Probing Axion-like Particles with Gravitational Waves

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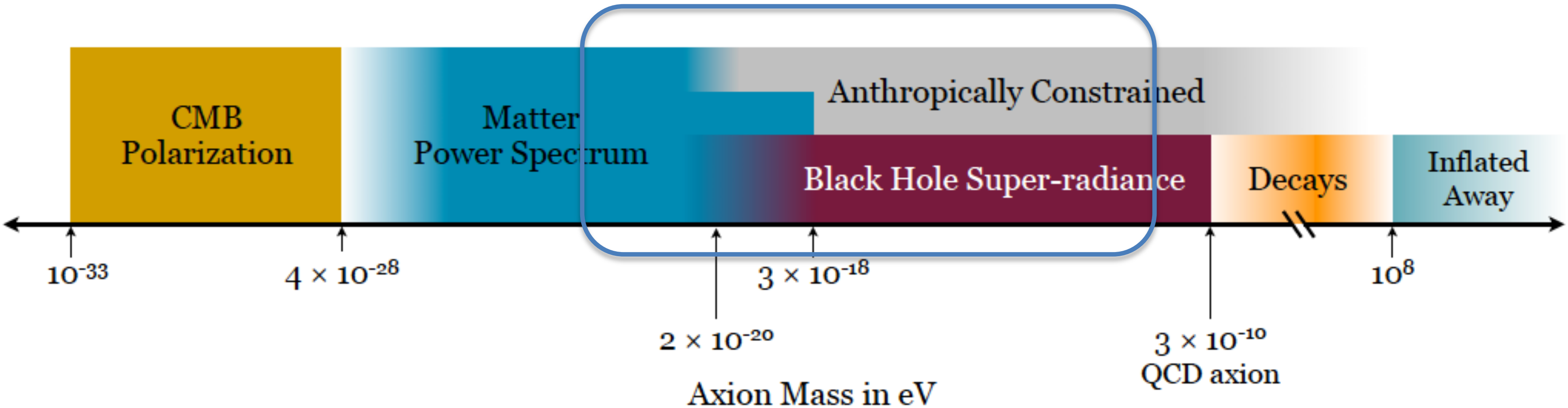
Axion-like particles



String Axiverse: Arvanitaki et al. PRD 2010

Content

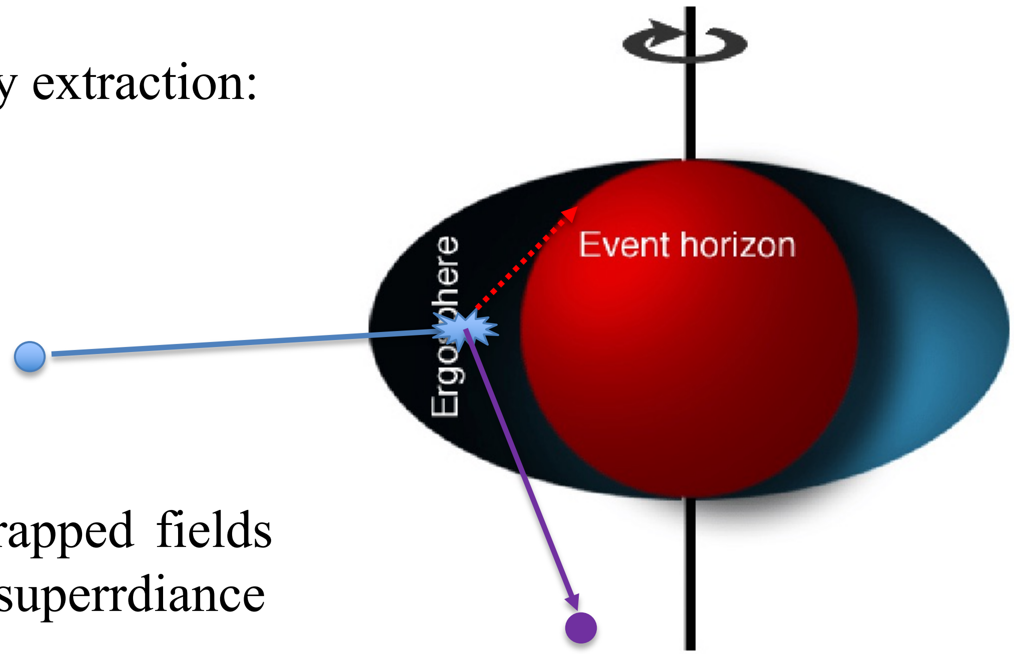
- Black hole with axion clouds
  - LIGO constraints: spin, continuous wave and stochastic gravitational wave background
  - Constraints and implications for motions of stellar-mass black hole binaries
  - Future observation with EMRIs (extreme mass-ratio inspirals).
- Neutron star binary constraints

Black hole superradiance

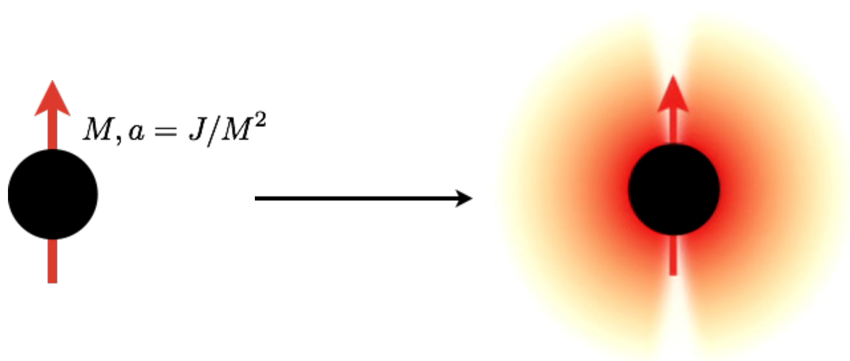
- Penrose process with energy extraction:

$E_1 = E_2 + E_3$, $E_2 < 0$

$\to E_1 > E_3$



- Switch particle to fields: trapped fields with continuous extraction:superrdiance



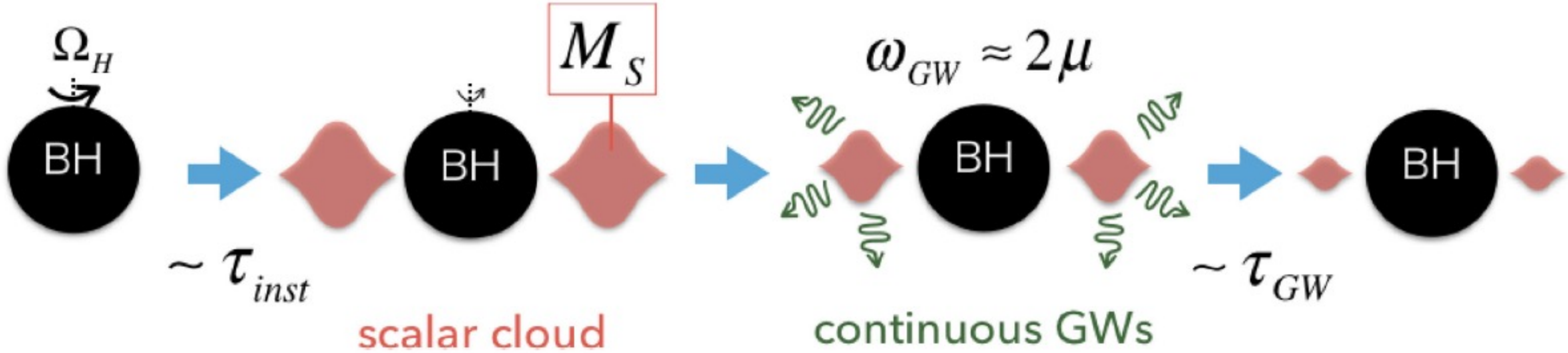
Penrose 1969
Press & Teukolsky 1972
Zouros & Eardley 1979
Detweiler 1980

Superradiant Cloud

- Superradiant process transfers black hole angular momentum to the axion cloud, until $\omega = m\,\Omega_H$
- Defining a dimensionless quantity $\alpha \sim$ BH size/axion wavelength

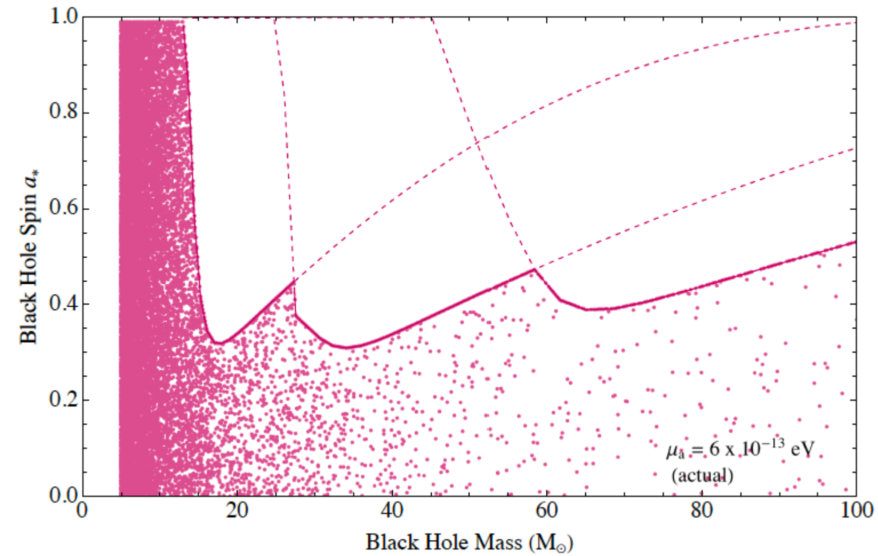
$$\alpha \equiv \mu M \simeq 0.1 \left(\frac{M}{10 M_\odot}\right) \left(\frac{\mu}{10^{-12}\text{eV}}\right)$$

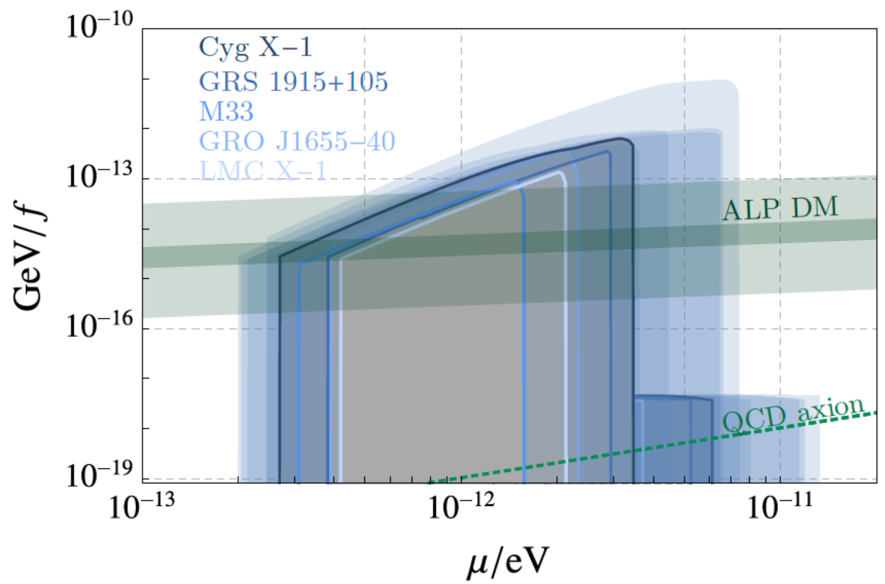
- Two relevant timescales:
  - Growth timescale ~ 12 days $(0.1/\alpha)^9 (\mathrm{M}/10\, M_\odot)$
  - GW radiation decay timescale ~ 10^9 years $(0.1/\alpha)^{15} (\mathrm{M}/10\, M_\odot)$
- Cloud mass ~ α M



Black hole spin constraint

- BHs spin down to saturate the superradiant instability, so BHs with mass match axion wavelength should have low spins [Avarnitaki et al. PRD 2016].
- Current spin measurement of X-ray binaries may be used to place constraints. Caveats: lifetime unknown, accretion history unknown…
- LIGO and LISA observations can be used to place constraints for 5 to 6 orders of magnitude.





Baryakhtar et al, PRD (2016)

GW231123 and GW190517

$$M_1 = 137^{+22}_{-17} M_\odot, M_2 = 103^{+20}_{-52} M_\odot$$

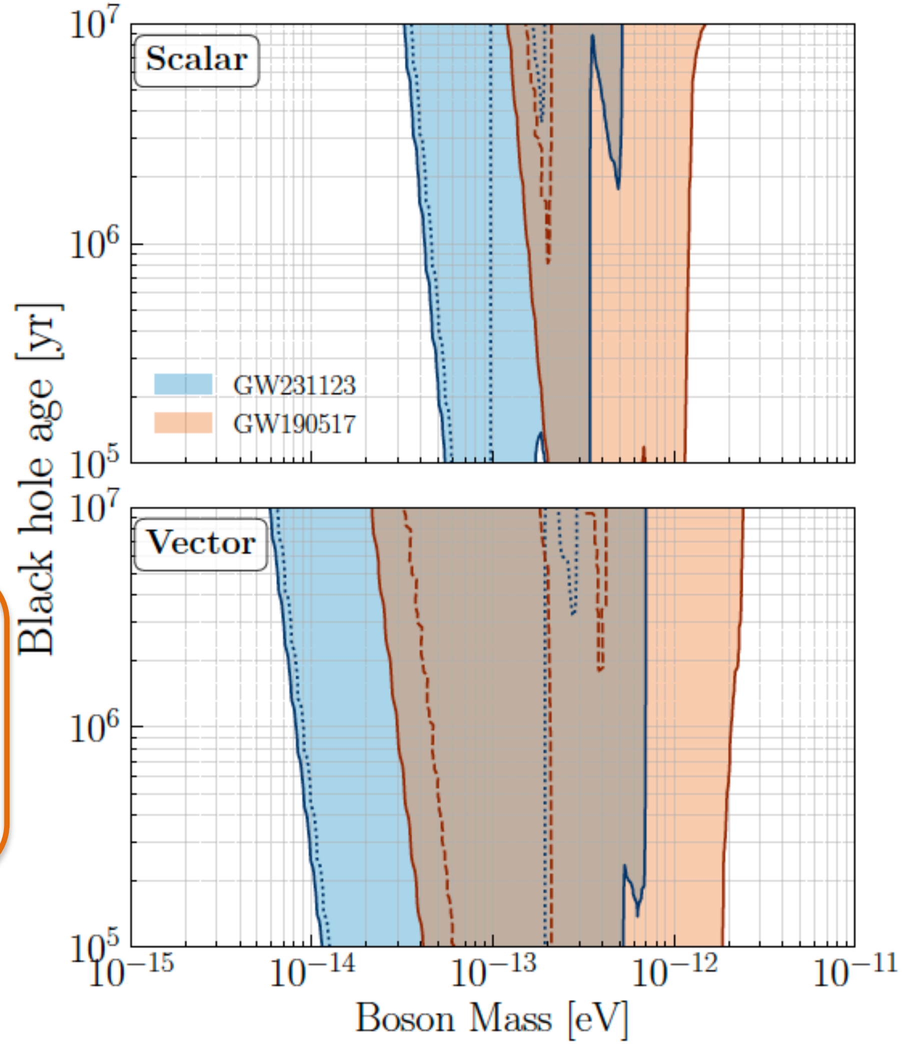
$$\chi_1 = 0.9^{+0.10}_{-0.19}, \qquad \chi_2 = 0.8^{+0.20}_{-0.51}$$

GW231123

$$M_1 = 39.2^{+13.9}_{-9.2} M_\odot, M_2 = 24.0^{+7.4}_{-7.9} M_\odot$$

$$\chi_1 = 0.9^{+0.09}_{-0.30}, \qquad \chi_2 = 0.62^{+0.34}_{-0.54}$$

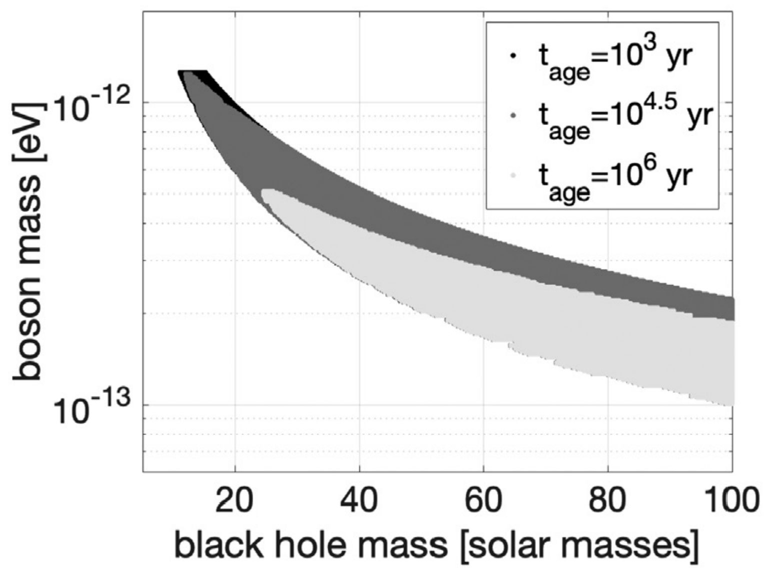
GW190517

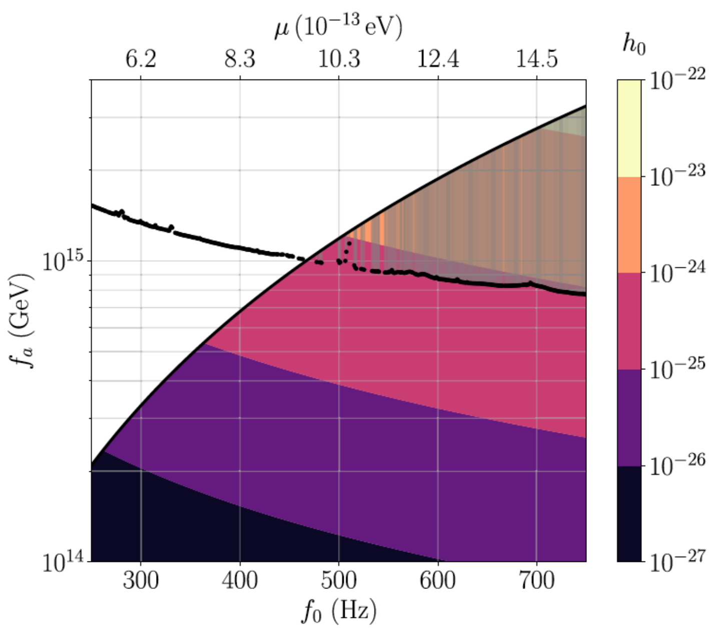


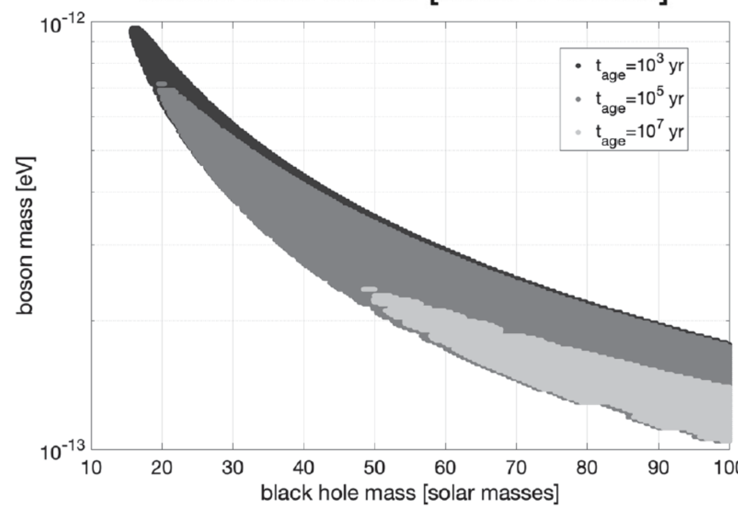
Aswathi et al, arXiv (2025)

Cloud radiation: continuous wave

- Ground-based detectors are sensitive to cloud radiation for bason mass ~ 10^{-14} - 10^{-11} eV
- All sky-search for scalar bosons [LVC 2022]
- Targeted galactic sources [LVC 2022]
- Cygnus X-1 [Sun, Brito, Isi, PRD 2020]
- LVC search for vector cloud radiation from remnant BHs.



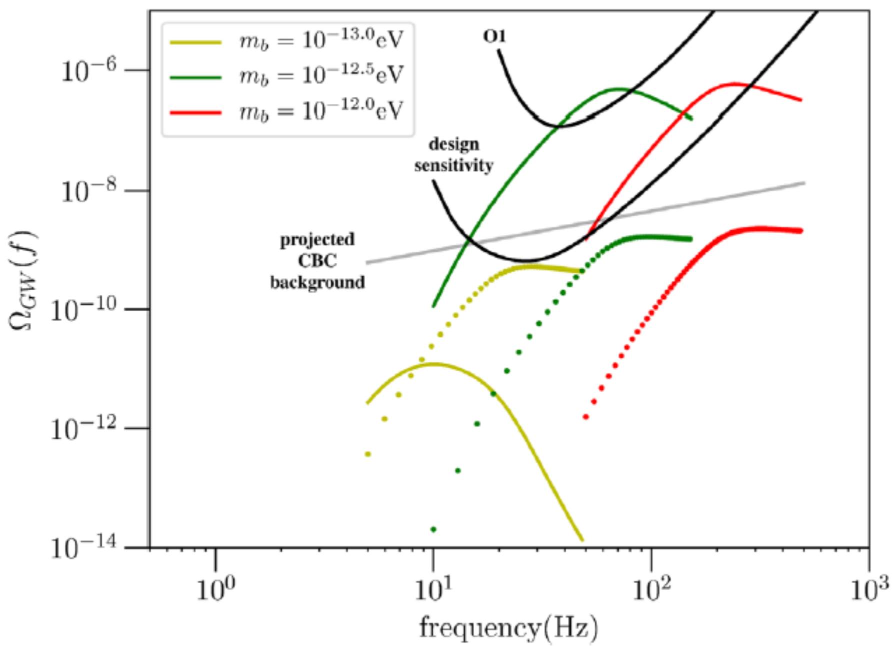


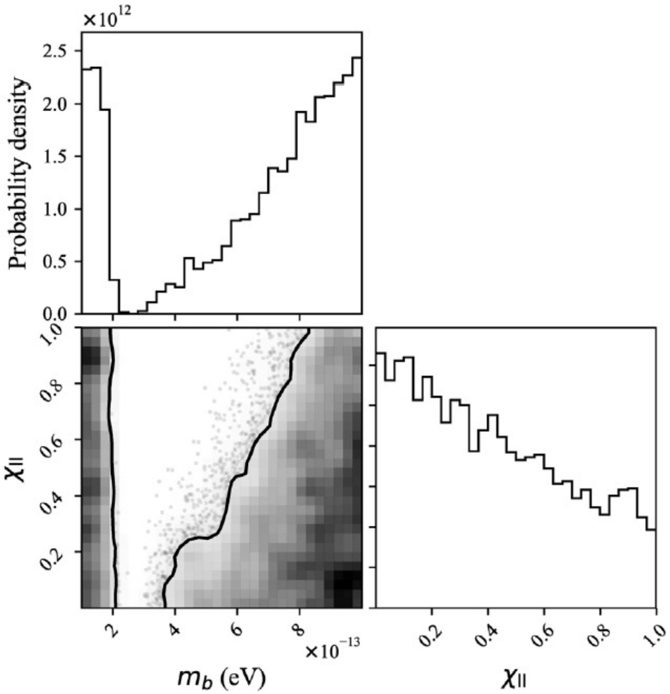


Cloud radiation: stochastic background

- Close (<10 Mpc) sources may be resolved by the continuous wave search, where further sources contribute to a stochastic background

- Based on a model of BH distribution (mass, spin, distance), a constraint has been placed on the axion mass from ~ [2-4] 10^{-14} eV [Tsukada et al. PRD 2019]





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Black hole binary with clouds: important questions

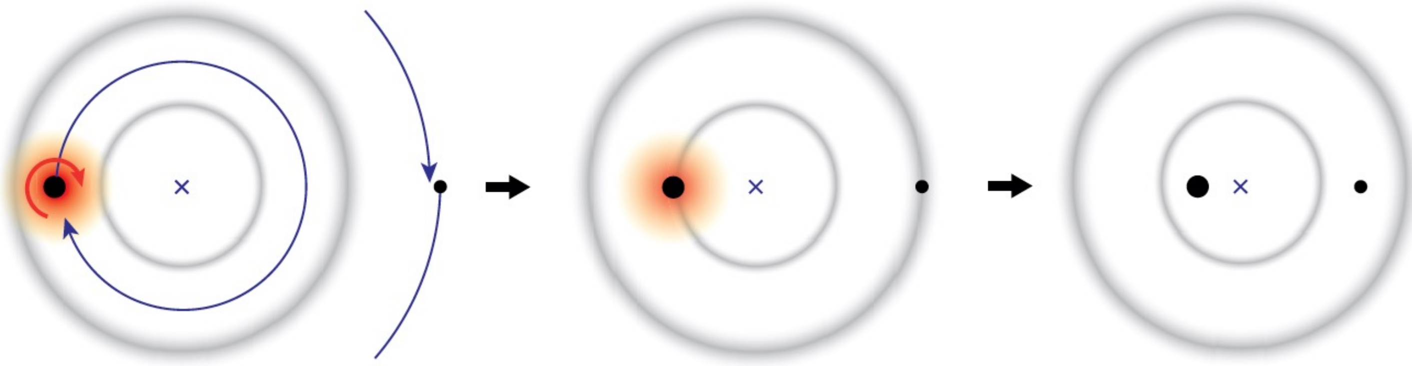
- Will the Axion clouds survive till the close separations (between the black holes)?

- What are the dynamical effects of the clouds if they survive to close distances?

- How do we use the dynamical effects to probe/constrain these ALPs?

Cloud dynamics in black hole binary

- Binary companion's tidal field induces level mixing in the cloud (Baumann et al. 2018). Excitation of decaying modes at resonance may lead to cloud depletion.



- This picture needs to be reconsidered with caution, i.e. by including the energy level drift associated with cloud depletion (nonlinear effects), and the astrophysical evolution path

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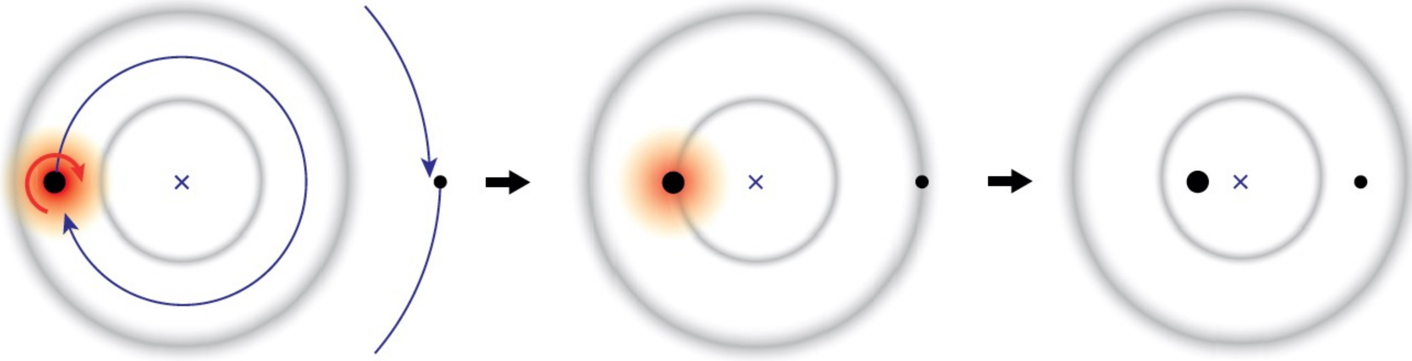

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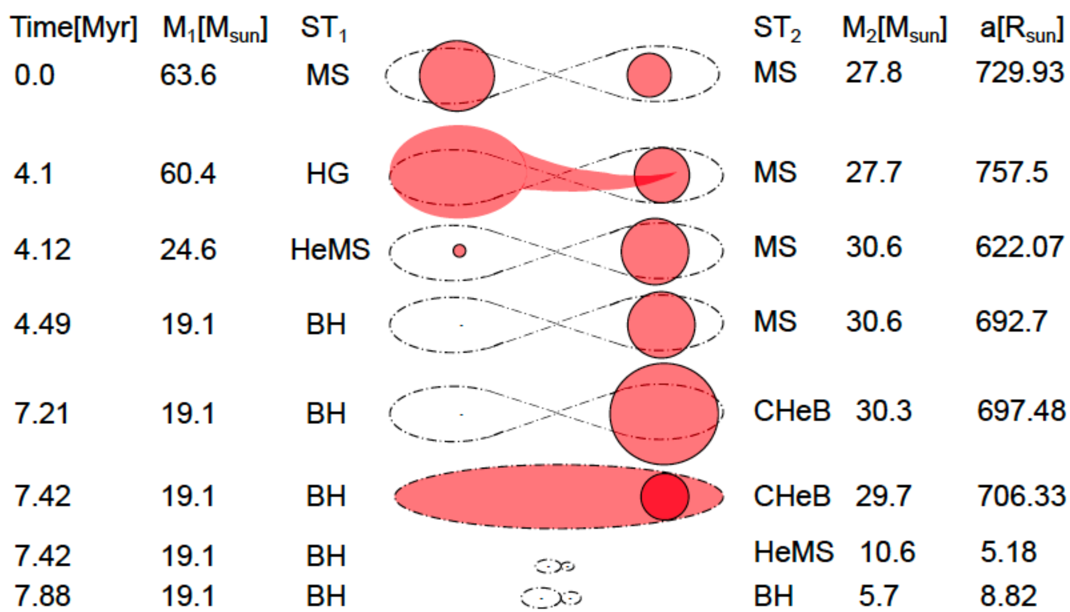
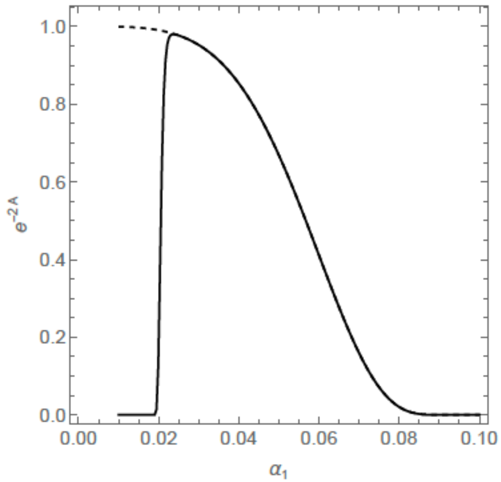
Astrophysical black hole binary evolution

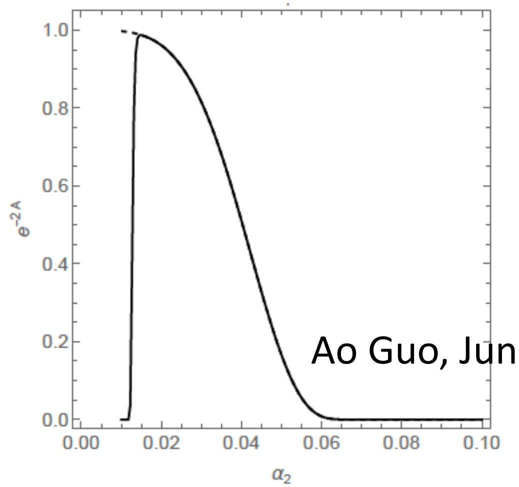
- Black hole binary observed by LIGO or LISA will likely experience processes that significantly reduce the binary separation in a short time, i.e. the common envelope phase, so that the binary can merge in cosmic time. The cloud evolution has to be considered in such realistic setting [Zhang, Guo, HY, 2024]



Cloud within LISA band

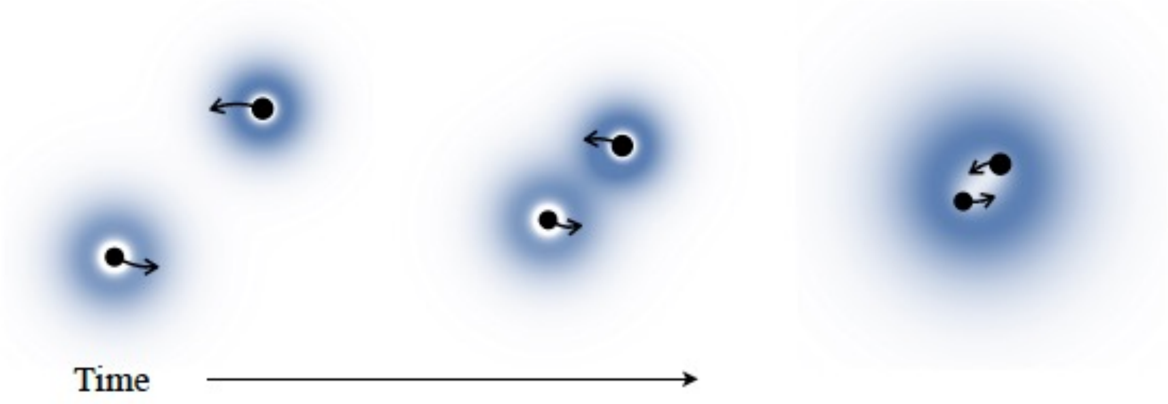
- We find significant parameter range where cloud survives to the LISA band:





Ao Guo, Jun Zhang, HY, PRD (2024)

- Before entering LIGO band, we find resonant cloud transfer between black holes. The cloud likely survives into the LIGO band.

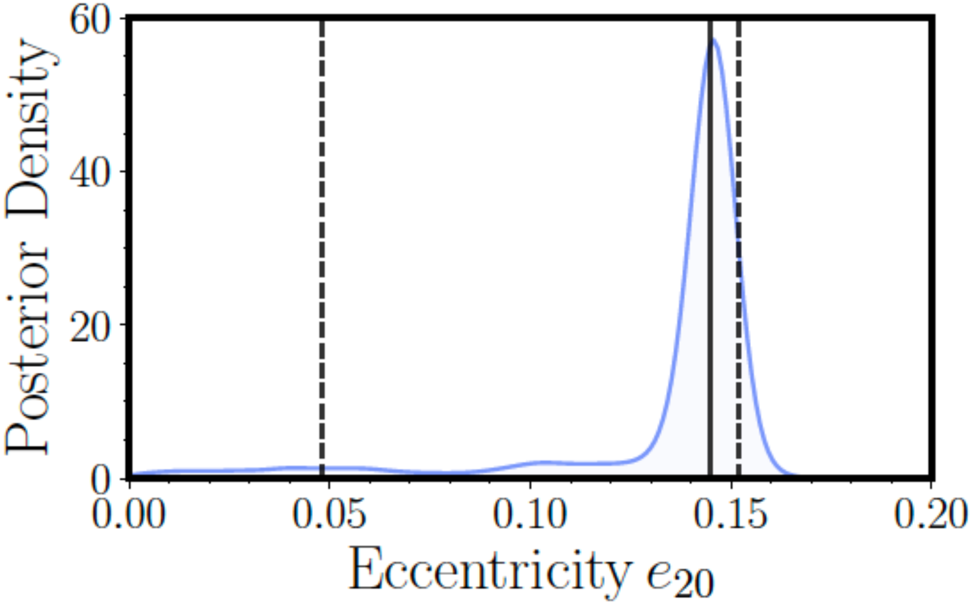


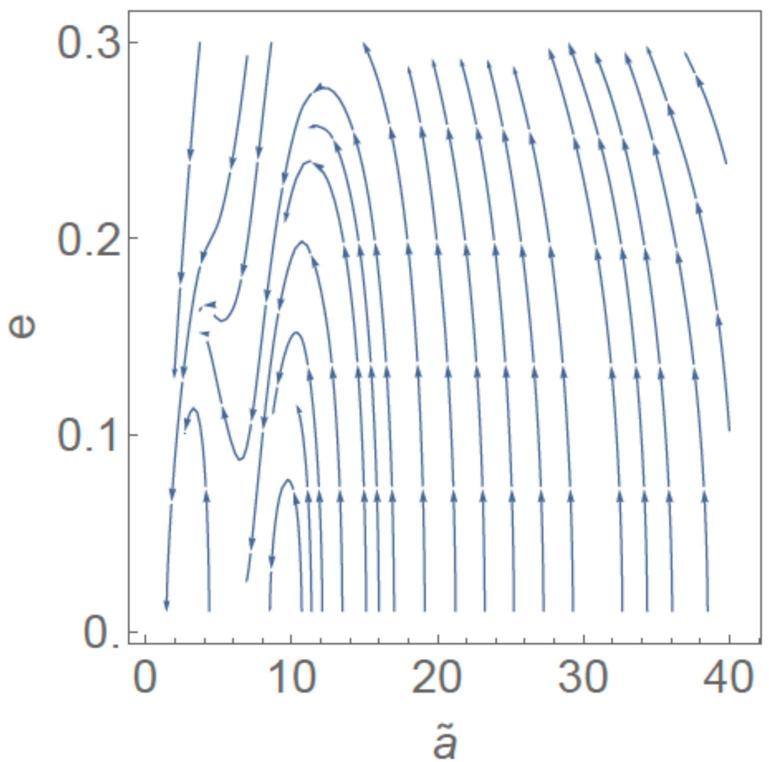
Eccentricity excitation

- Eccentricity may be excited due to coupling with cloud states, which offers an explanation for the eccentric BHNS : GW200105

Ao Guo, Qi-yan Zhang, HY, Jun Zhang, (2025)

$$e \sim \mathcal{O}(0.1) \times \left(\frac{\alpha}{0.1}\right)^3 \left(\frac{5M_\odot}{M}\right)$$





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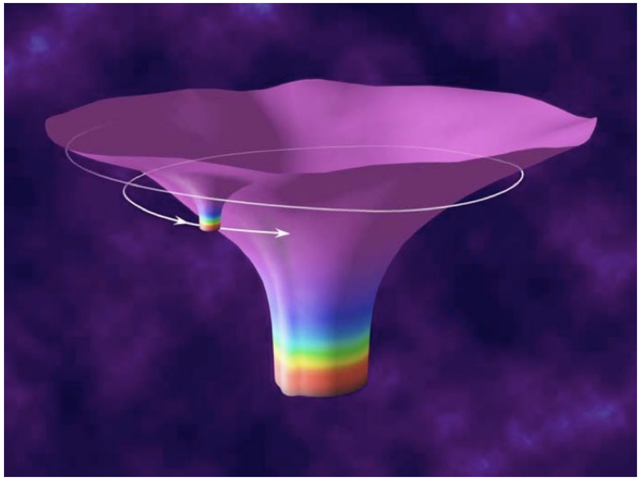
Extreme Mass Ratio Inspirals (EMRIs)

- Extreme mass-ratio inspirals: stellar-mass object (black holes, neutron stars, compact stars) orbiting around the massive black hole (10^5-10^7 solar mass).
- A typical EMRI is in-band for 10^4-10^5 cycles.
- EMRI→ideal tool for measuring small perturbations: opportunities for studying astrophysics and fundamental physics



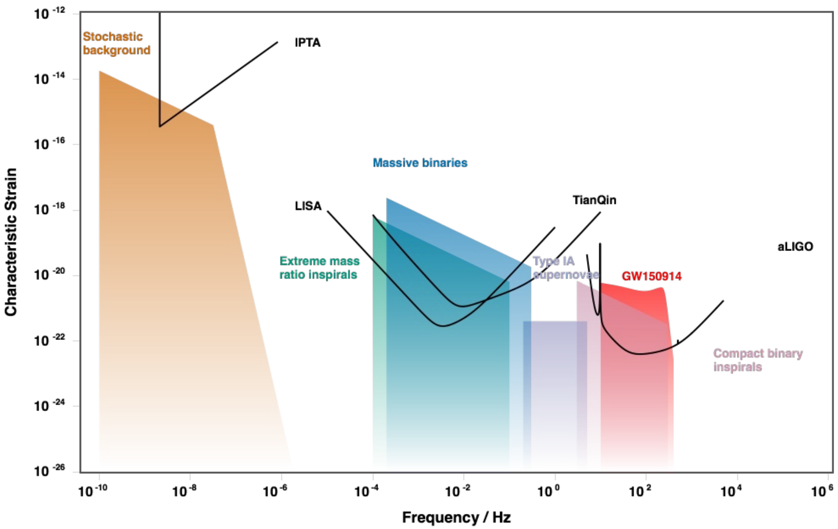
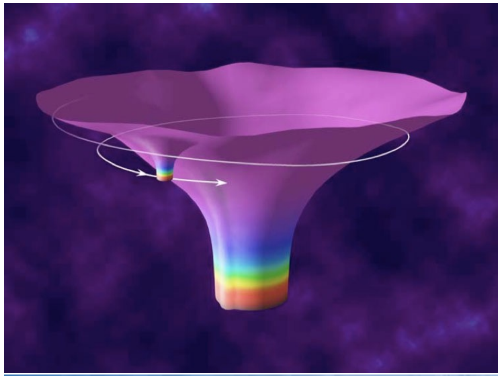
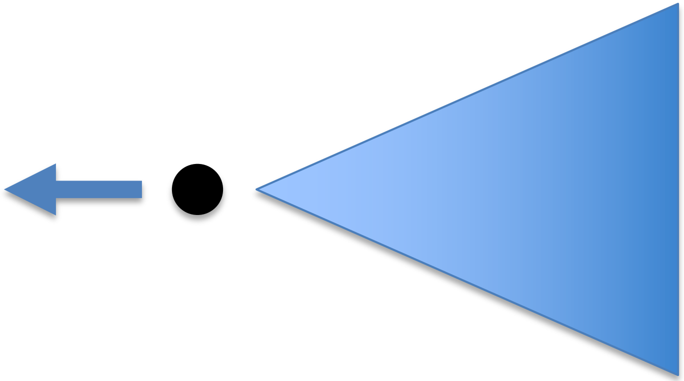


Figure adapted from gwplotter.com

Cloud interaction: extreme mass-ratio inspirals

- Cloud possibly exists for EMRIs due to BH superradiance. Main interaction: dynamical friction [Zhang, HY, PRD 2020], modified gravitational potential, modified gravitational wave flux.



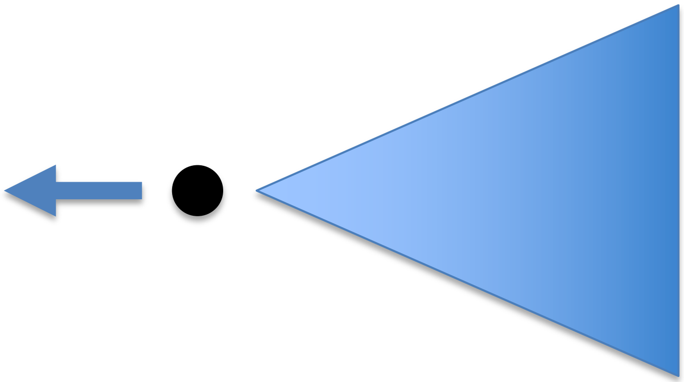


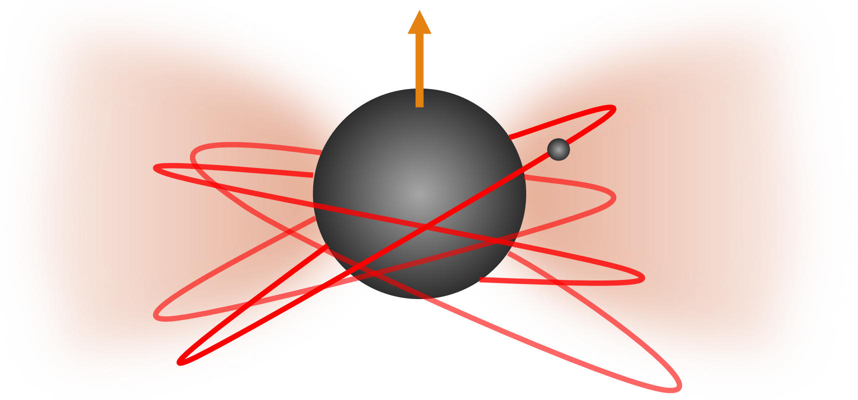
EMRIs within a cloud

- There are two major dissipation channels: scalar radiation and gravitational wave radiation.

- Scalar radiation is physically equivalent to the dynamic friction of the scalar field on the point mass.

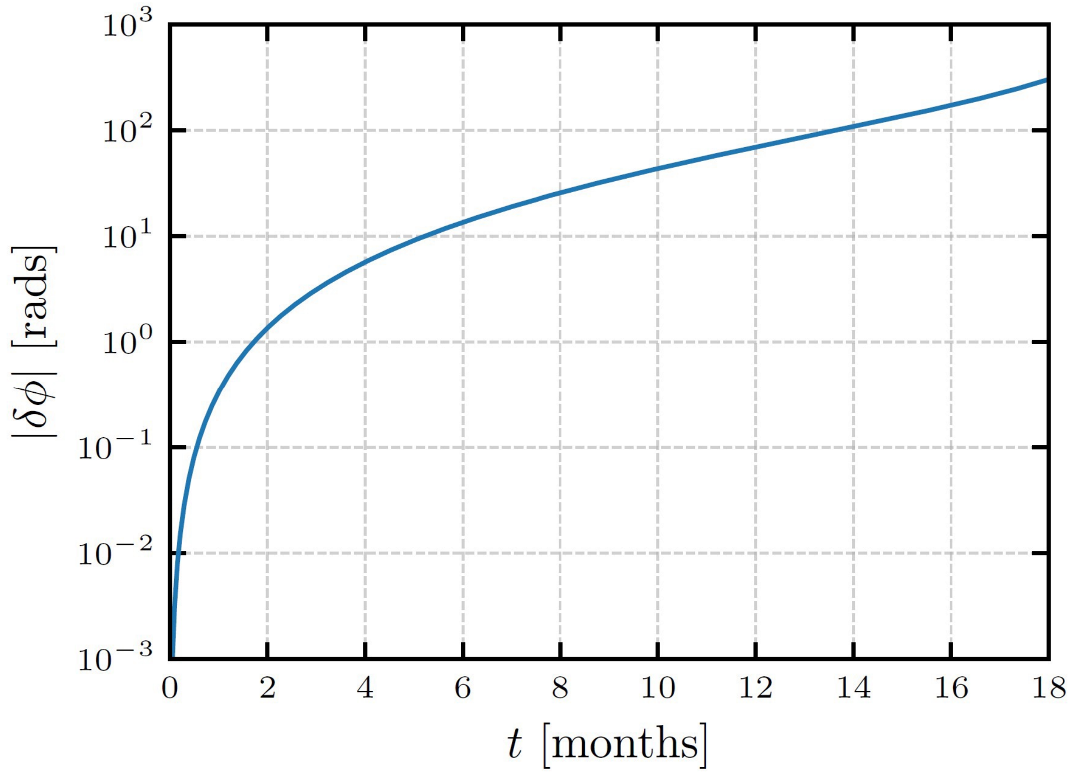
- The modulation of gravitational radiation needs to be computed using the modified Teukolsky equation [Dongjun Li, et al. HY in preparation]





Scalar sector

$$M = 10^6 M_\odot,\ \epsilon = 10^{-5},\ \mu M = 0.3,\ M_c = 10^{-4} M,\ a = 0.88M$$



(Li, Weller, Bourg, LaHaye, Yunes, & HY, arXiv 2507.02045)

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Probing ALPs with neutron stars

- Light axions may be sourced by neutron stars due to coupling with nuclear matter. Phase transitions occurs if NS radius is > some critical value.

$$V(a) = -m_\pi^2 f_\pi^2 \epsilon \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a}\right)} - m_\pi^2 f_\pi^2 \left[\left(\epsilon - \frac{\sigma_N n_N}{m_\pi^2 f_\pi^2}\right) \left|\cos\left(\frac{a}{2f_a}\right)\right|\right.$$

- This generally happens if $f_a < 10^{18}$Gev. Axion profile shows up.

$$Q_{1,2} = \pm 4\pi^2 f_a R_{1,2}$$

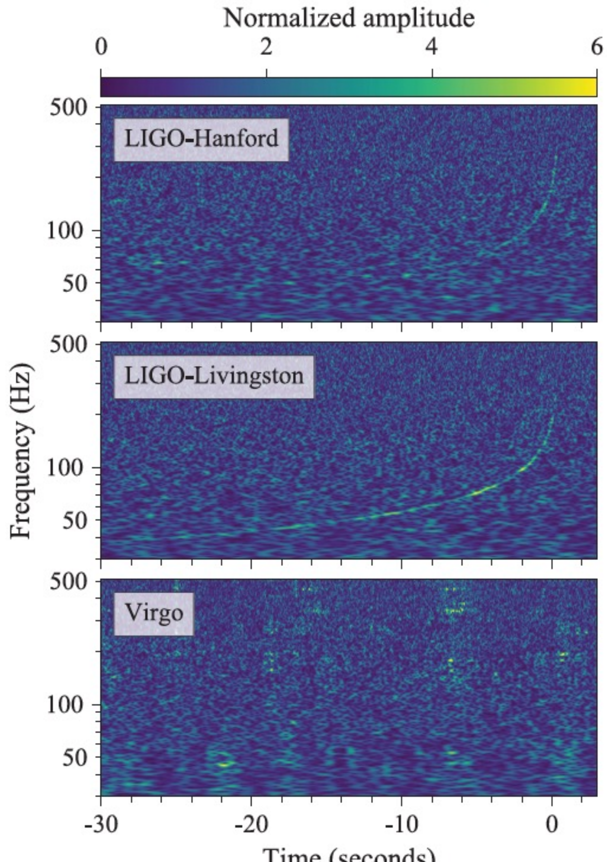
- Each NS carries an Axion charge $Q_{1/2}$. The dipole radiation of Axion field also takes away orbital energy, so the GW phase is modified.

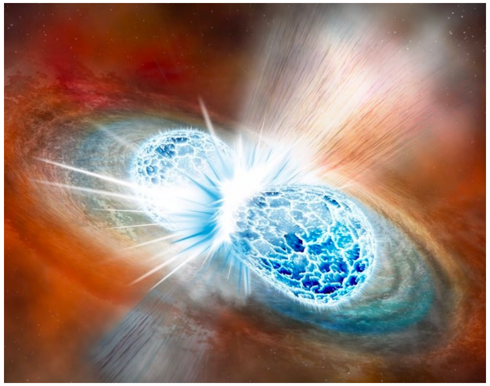
$$P_a = \frac{(Q_1 M_2 - Q_2 M_1)^2}{12\pi (M_1 + M_2)^2} r^2 \Omega^4 \left(1 - \frac{m_a^2}{\Omega^2}\right)^{3/2}$$

Zhang,.., HY, PRL 2021

Constraints from GW170817

- A modified gravitational waveform due to axion radiation and modification in the binding energy can be derived.
- With the BNS data from GW170817 the axion field interaction strength can be constrained using Bayesian parameter estimation.





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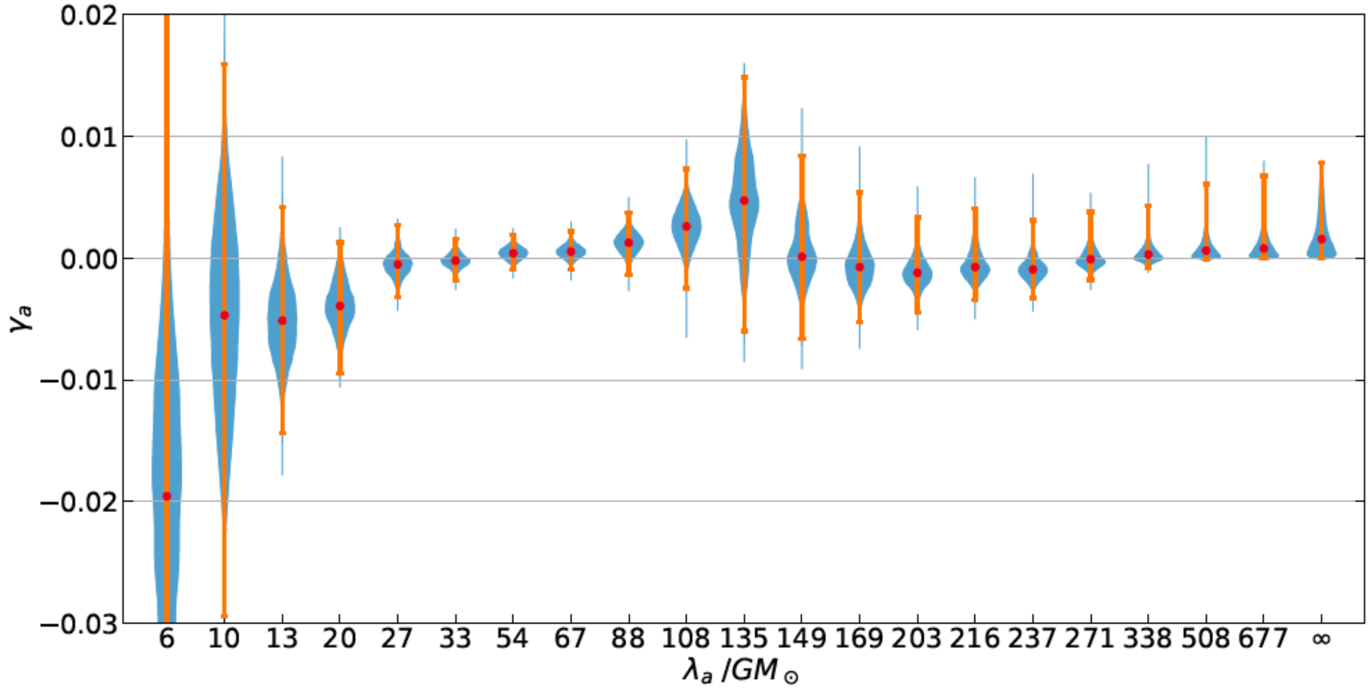
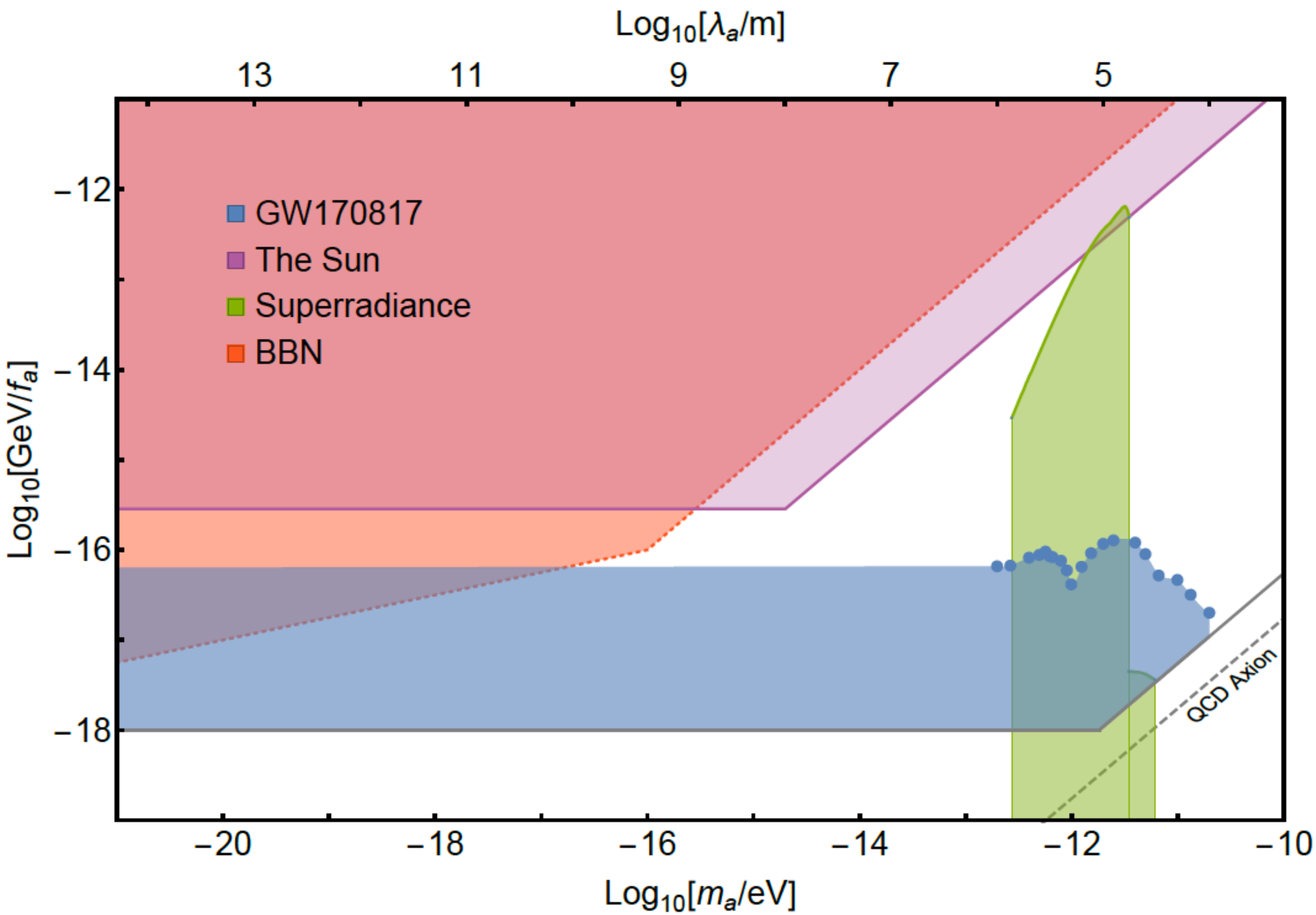


ALP Constraint from GW170817



Conclusion

- Axions may be excited around spinning black holes if wavelength comparable to BH size.
- Existing constraints using BH spin, continuous wave, stochastic GW background. Next frontier is to understand the impact in binary motion.
- Extreme mass-ratio inspirals will also be ideal probe for avion clouds.
- Neutron star binary has already provided constrains on axions with nuclear couplings.