Probing ultralight particles with gravitational waves

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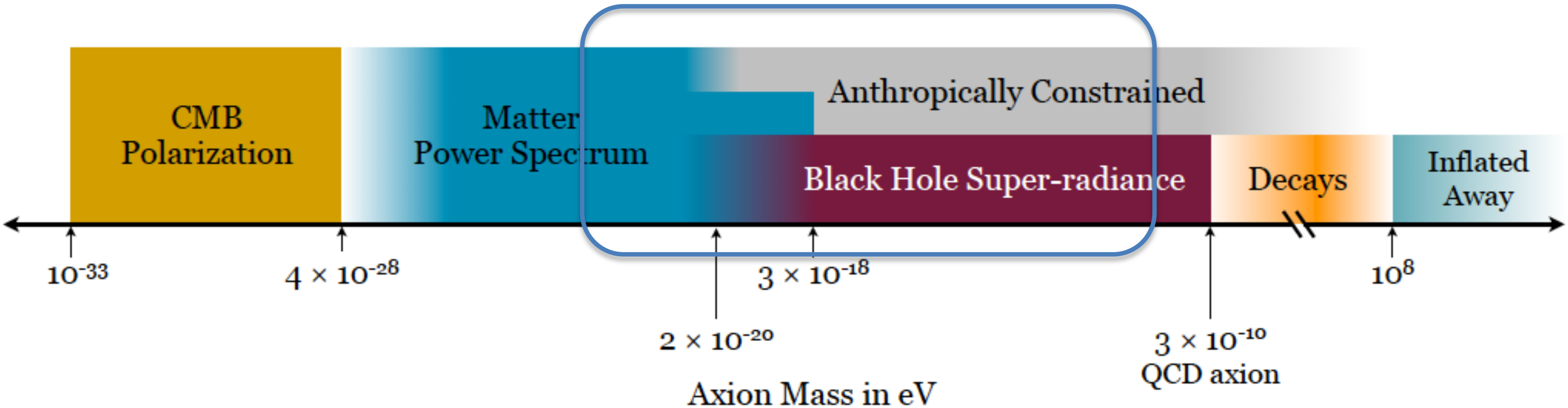
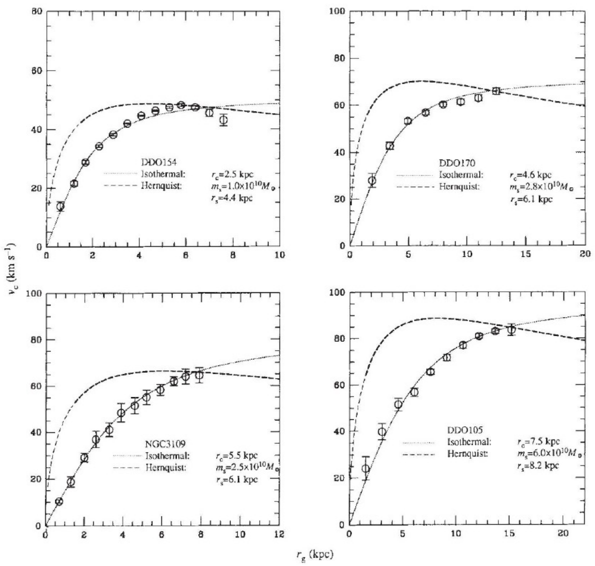
Axion-like particles

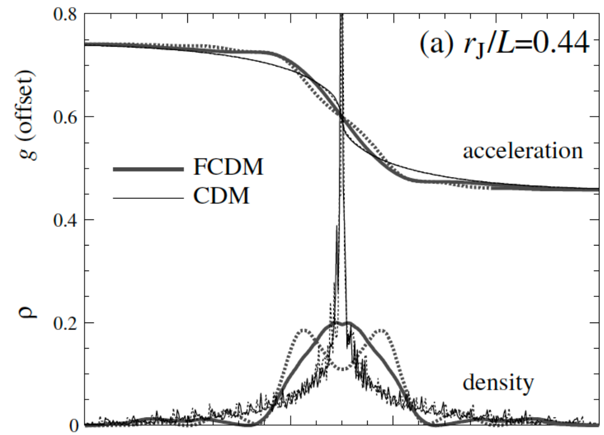


String Axiverse: Arvanitaki et al. PRD 2010

Fuzzy Dark Matter

- Fuzzy dark matter was initially introduced to explain the cuspy core problem [Ben Moore, Nature 1994] [Wayne, Barkana, Gruzinov, 2000]





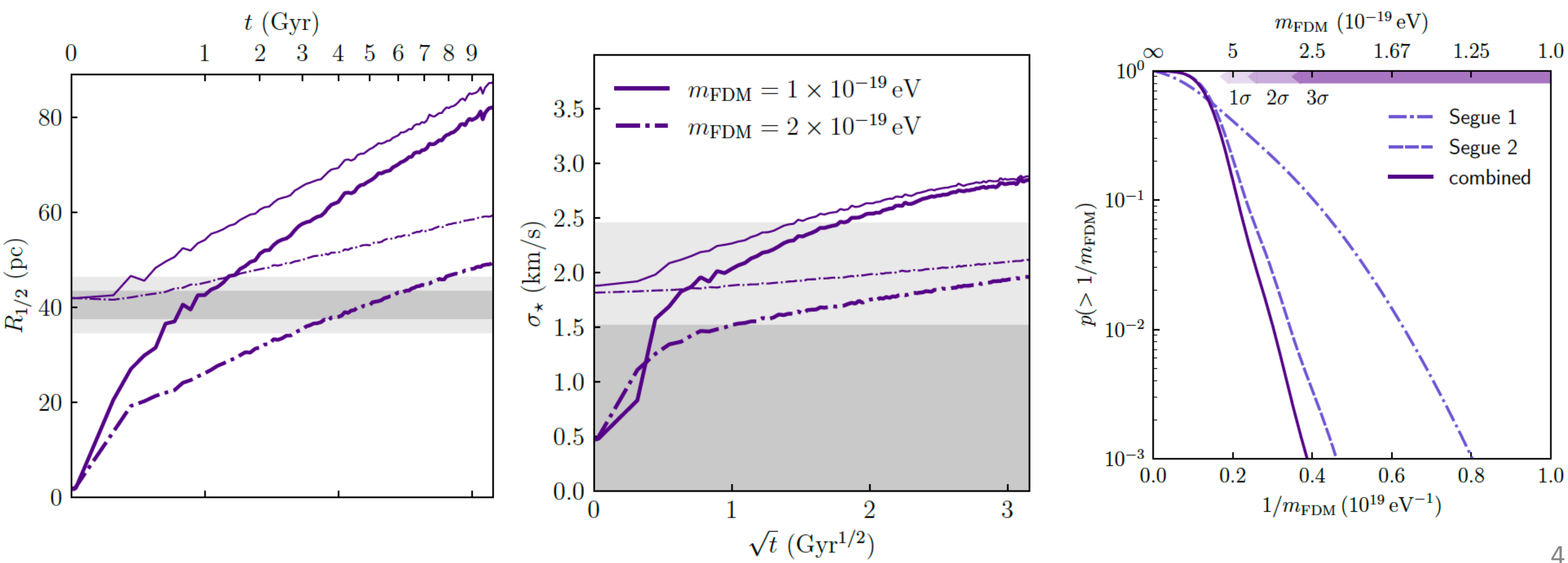
- The relevant de Broglie wavelength ~ 1kpc, particle mass ~10^{-22} eV

- Many existing constraints: PTA, lensing, Lyman-α forest, 21cm measurement, etc.

Dwarf galaxy constraints on Fuzzy Dark Matter

- Gravitational potential fluctuation of fuzzy dark matter will dynamically heat the star motion, especially in ultra-faint dwarf galaxies (velocity dispersion < 3km/s and size < 40 pc).

- Measurements of stellar velocities of Segue 1 and Segue 2 ultra-faint dwarf galaxies places strongest constraint on the axion mass < 3 10^{-19} eV [Dalal, Kravtsov 2022]



Content

- Axion as a dark matter candidate. Previous discussions
- Binary black holes with axion clouds
  - Cloud evolution for astrophysical stellar-mass black hole binary
  - Influence on the EMRI (extreme mass-ratio inspiral) and stellar-mass binary waveform
- Neutron star binary constraints

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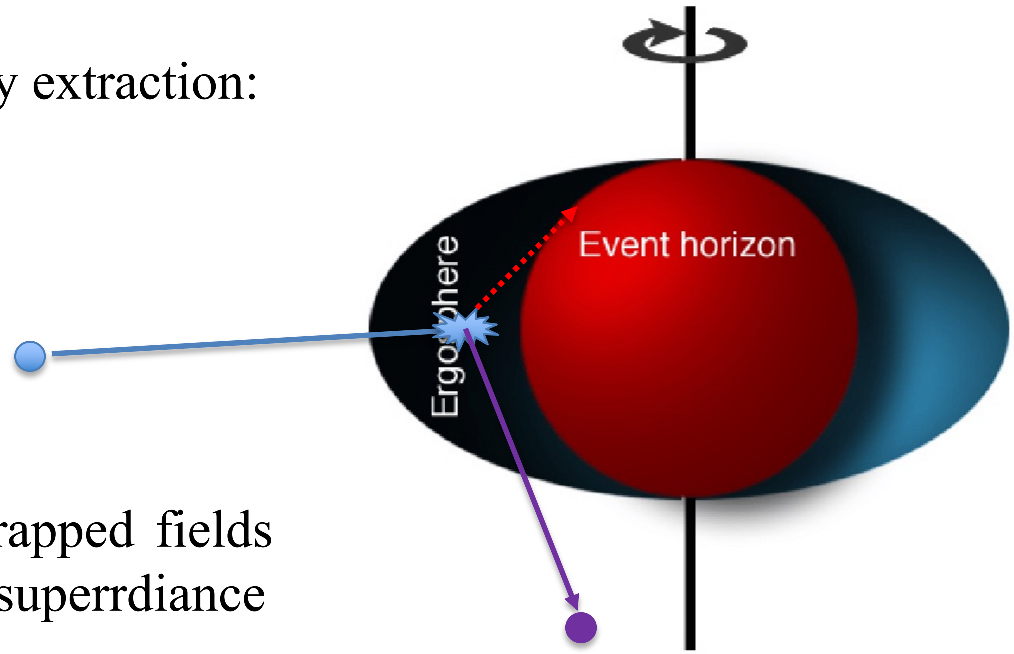
Black hole superradiance

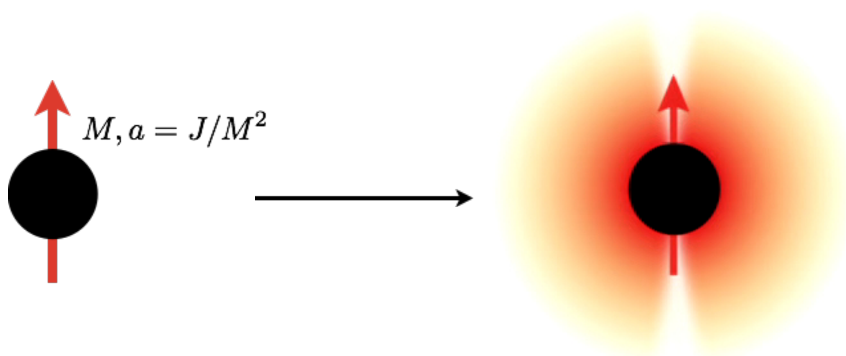
- Penrose process with energy extraction:

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

$\rightarrow E_1 > E_3$



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



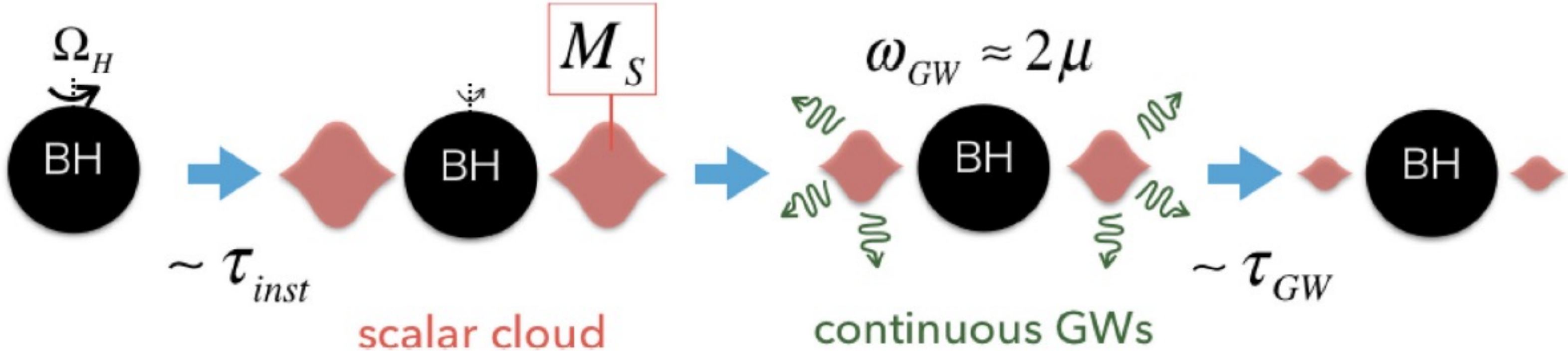
Penrose 1969
Press & Teukolsky 1972
Zouros & Eardley 1979
Detweiler 1980

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 $(0.1/\alpha)^9 (\text{M}/10\, M_\odot)$
  - GW radiation decay timescale ~ 10^9 years $(0.1/\alpha)^{15} (\text{M}/10\, M_\odot)$
- Cloud mass ~ α M

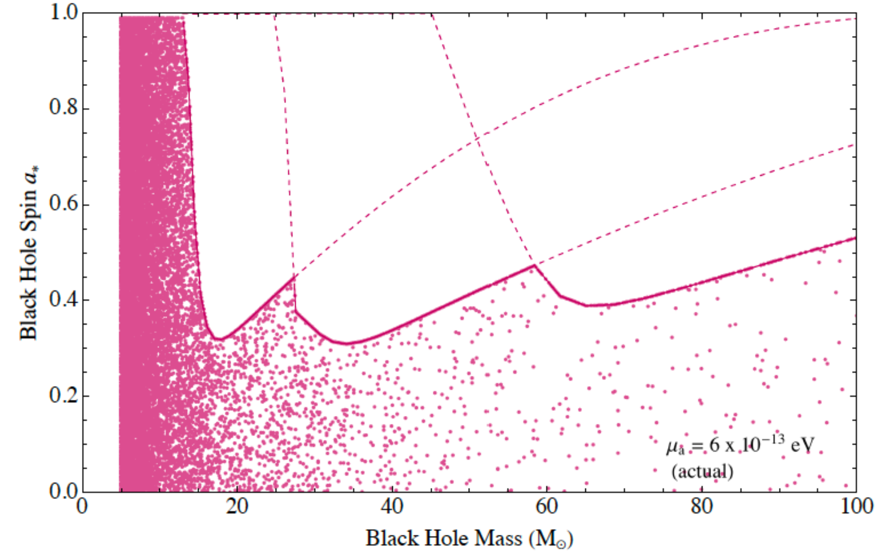


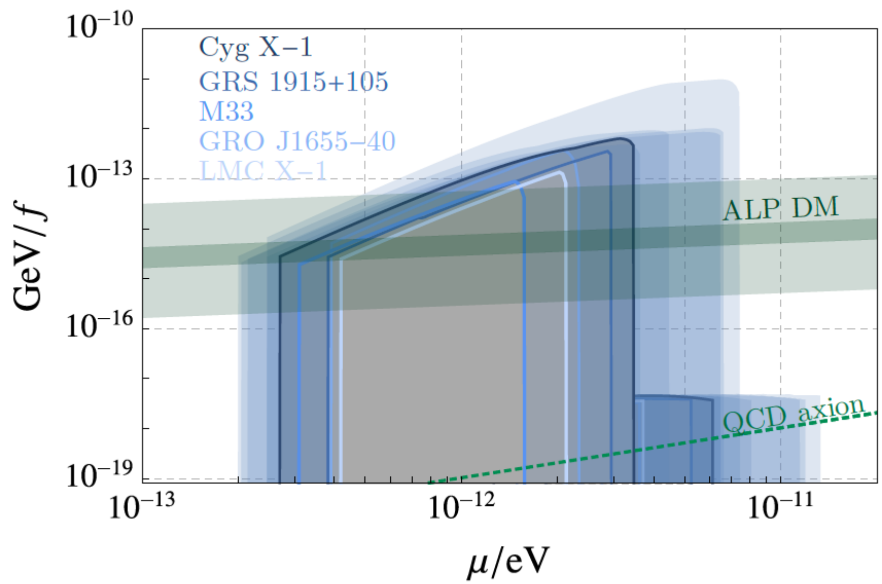
Black hole spin constraint

- 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…

- Future LIGO and LISA observations can be used to place constraints for 5 to 6 orders of magnitude.

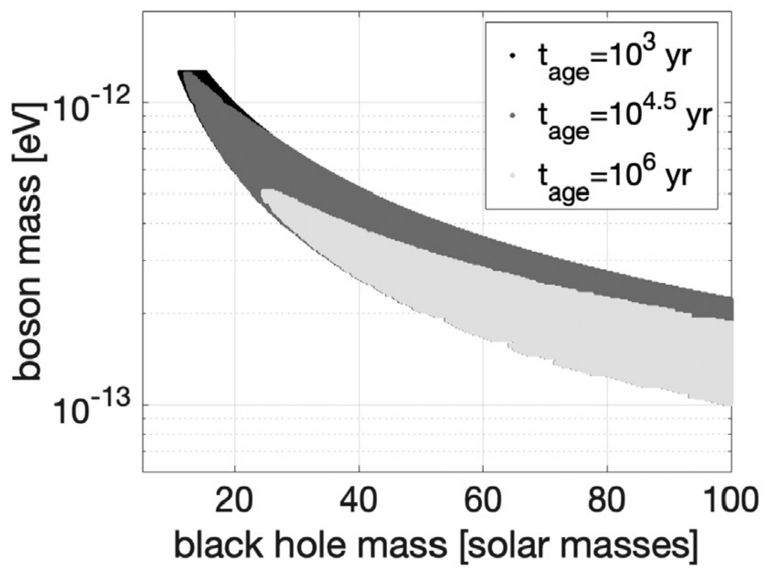


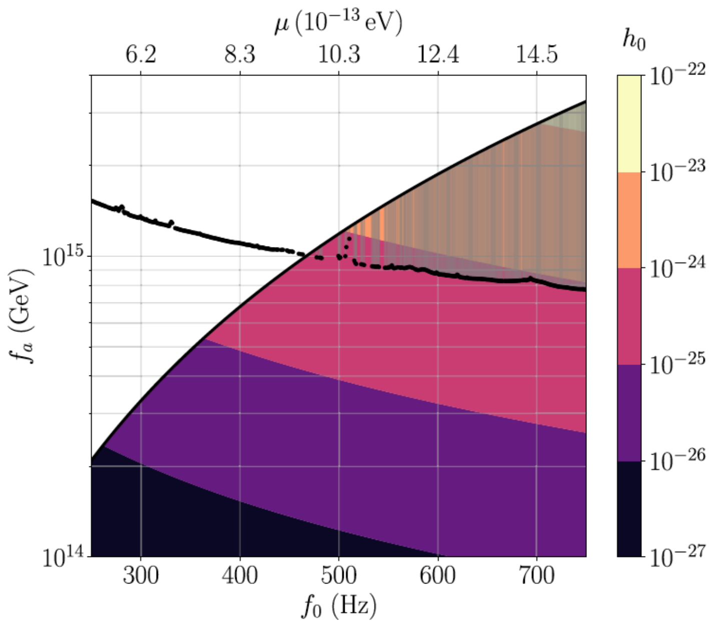


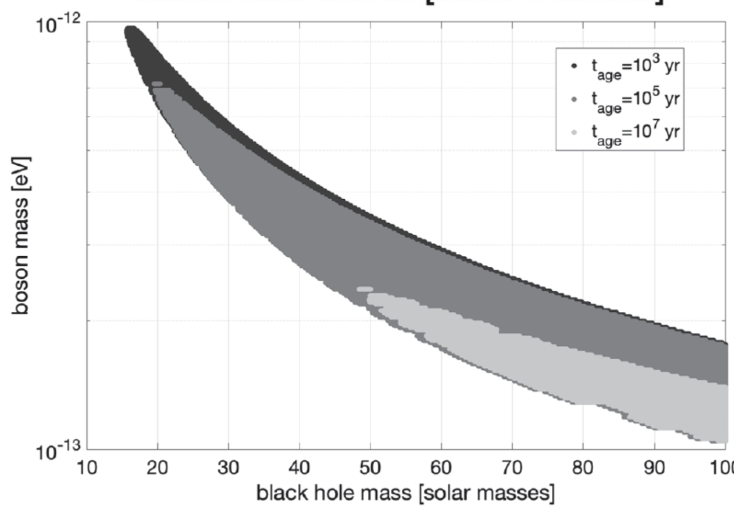
Baryakhtar et al, PRD (2016)

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.



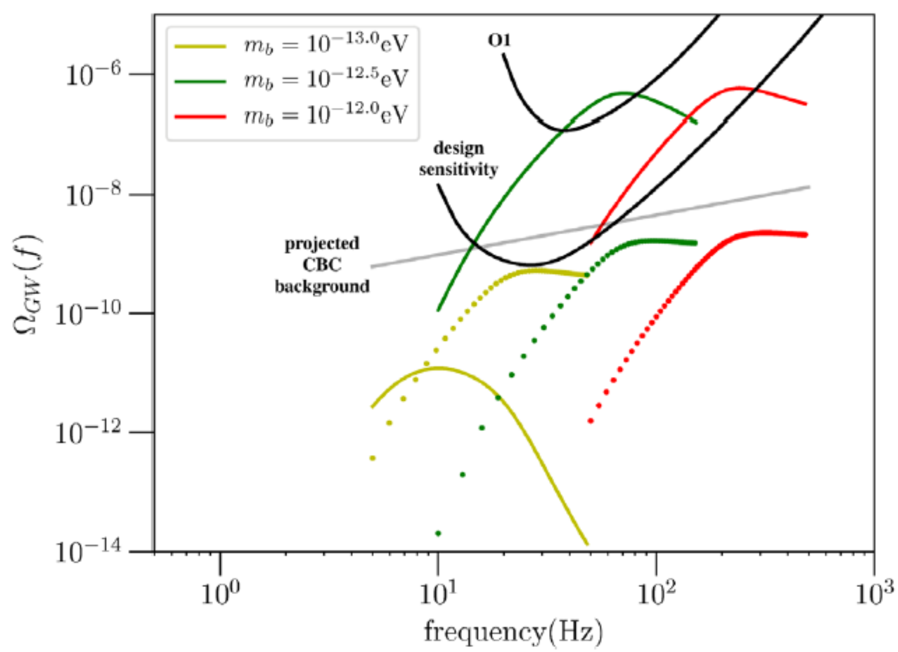


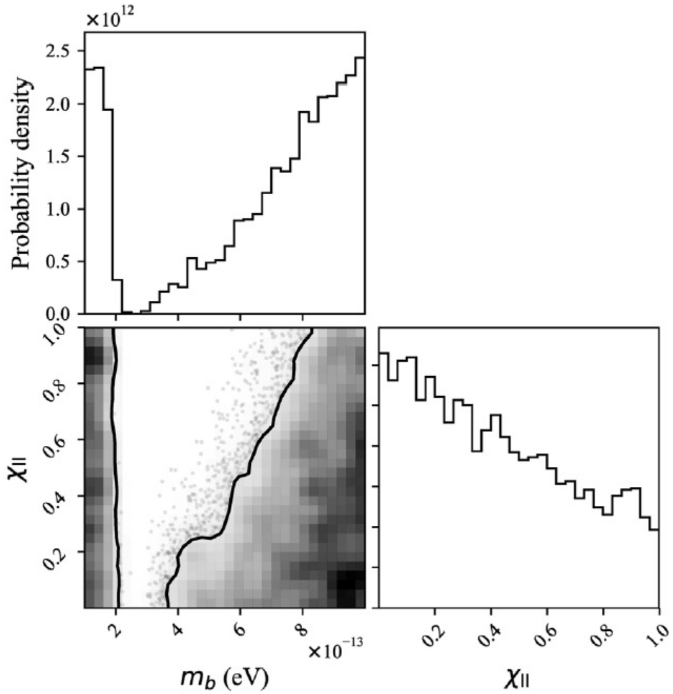


Cloud radiation: stochastic background

- 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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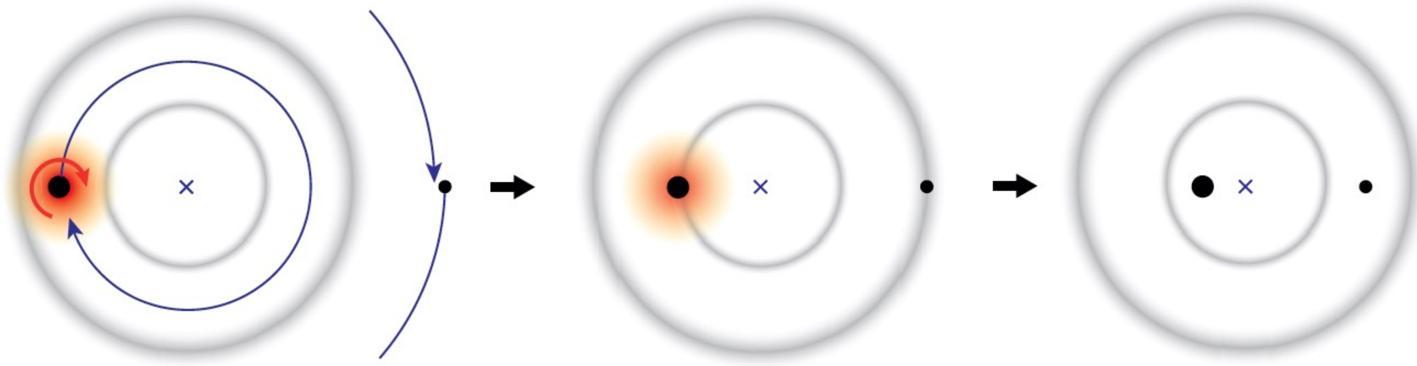
Cloud dynamics in black hole binary

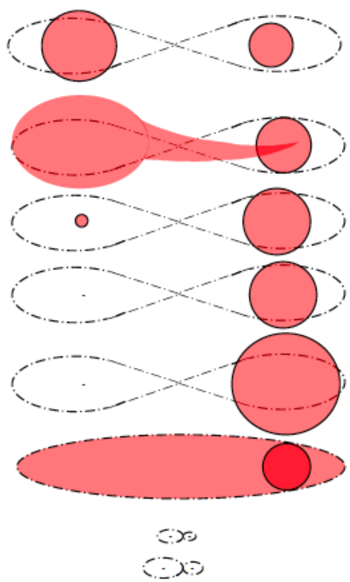
- Binary companion's tidal field induces level mixing in the cloud (Baumann et al. 2018). Excitation of decaying modes at resonance may lead to cloud depletion.



- 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

Astrophysical black hole binary evolution

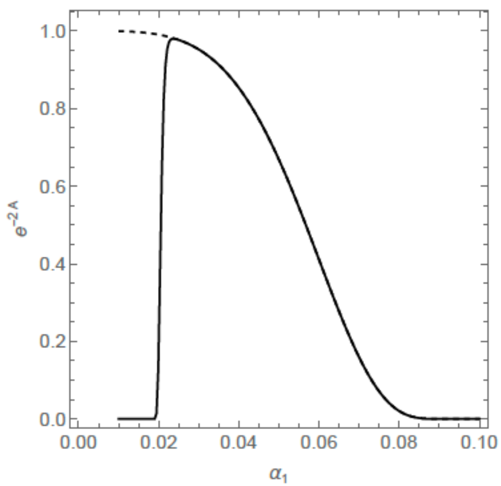
- Black hole binary observed by LIGO or LISA will likely experience processes that significantly reduce the binary separation in a short time, i.e. the common envelope phase, so that the binary can merge in cosmic time. The cloud evolution has to be considered in such realistic setting [Zhang, Guo, HY,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

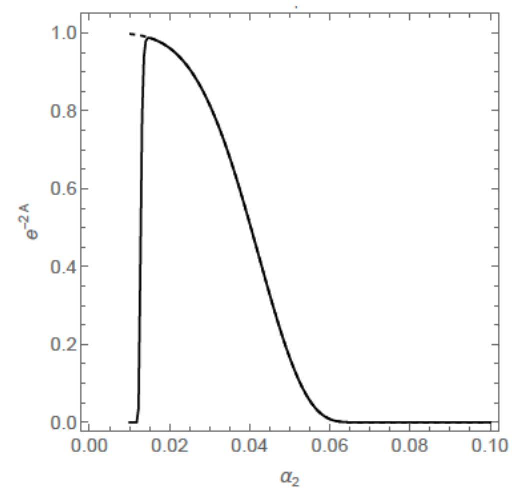


Time[Myr]	$M_1[M_{sun}]$	ST_1	ST_2	$M_2[M_{sun}]$	$a[R_{sun}]$
0.0	63.6	MS	MS	27.8	729.93
4.1	60.4	HG	MS	27.7	757.5
4.12	24.6	HeMS	MS	30.6	622.07
4.49	19.1	BH	MS	30.6	692.7
7.21	19.1	BH	CHeB	30.3	697.48
7.42	19.1	BH	CHeB	29.7	706.33
7.42	19.1	BH	HeMS	10.6	5.18
7.88	19.1	BH	BH	5.7	8.82

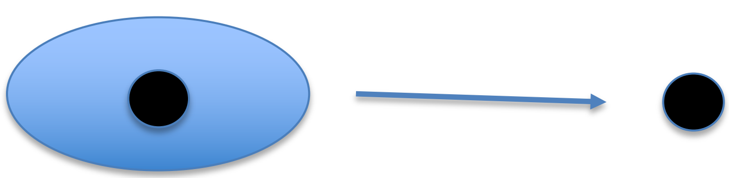
Cloud within LISA band

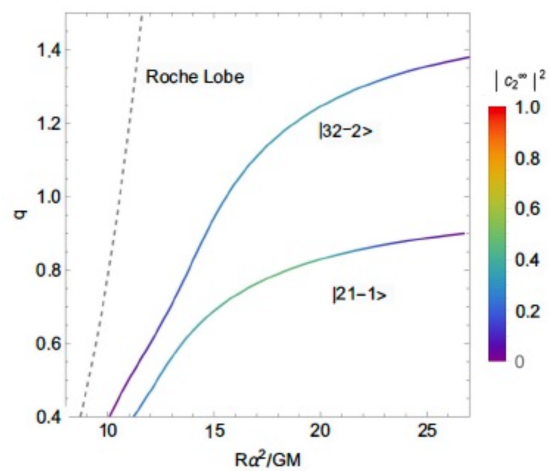
- We find significant parameter range where cloud survives to the LISA band:





- Before entering LIGO band, we find resonant cloud transfer between black holes. The fate in LIGO band unknown.

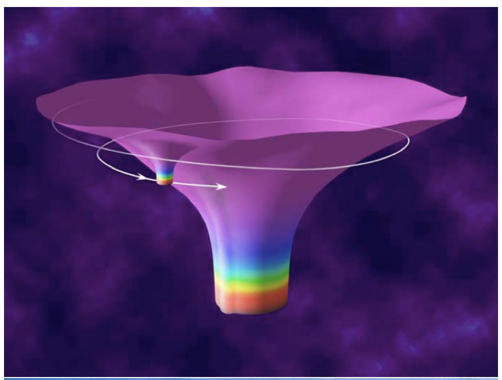


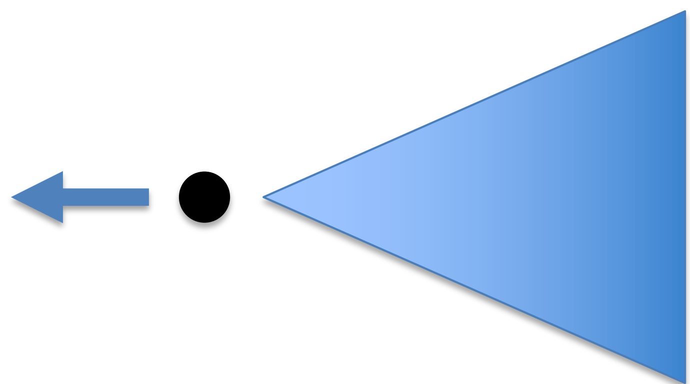


Cloud interaction: extreme mass-ratio inspirals

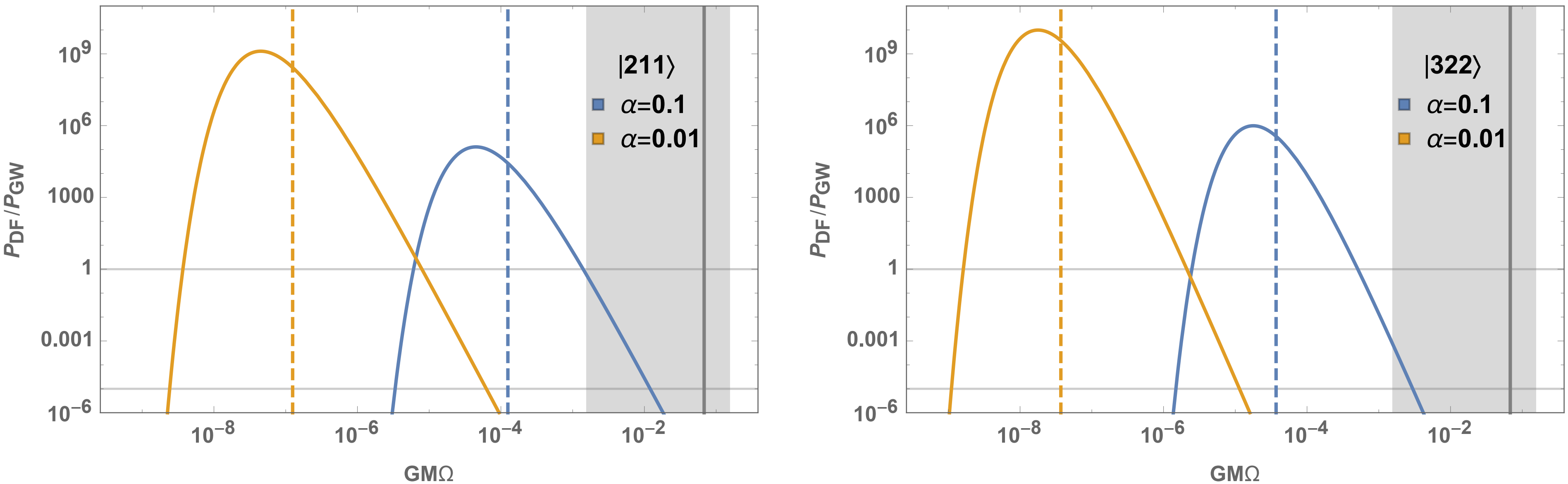
- Binary black holes with cloud(s) around individual BH may have dynamical influence on the binary motion.

- Cloud exists for EMRIs (extreme mass-ratio inspirals, one of main sources of LISA). Main interaction: dynamical friction [Zhang, HY, PRD 2020], modified gravitational potential, modified gravitational wave flux.





Detectable parameter range



Zhang, HY, PRD 2020

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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.

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

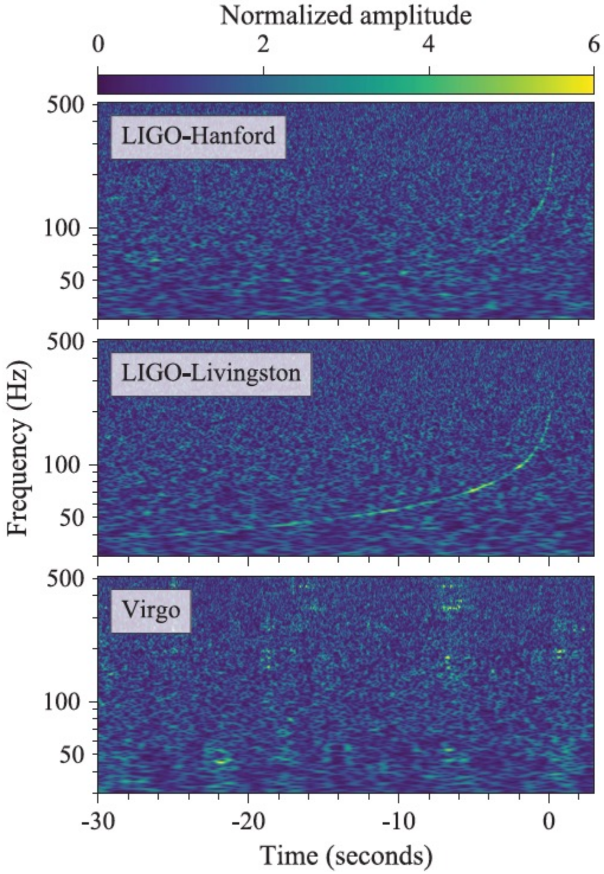
- Each NS carries an Axion charge $Q_{1/2}$. The dipole radiation of Axion field also takes away orbital energy, so the GW phase is modified.

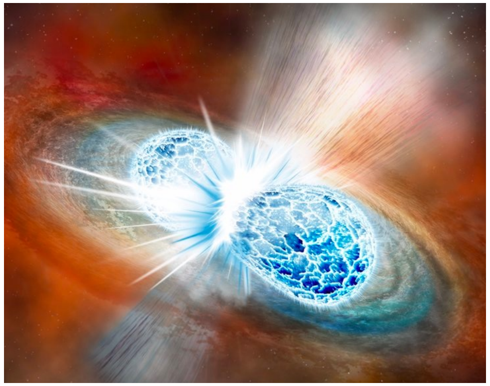
$$P_a = \frac{(Q_1 M_2 - Q_2 M_1)^2}{12\pi (M_1 + M_2)^2} r^2 \Omega^4 \left(1 - \frac{m_a^2}{\Omega^2}\right)^{3/2}$$

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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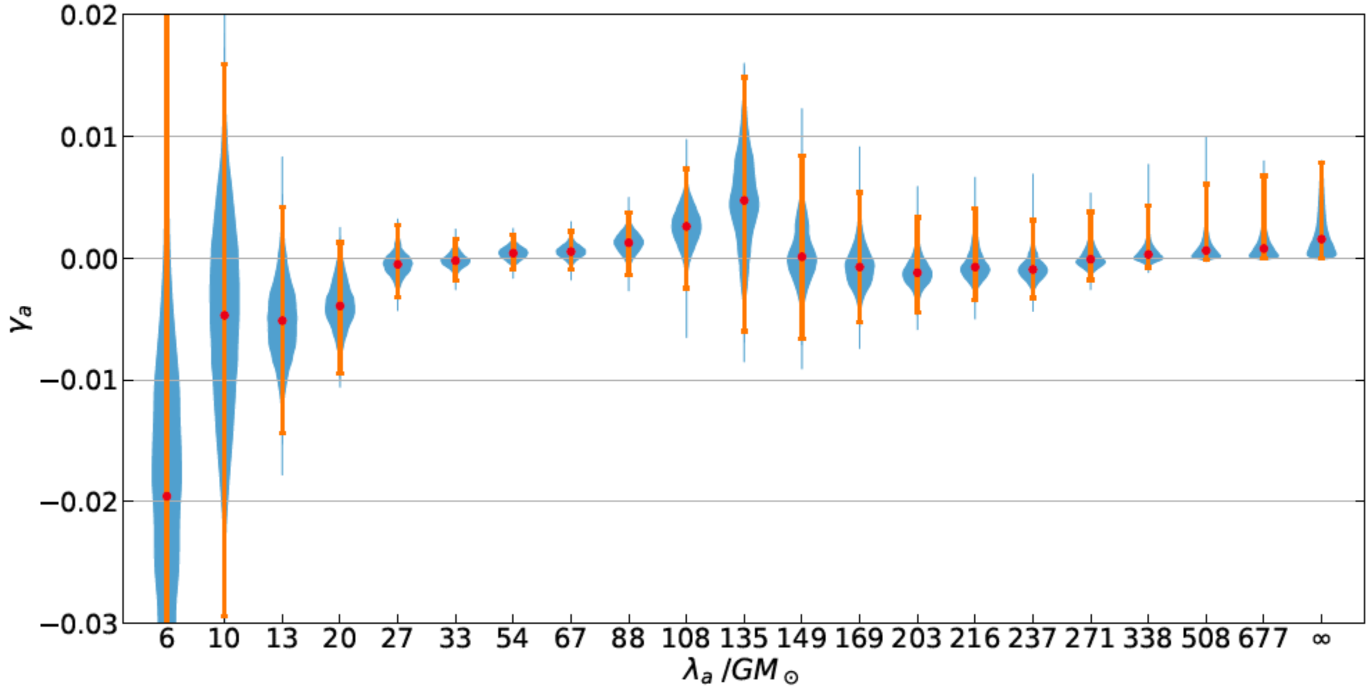
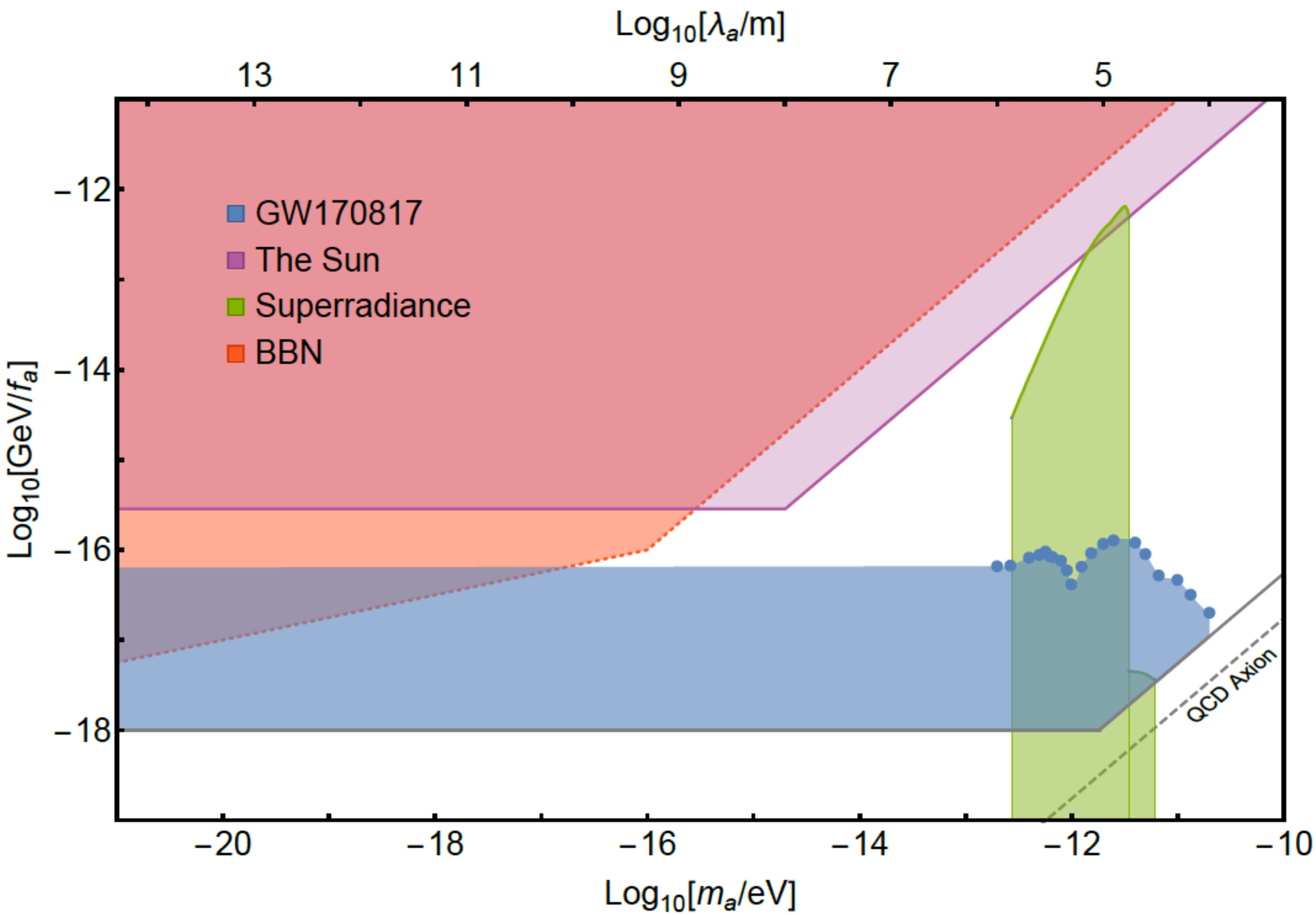


ALP Constraint from GW170817



Conclusion

- Rotating black holes may superradiantly excite ultra-light particles to form a “cloud”.
- By considering astrophysical evolution for BBH binaries, such clouds may survive up to the LISA band, or even the LIGO band.
- Extreme mass-ratio inspirals within Axion clouds may have modified dynamics and detectable phase shift (LISA).
- Binary neutron star merger event can be used to constrain Axion models with coupling to the nuclear sector.