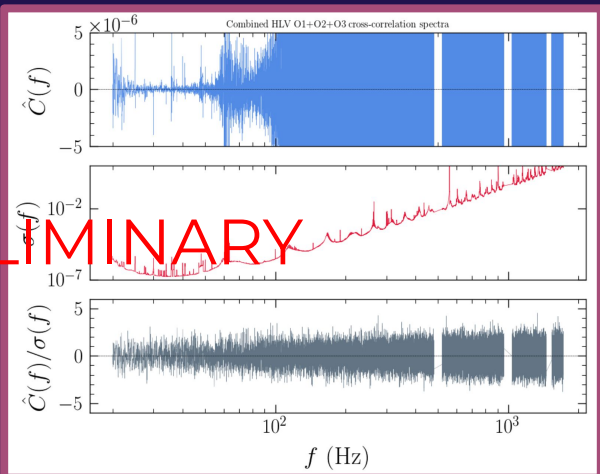
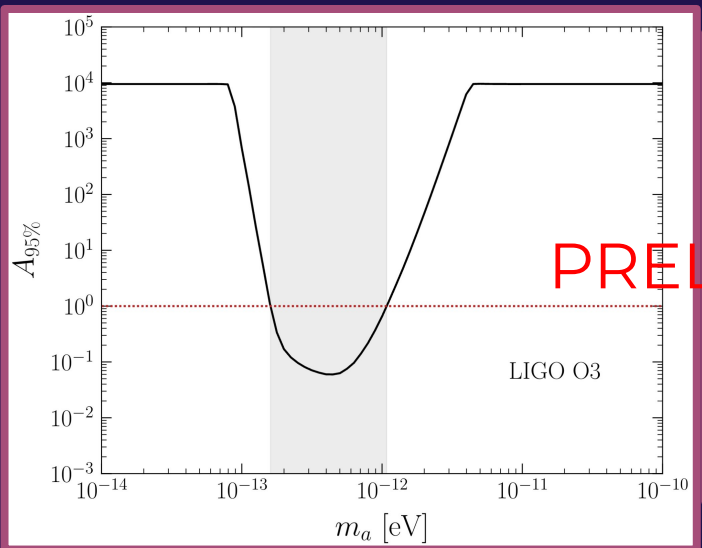
Projections



More speculative scenarios discussed in our paper that can reach beyond 10^{-10} eV ... (high freq. det. like MWBs useful there!)

Extension 1: LVK Data Analysis

- Can use current data, e.g. constraints on the *stochastic* GW background with LVK to constrain the EG signal for axions mentioned earlier
- Preliminary results seem similar, slightly weaker, from e.g. overlap reduction fn.
- more to understand re: LVK data reduction

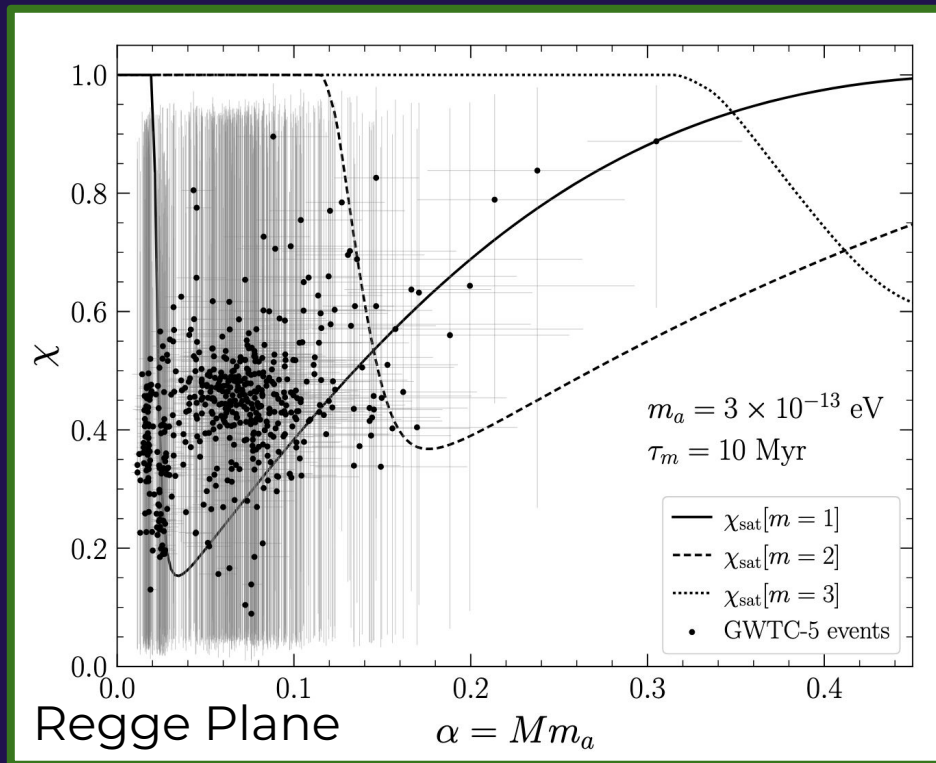


Extension 2: LVK Spin-down

ON, B. Safdi, C. Welch, 2607.01317

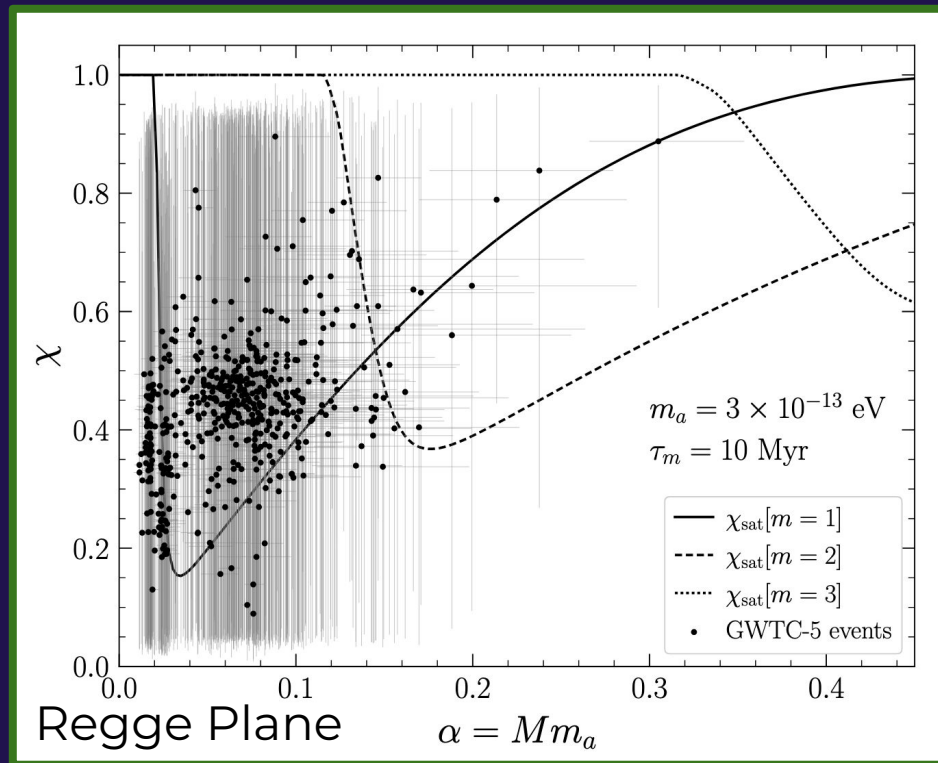
LIGO-Virgo-KAGRA (LVK): GWTC-5
– ~257 BBH events!

(cf. ~45 in GWTC-2 (Ng et al, 2021))



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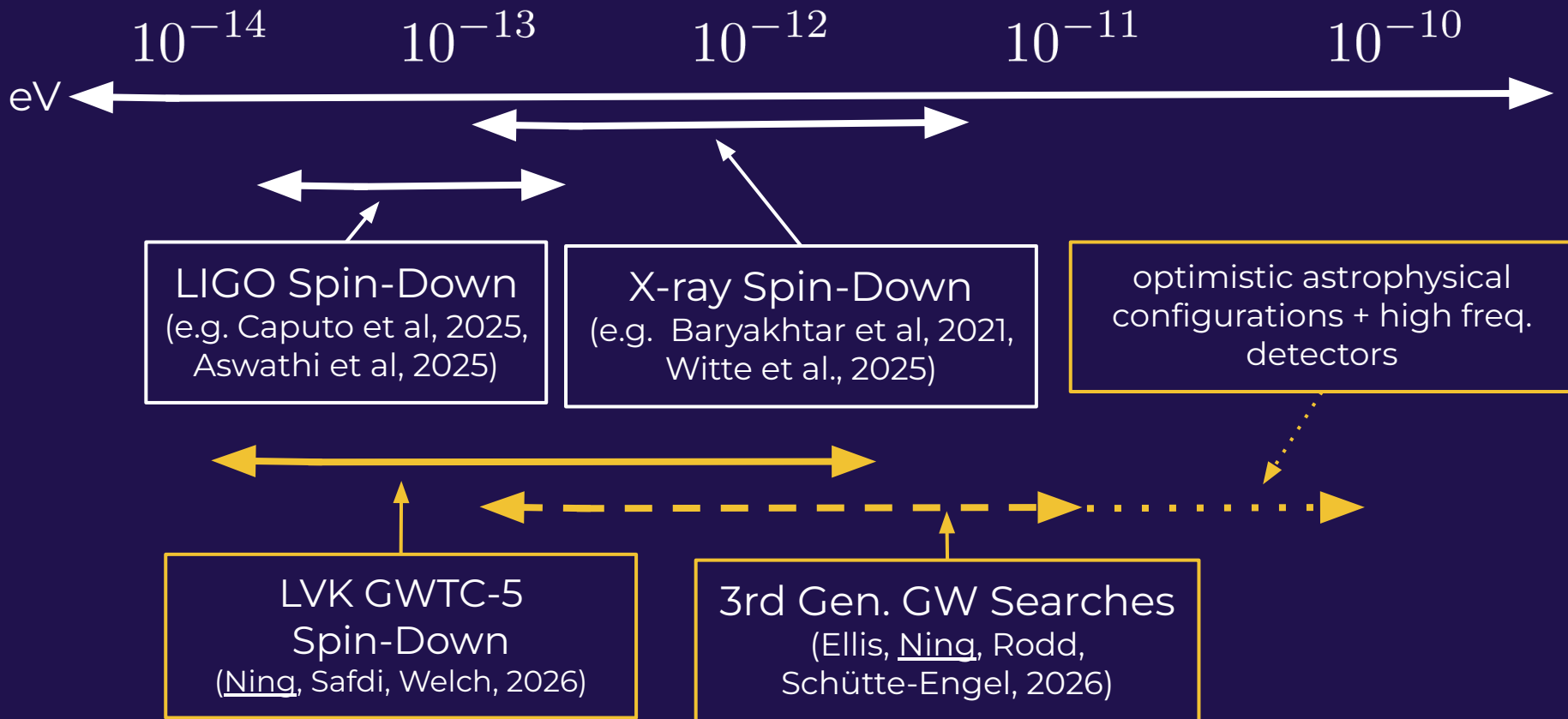
(cf. ~45 in GWTC-2 (Ng et al, 2021))

Along saturation spin curves:
SR spins BH down to this value
→ evidence for axions

Above saturation spin curves:
SR should have spun down →
evidence against axions

Constrain axions $\sim 2\text{e-14} - 3\text{e-12 eV}$

SR Axion Searches



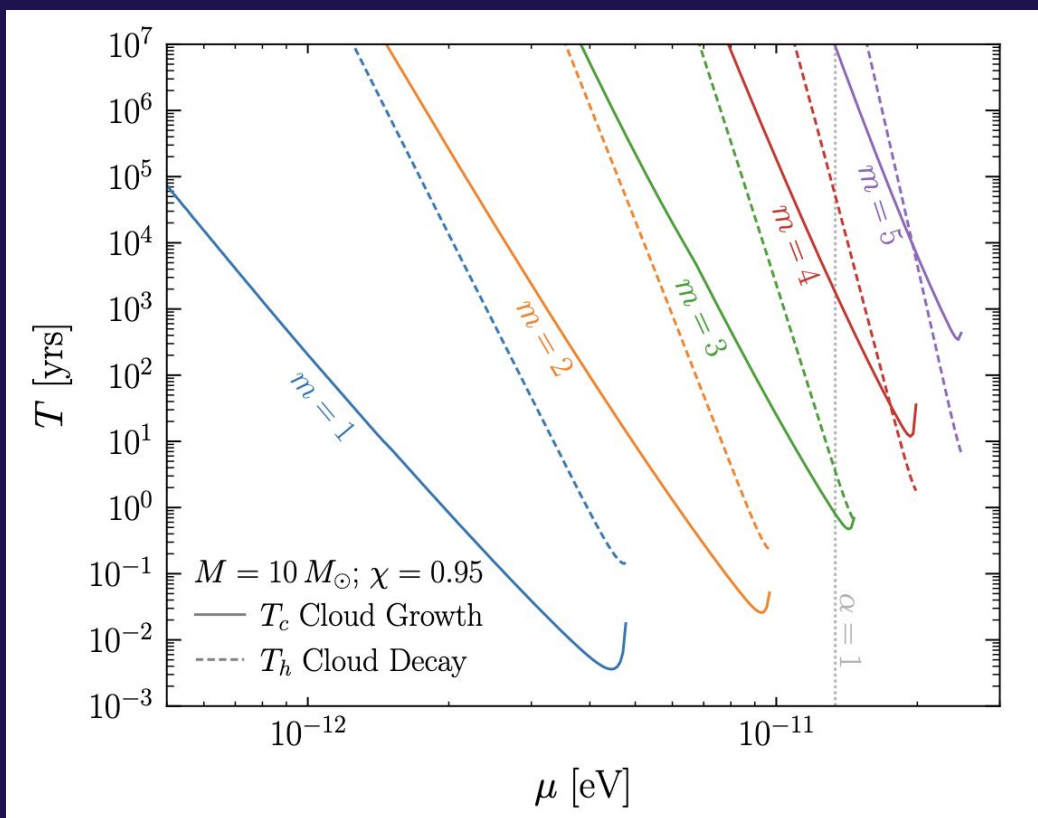
Conclusions and Outlook

- Superradiance a promising avenue to probe ultralight bosons like axions
- Conducted systematic studies of BH population searches for superradiance evidence of axions
- Completely different systematic uncertainties from existing searches
- Signatures excitingly within reach of current and future GW observatories



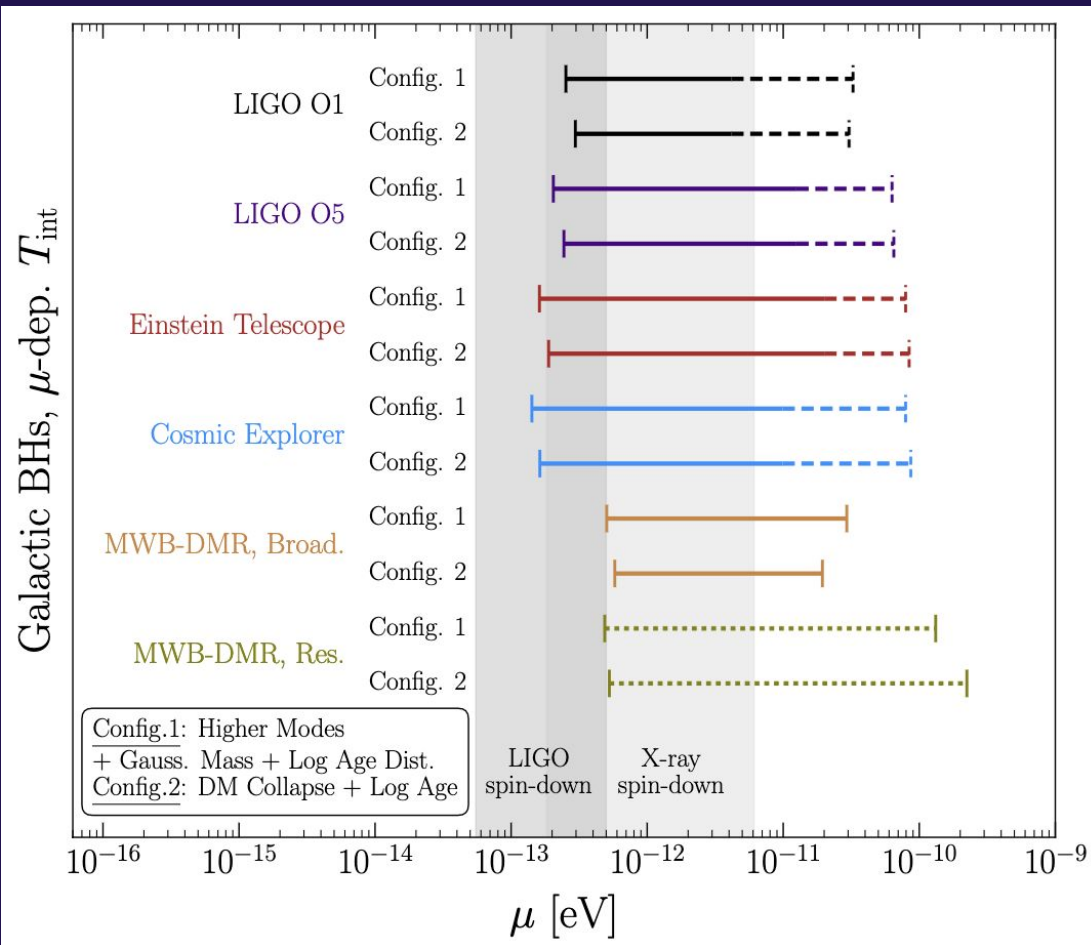
Thanks for listening!

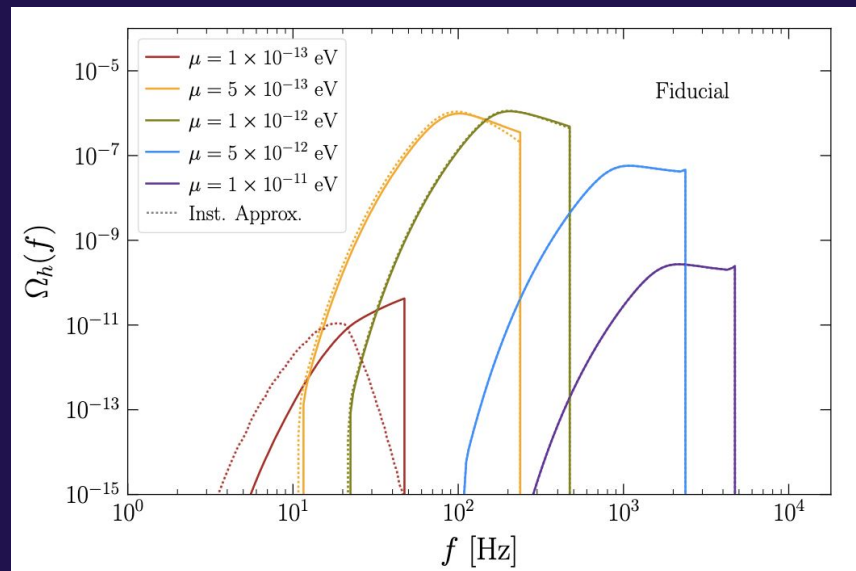
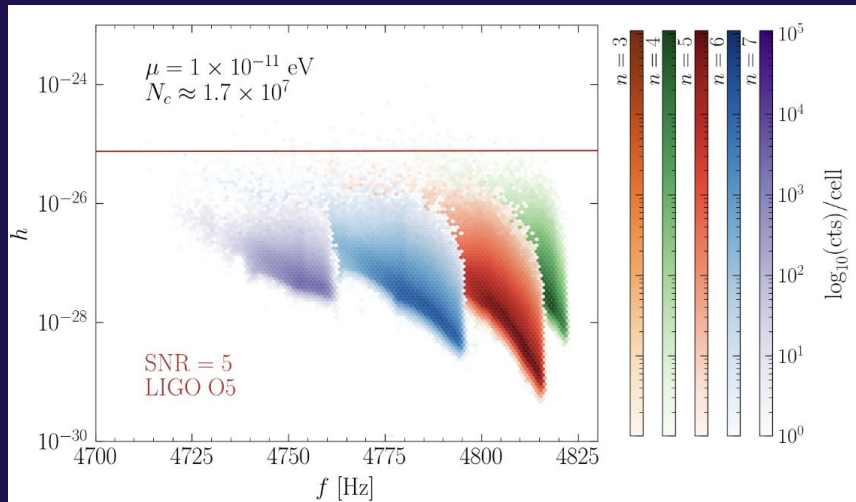
Appendices



Galactic BHs Systematic Configurations	
Name	Description
Fiducial	Our fiducial analysis is defined by the following choices: • A Salpeter-like BH mass distributed $\xi(M) \propto M^{-2.35}$ restricted to masses in $5 M_{\odot} - 20 M_{\odot}$ [42, 85] • A uniform initial spin distribution $\chi \in U[0, 1]$ • A BH age distribution that follows the Milky Way SFH as in Ref. [99] • Separate BH spatial distributions following the mass density profiles for the thin disk, thick disk, and bulge; see Eq. (13) [42, 100–102] • Include only the lowest 211 superradiant mode
Higher Modes	Inclusion of higher superradiant modes
Gauss. Mass Dist.	Change the BH mass distribution to a Gaussian centered at $\mu = 9.2 M_{\odot}$ and $\sigma = 3.3 M_{\odot}$ following the fit in Ref. [85], although restricted to $M \geq 1.4 M_{\odot}$
Exp. Mass Dist.	Change the BH mass distribution to a delayed exponential with $M_{\min} = 5.3 M_{\odot}$ and $M_0 = 4.7 M_{\odot}$ following the fit in Ref. [85]
Cons. Spin	Conservative spin: initial spin distribution $\chi \in U[0, 0.5]$
Opt. spin	Optimistic spin: initial spin distribution $\chi \in U[0.5, 1]$
Diffuse Spatial Dist.	Same BH spatial distribution but double scale radii and heights, loosely inspired by natal kicks in Ref. [103]
Log Age Dist.	Change the BH age distribution to log-uniform between $10^3 - 8 \times 10^9$ yrs for the thin disk, $10^3 - 10^{10}$ yrs for the thick disk, and $10^9 - 1.3 \times 10^{10}$ yrs for the bulge [42]
LIGO Mass Dist.	Change the BH mass distribution to the primary mass distribution observed in the LIGO GWTC-3 catalog [94]
LIGO Spin Dist.	Change the BH spin distribution to the inferred component spin distribution observed in the LIGO GWTC-3 catalog [94]
LIGO Mass+Spin Dist.	Combines both the LIGO mass and spin distributions

Extragalactic BHs Systematic Configurations	
Name	Description
Fiducial	The configuration for our fiducial analysis is defined as follows: • SFR $\psi(z)$ from Ref. [116] (galaxy lum. function) • IMF $\xi(M_{\star})$ from Ref. [115] • Allowable BH mass range: $5 M_{\odot} \leq M \leq 50 M_{\odot}$ • Stellar lifetimes $\tau(M_{\star})$ from Ref. [117] • BH mass - stellar mass relation $g[M_{\star}, Z(z)]$ from Ref. [92] • Metallicity evolution $Z(z)$ from Ref. [118] • Uniform initial spin distribution, $\chi \in [0, 1]$ • Non-instantaneous superradiance emission $\dot{E}_h \neq E_h \delta(t - t_b)$ • Only the 211 superradiant mode is included
Higher Modes	Inclusion of higher superradiant modes
Low BHs	Lower BH mass cutoff $5 \rightarrow 2 M_{\odot}$
High BHs	Upper BH mass cutoff $50 \rightarrow 100 M_{\odot}$
Cons. Spin	Conservative spin: initial spin distribution $\chi \in [0, 0.5]$
Opt. spin	Optimistic spin: initial spin distribution $\chi \in [0.5, 1]$
SFR GRB	Gamma-Ray Burst (GRB)-inferred alternate SFR $\psi(z)$ from Ref. [116]
With BBH Mergers	Add the BBH merger population, which follows a different mass and spin distribution (see App. C), adopting the prescription in Ref. [38]
LIGO Mass Dist.	As for the galactic systematics in Tab. I
LIGO Spin Dist.	"
LIGO Mass+Spin Dist.	"





some equations

$$M_c(t) = \frac{M_c^f}{1 + t/T_h},$$

$$\tau_c \simeq \frac{M}{2C_{n\ell} m^{2\ell+1}} \alpha^{-4\ell-5}.$$

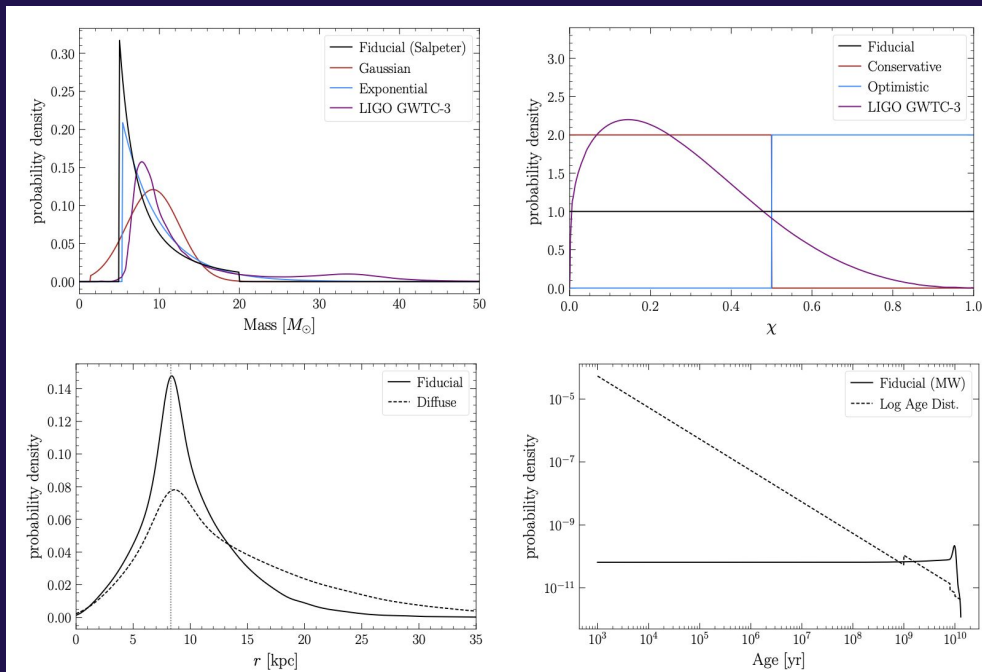
$$T_h = \frac{M^2}{D_{n\ell} M_c^f} \alpha^{-4\ell-10}.$$

$$T_c \simeq \tau_c \ln(M_c^f / \mu).$$

$$h = \frac{2\sqrt{\pi \dot{E}_h}}{\omega_R r},$$

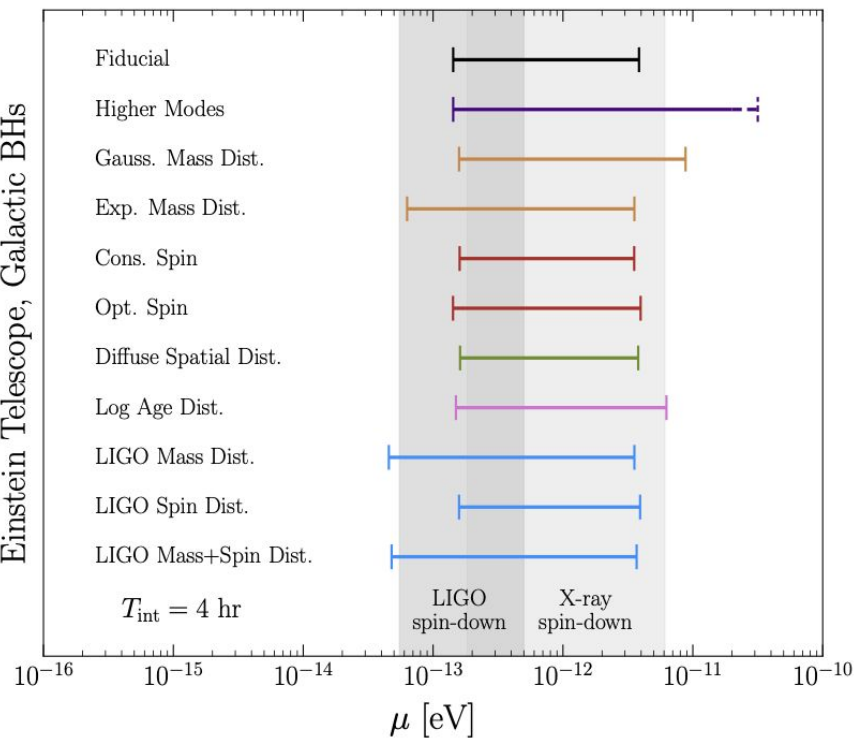
$$\dot{E}_h = D_{n\ell} \left(\frac{M_c}{M} \right)^2 \alpha^{4\ell+10},$$

Galactic Details

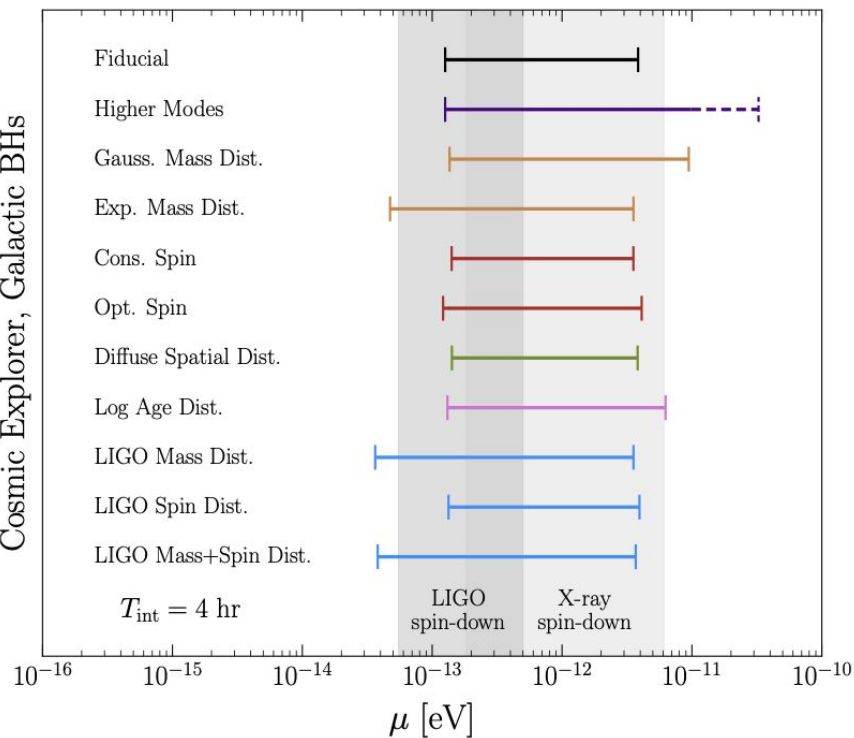


$$\text{SNR} = \frac{h\sqrt{T_{\text{int}}} N^{1/4}}{\sqrt{S_n(f)}}.$$

Einstein Telescope, Galactic BHs



Cosmic Explorer, Galactic BHs

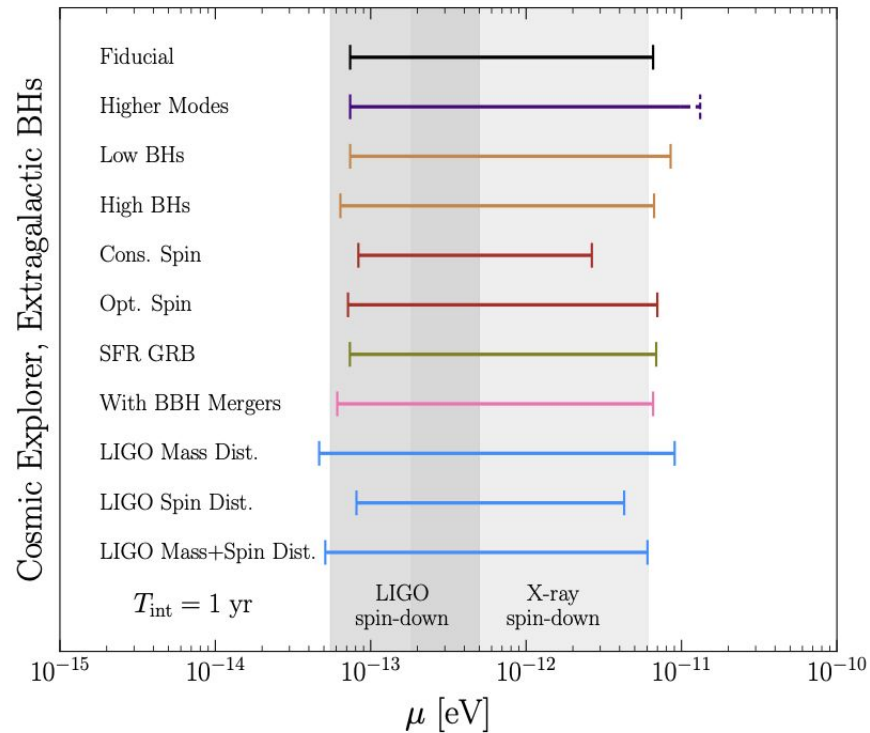
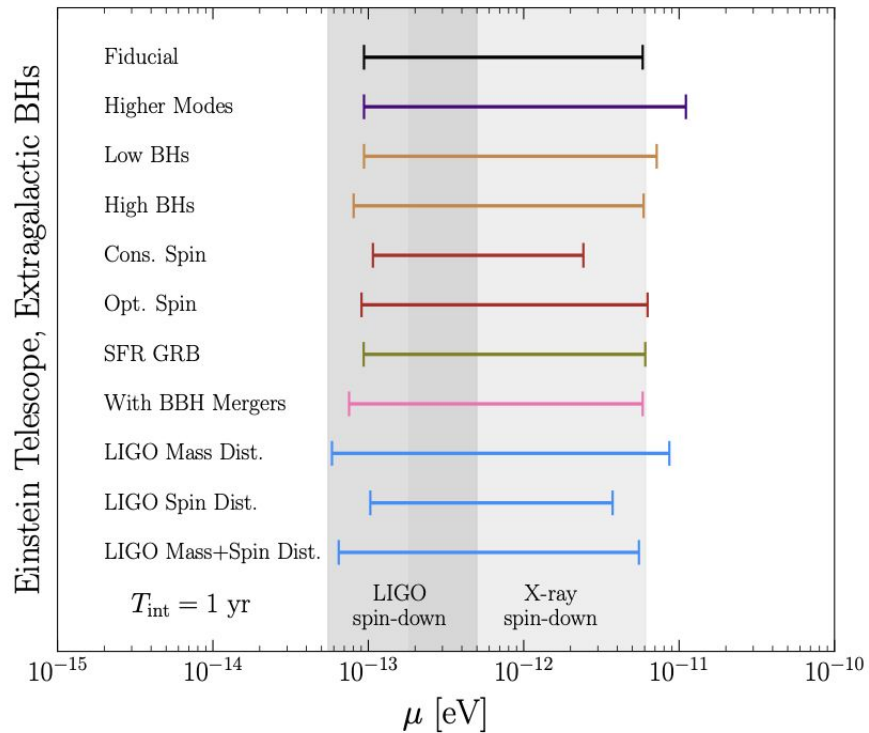


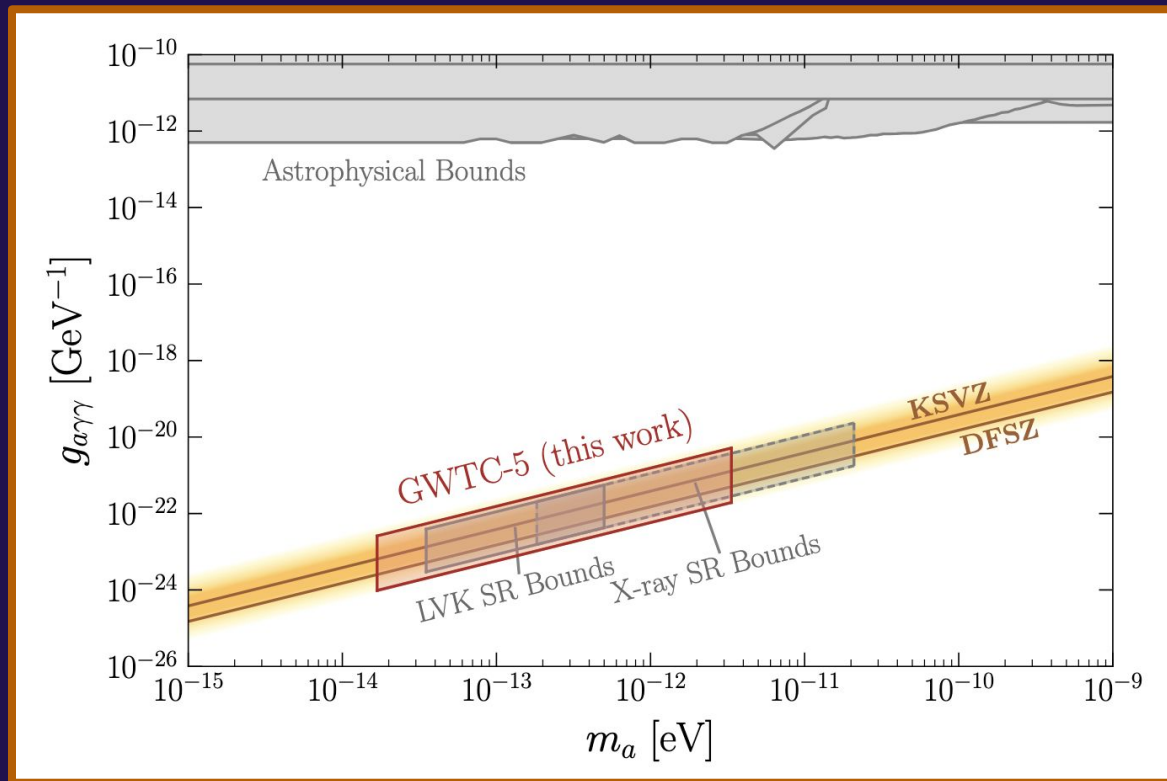
Stochastic Calculation

$$\begin{aligned} R_{\text{BH}}(z, M) &\equiv \frac{dN}{dt dV dM}(z, M) \\ &= \int dM \frac{dN_{\star}}{dt dV dM_{\star}}(t(z) - \tau(M_{\star}), M_{\star}) \\ &\quad \times \delta(M_{\star} - g^{-1}[M, Z(z)]). \end{aligned}$$

$$\text{SNR} = \frac{3H_0^2}{4\pi^2} \left[T_{\text{int}} \int_0^{\infty} df \left(\frac{\Omega_h(f)}{f^3 S_n(f)} \right)^2 \right]^{1/2},$$

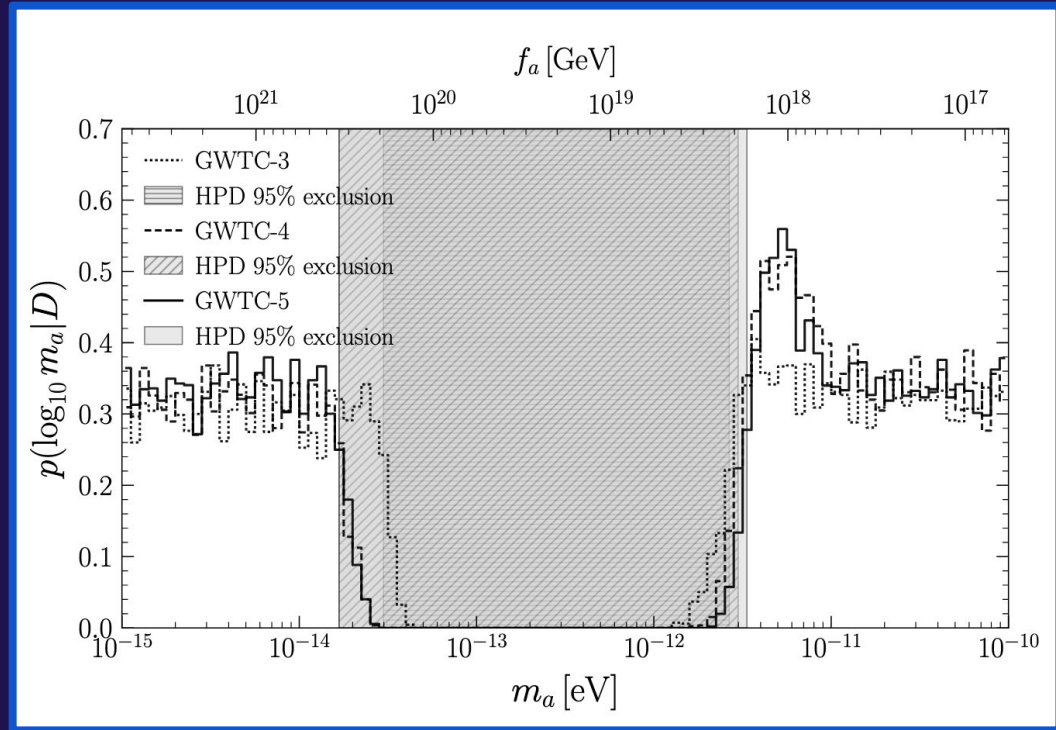
$$\begin{aligned} \Omega_h(f) &= \frac{f}{\rho_c} \int dz dM d\chi dt_b \frac{dt}{dz} \frac{dN}{dt_b dV dM d\chi} \\ &\quad \times \frac{dE_h}{dt}[t - t_b] \delta(f(1+z) - f_s), \end{aligned}$$





Hierarchical Likelihood using GWTC PEs

- Model natal spin distribution, merger times for each event (hyperparams)
- Incorporate GWTC PEs for masses and spins
- Infer the marginalized posterior for axion mass m_a
- Derive exclusion from the posterior dip structure



+ testing systematic uncertainties: natal spin and merger time distributions, axion mass prior, and more