Axion Cloud Decay

due to the Axion-photon Conversion with Background Magnetic Fields

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in collaboration with : **Chul-Moon Yoo,** Yusuke Sakurai,

Keitaro Takahashi, Yohsuke Takamori, Daisuke Yamauchi

accepted by PASJ (arXiv:2103.13227)

Axion

QCD axion, string axion, … etc

- I will skip all the details about axion

  -> see Obata-san's talk

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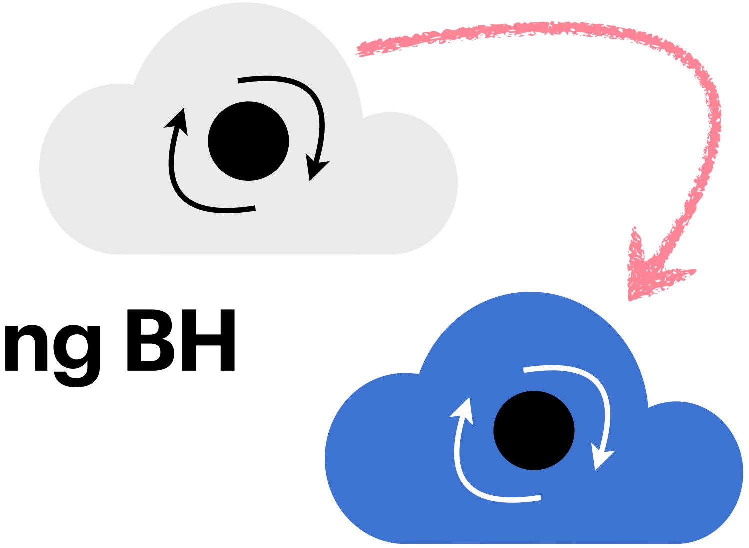
axion cloud

= quasi bound state of axion around a rotating BH

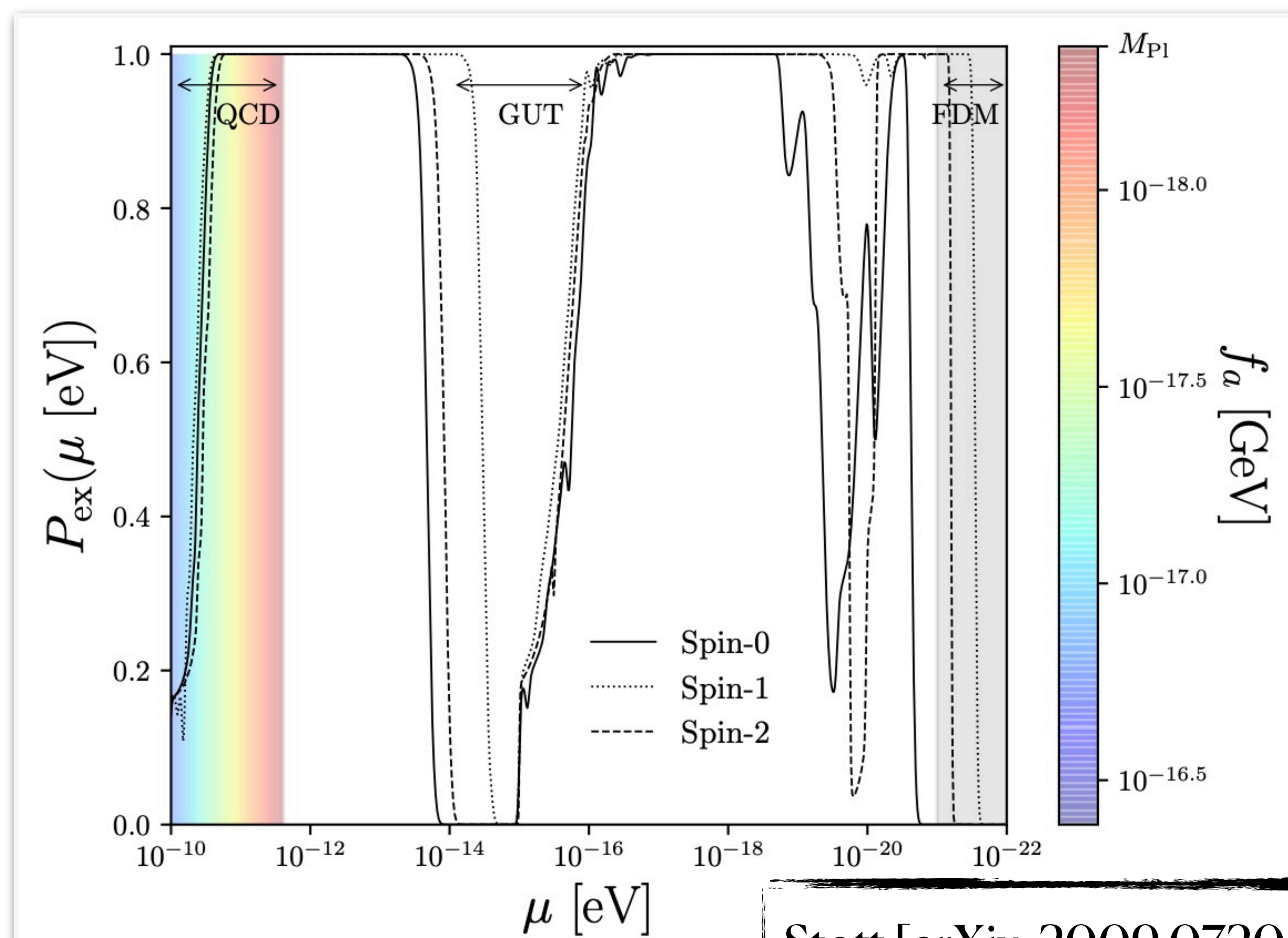


- axion cloud may grow by the **superradiant instability**.

- axion may efficiently extract the angular momentum of a BH

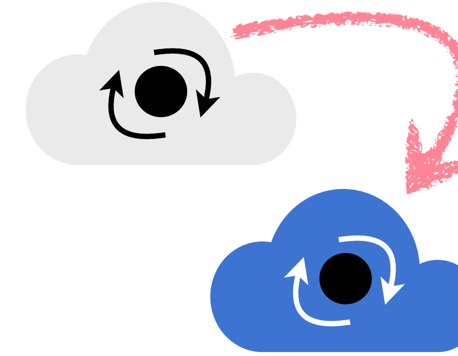
  ⇒ no rotating black holes
  in our universe ?

  ⇒ constraints on axion
  (its mass & coupling)
  from the existence of
  spinning BHs



Stott [arXiv: 2009.07206]

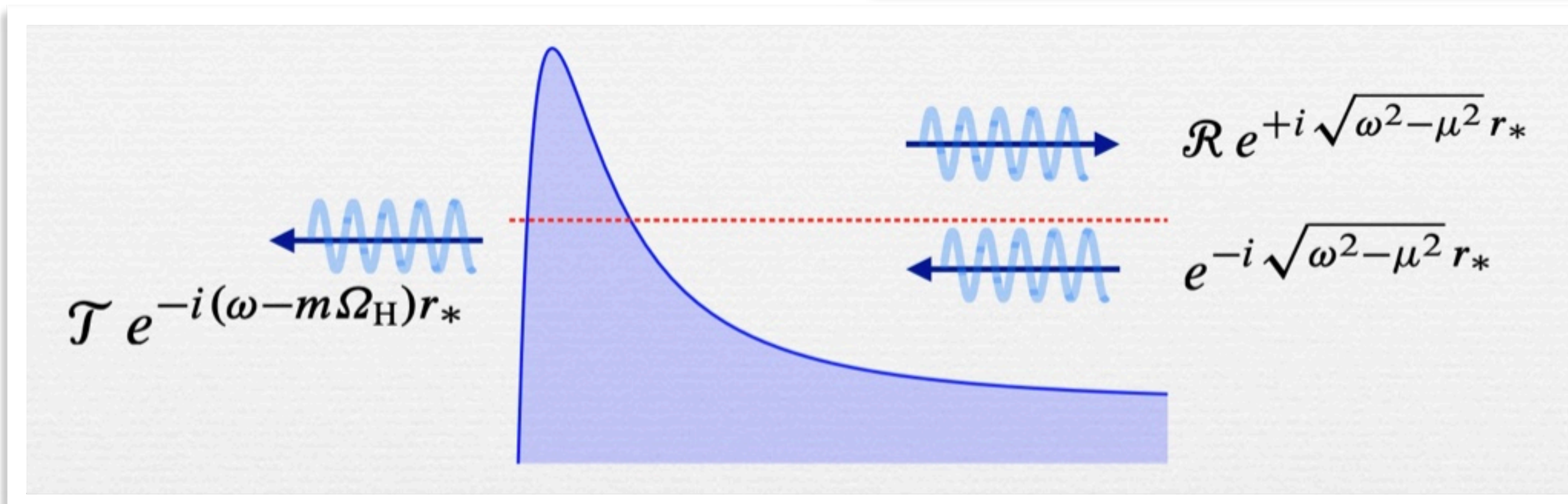
superradiant instability



Ω_H

- axion around a Kerr BH : $\phi = e^{-i\omega t} e^{im\varphi} S(\theta)\Phi(r)$

$$(\Box^{\text{Kerr}} - \mu^2)\phi = 0 \longrightarrow \boxed{-\frac{\mathrm{d}^2}{\mathrm{d}r_*^2}\Phi + V_{\text{eff}}\,\Phi = \omega^2\Phi}$$



$$|\mathcal{R}|^2 + \frac{\omega - m\Omega_{\rm H}}{\sqrt{\omega^2-\mu^2}}|\mathcal{T}|^2 = 1$$

from Wronskian

for the modes ω - m ΩH > 0

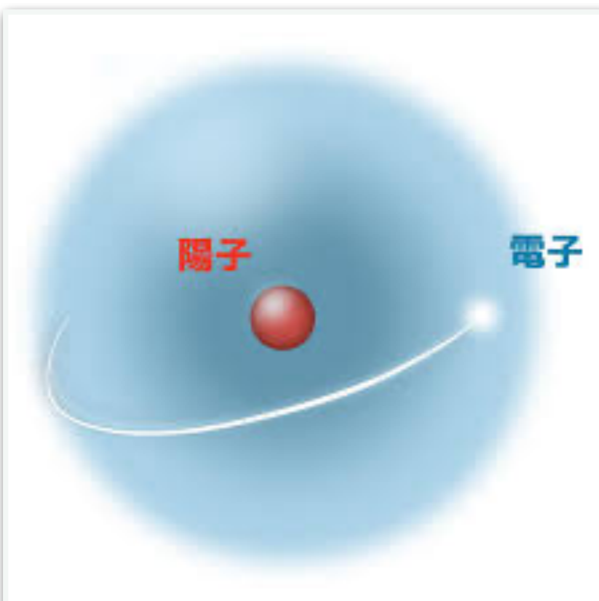
$$\boxed{|\mathcal{R}|^2 > 1}$$

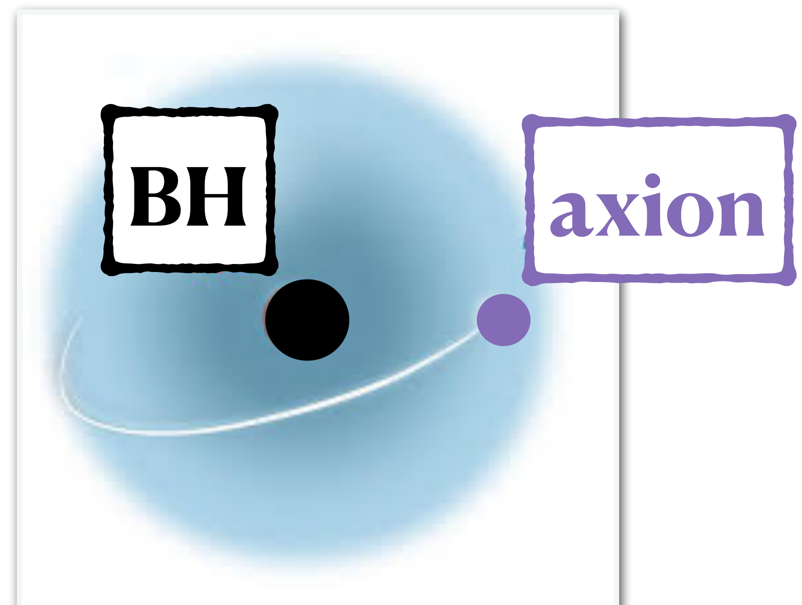
superradiance

Gravitational atom

similarity to a hydrogen atom

- the basic eq. ~ that for a **hydrogen atom** in the far region :





hydrogen atom

⇔ **electro-magnetic force**

$\alpha = e^2/4\pi$

gravitational atom

⇔ **gravitational force**

$\alpha = G M_{BH} m$

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stability of the axion cloud

magnetic fields in the universe could affect the axion cloud ??

- Since the axion-BH system can be a GW source (cf. bosenova), the stability of the axion cloud draw much attention recently.

  → self-interaction of axion, gravitational back reaction, effect from the third body etc

  cf. 2012.03473

- Although axion (massive particle) cannot escape from a BH, photon (massless particle) can escape from a BH !!

- Magnetic fields are ubiquitous in the universe... any effect ??

Gravitational atom

✓ In the far region, eq. reduces to that for the **hydrogen atom**

$$\Box^{\mathrm{Kerr}}\,\Phi + m^2\Phi = 0$$

$$\left[-\frac{1}{2r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\frac{\mathrm{d}}{\mathrm{d}r}\right) - \frac{\alpha}{r} + \frac{\ell(\ell+1)}{2r^2} + \frac{1-\omega^2}{2}\right] R_0^{\mathrm{far}} = 0\,.$$

$$\Phi\left(t,\mathbf{r}\right) = e^{-i\omega t + im\phi}R(r)S(\theta)$$

$\alpha = G\, M_{BH}\, \mu$: gravitational fine structure constant

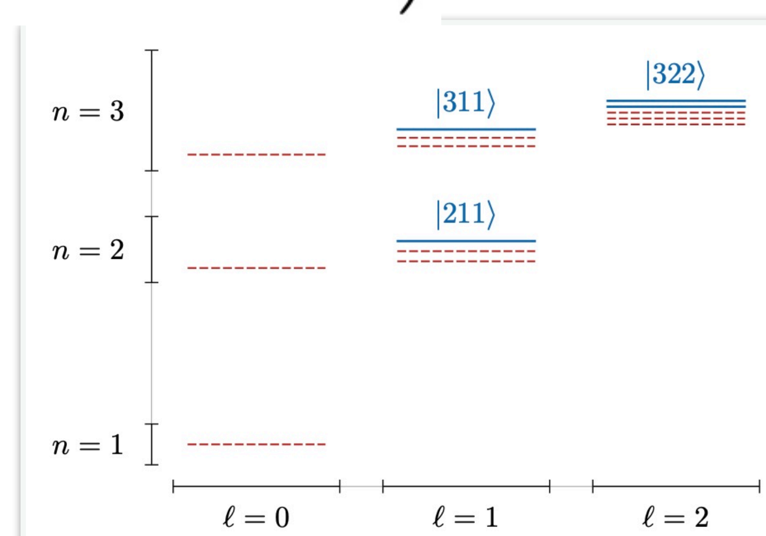
✓ The (complex) frequency of each eigenstate ($\omega = E + i\,\Gamma$):

$$E_{nlm} = \mu\left(1 - \frac{\alpha^2}{2n^2} - \frac{\alpha^4}{8n^4} - \frac{(3n-2l-1)\alpha^4}{n^4(l+1/2)} + \frac{2\tilde{a}m\alpha^5}{n^3 l(l+1/2)(l+1)} + O(\alpha^6)\right)$$

$$\Gamma_{nlm} = 2\tilde{r}_+ C_{nlm}(m\Omega_H - \omega_{nlm})\alpha^{4l+5}$$

$$T_{211}^{(\mathrm{growth})} \sim \frac{10^6\ \mathrm{yrs}}{\tilde{a}}\left(\frac{M_B}{M_\odot}\right)\left(\frac{0.012}{\alpha}\right)^9$$

$$T_{211}^{(\mathrm{deplete})} \sim 10^8\ \mathrm{yrs}\left(\frac{M_B}{M_\odot}\right)\left(\frac{0.053}{\alpha}\right)^{15}$$



[2009.11106]

Gravitational Collider Physics via Pulsar-Black Hole Binaries

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We propose to use pulsar-black hole binaries as a probe of gravitational collider physics. Induced by the gravitation of the pulsar, the atomic transitions of the boson cloud around the black hole back-react on the orbital motion. This leads to the deviation of binary period decrease from that predicted by general relativity, which can be directly probed by the Rømer delay of pulsar time-of-arrivals. The sensitivity and accuracy of this approach is estimated for two typical atomic transitions. It is shown that once the transitions happen within the observable window, the pulsar-timing accuracy is almost always sufficient to capture the resonance phenomenon.

[2106.13484]

GRAVITATIONAL COLLIDER PHYSICS VIA PULSAR-BLACK HOLE BINARIES II: FINE AND HYPERFINE STRUCTURES ARE FAVORED

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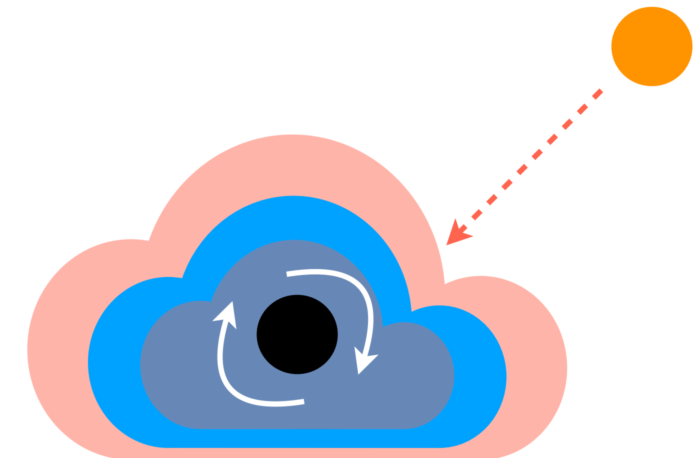
Abstract

A rotating black hole can be clouded by light bosons via superradiance, and thus acquire an atom-like structure. If such a gravitational atom system is companioned with a pulsar, the pulsar can trigger transitions between energy levels of the gravitational atom, and these transitions can be detected by pulsar timing. We show that in such pulsar-black hole systems, fine and hyperfine structure transitions are more likely to be probed than the Bohr transition. Also, the calculation of these fine and hyperfine structure transitions are under better analytic control. Thus, these fine and hyperfine structure transitions are more ideal probes in the search for gravitational collider signals in pulsar-black hole systems.

add a companion



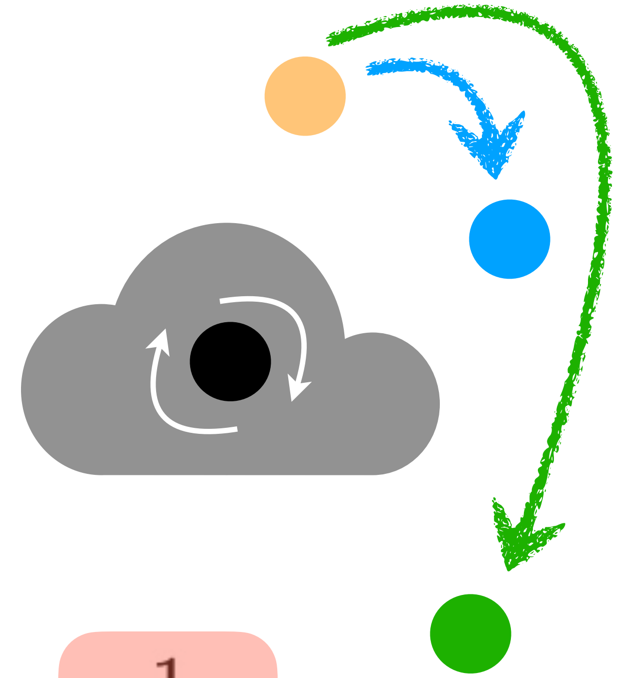
✓ A binary companion (BH or pulsar) exert **periodic gravitational perturbation** on the cloud.
→ induce resonances = **Landau-Zener transitions**

✓ **diabatic (not adiabatic) transition** b/w the two energy states (no such transition will take place through an adiabatic process)

✓ The transitions are accompanied by **energy exchanges b/w the cloud and the binary companion**.

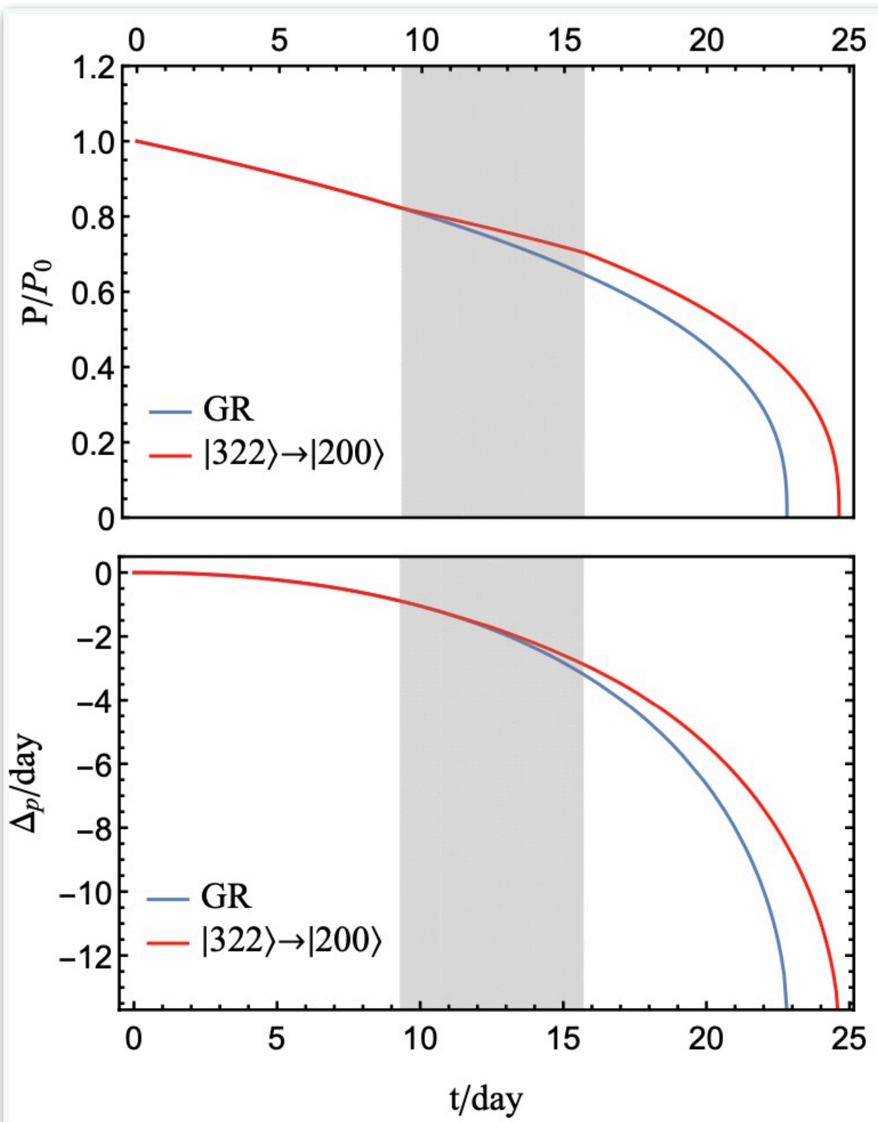
✓ **floating** : the cloud releases its energy → sink slower
sinking : the cloud drains energy → sink faster
⇒ distinctive deviations from the orbital period derivative in GR

Resonances



✓ The changing rate of the orbital period

$$\dot{P} = -\frac{96}{5}(2\pi)^{8/3}(GM_B)^{5/3}\frac{q}{(1+q)^{1/3}}P^{-5/3} \times \boxed{\frac{1}{1 \pm \delta}}$$



+ for floating & - for sinking

q = M_{pulsar}/M_{BH}

$$\delta = \frac{\Delta t_c}{\Delta t} \simeq \frac{1}{4}\frac{(1+q)^{4/3}}{q^2}\left(\frac{\alpha}{0.07}\right)\frac{S_{c,0}}{M_B^2}$$

Sc,0 : initial angular momentum of the cloud
Δt : original resonance duration
Δtc : the extra resonance duration

Figure 3. Upper panel: Orbital period as a function of time during a floating-orbit resonance $|322\rangle \rightarrow |200\rangle$. Lower panel: The deviation in the periastron time shift due to this resonance. The gray region represents the total resonance time $\Delta t + \Delta t_c$. The parameters are chosen as $M_B = 4M_\odot$, $M_P = 1.4M_\odot$, $\alpha = 0.1$, $e = 0$. The resonance period under this set of parameters is $P_r = 3.6$ s.

Radio sensitivity

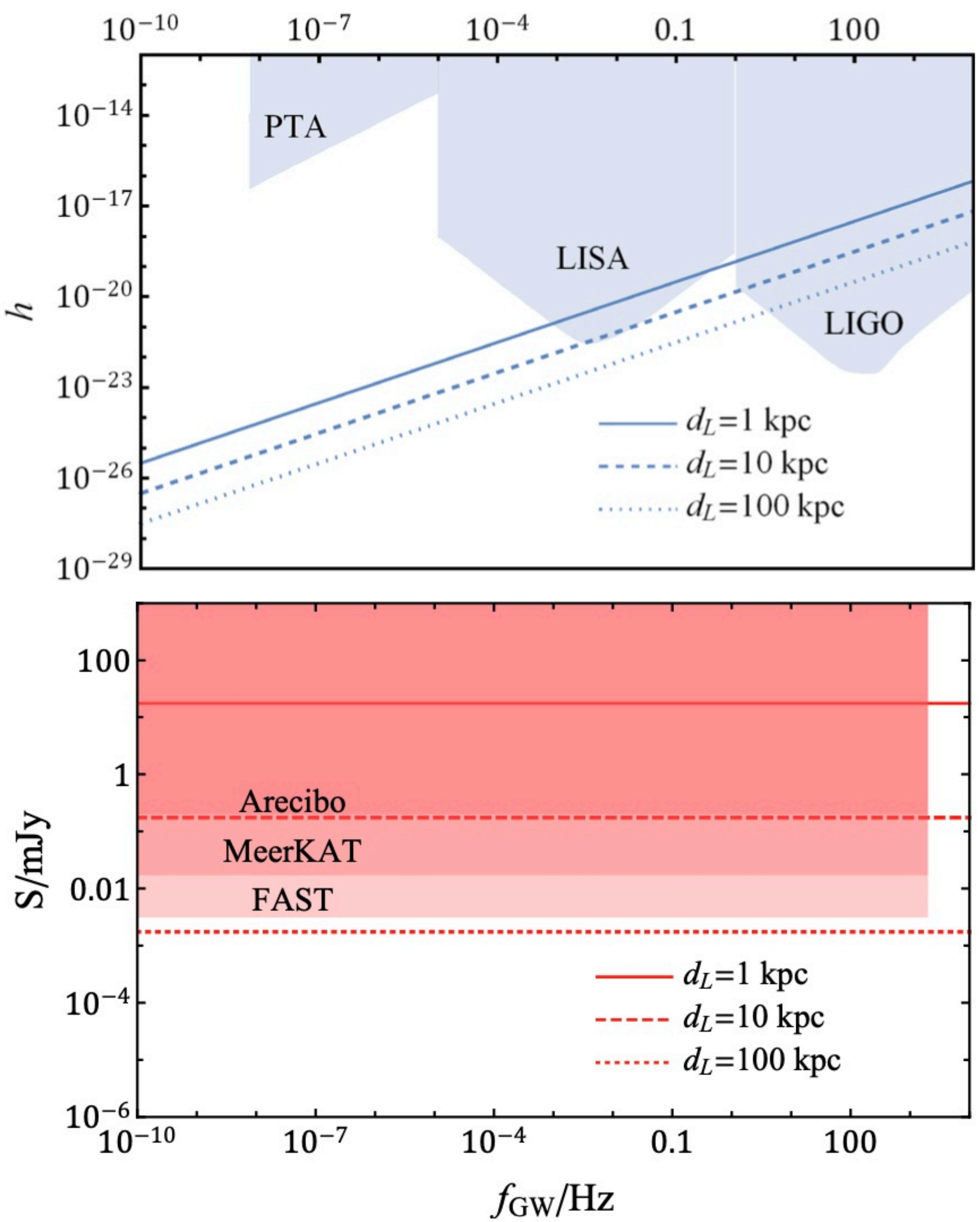


Figure 1. Sensitivity of the GW channel vs sensitivity of the radio channel for a PSR-BH binary. Three different distances typical among the observed pulsars are chosen for comparison. They are plotted using solid, dashed and dotted lines as labeled in the figure. The GW sensitivity curves for LIGO, LISA and PTA are borrowed from [23]. The minimal radio flux density for Arecibo, MeerKAT and FAST are taken to be 0.2, 0.017 and 0.0038 [19, 21, 24, 25]. Other parameters are chosen as $M_B = 1.4M_\odot$, $q = 1$ and an average pulsar pseudoluminosity at 1.4 GHz, $L_{1400} = 1$ mJy kpc^2. The high-frequency cutoff of radio telescopes at $f_{GW} = 2\times10^3$ Hz is due to the requirement 1 ms $\lesssim \tau < P = 2f_{GW}^{-1}$ in order that measuring orbital period through Rømer delay is possible. Notice that line segments that lie within the LIGO frequency are thus excluded. But this exclusion is only for solar-mass BHs with $M_B = 1.4M_\odot$. For BHs with different mass parameters, or for resonance happening at different frequencies, the LIGO bound can be evaded. This is the case for GCP resonances that we consider in Sect. IV.

and radio channel in Fig. 1. As is clear from the plot, the radio channel is not much dependent on the binary period, except for the cutoff at pulsar rotation period τ. Its sensitivity is more dependent on pulsar properties such as pseudoluminosity as well as distances. Although the signal-to-noise ratio quickly decreases as d_L^{-2}, pulsars with exceptionally large pseudoluminosity can still fall inside the sensitive region. As an example, $d_L = 1$ Mpc and $L_\nu = 10^4$ mJy kpc^2 gives $S \sim 10^{-2}$ mJy, which falls within the sensitive region of FAST. For short-distance pulsars ($d_L \lesssim 10^2$ kpc), observations in the radio channel can also be complementary for the blind regions of GW detectors.

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set-up

axion cloud around a BH with background magnetic fields

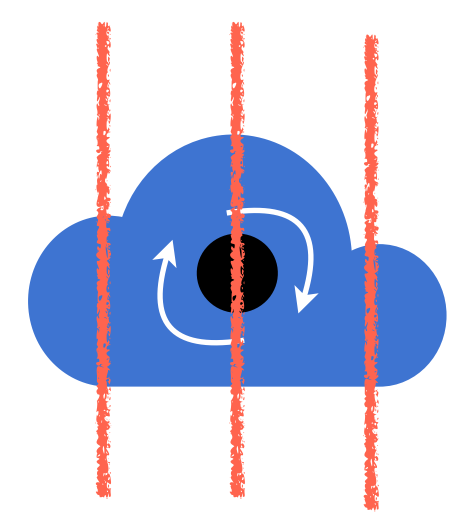
$$\mathcal{L} = -\frac{1}{2}(\nabla\phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}F_{\mu\nu}^2 - \frac{\kappa}{4}\phi\, F_{\mu\nu}{}^*F^{\mu\nu}$$

coupling b/w EM & axion ~ ϕ E・B

- We consider two types of configuration of BG M-fields

A, monopole magnetic field around a Sch. BH

B, uniform magnetic field along z axes around a Sch. BH (Wald's solution)



laugh sketch of the analysis

EOM : $$(\Box - \mu^2)\phi = \kappa\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$ **&** $$\nabla_\mu F^{\mu\nu} = -\kappa\, \tilde{F}^{\mu\nu}\nabla_\mu \phi$$

1, At BG, **axion cloud** form due to the effect of gravity of a BH

$$(\Box - \mu^2)\, \underline{\phi^{(0)}} = 0$$

2, **Axion** could generate EM waves through the coupling

$$\nabla_\mu \underline{F^{\mu\nu\,(1)}} = -\kappa\, \widetilde{F}^{\mu\nu} \underline{\nabla_\mu \phi^{(0)}}$$

3, **Generated EM waves** could backreact to **axion cloud**

through the same coupling -> axion cloud could decay

$$(\Box - \mu^2)\underline{\phi^{(1)}} = -\kappa\, \widetilde{F}^{\mu\nu} \underline{F_{\mu\nu}{}^{(1)}}$$

A, モノポール磁場 around a Sch. BH

$$\boxed{(\Box - \mu^2)\phi = \kappa F_{\mu\nu}\tilde{F}^{\mu\nu}} \quad \& \quad \boxed{\nabla_\mu F^{\mu\nu} = -\kappa \tilde{F}^{\mu\nu}\nabla_\mu \phi}$$

1, BG axion : $\phi = \phi^{n}{}_{lm} Y_{lm}$ (一番 grow する) [n,l]=[2,1] に注目

$$\phi \propto \frac{r}{a_0}\exp\left[-\frac{r}{a_0}\right] \qquad a_0 = (GM\mu^2)^{-1}$$

2, BG Axion → EM : axion が同じ lm (l=1) の EM を励起

$$\mathcal{D}^A A_r = \kappa\, iq\omega_0 r^{-1}\,\Phi \qquad A_r = -\kappa\, iq\omega^2 \int_0^\infty \mathrm{d}\xi\, \mathcal{G}(x\,,\xi)\xi^{-1}\Phi(\xi)$$

3, EM → Axion : $\mathcal{D}^\Phi \delta\phi + 2\omega_0\delta\omega\Phi = -\kappa\frac{iql(l+1)}{\omega_0 r^3}A_r$

$$\mathrm{Im}\delta\omega = q^2\kappa^2\left(\int \mathrm{d}\xi\cdots\right)^2 \propto \frac{\kappa^2 q^2}{\mu^2}(GM\mu^2)^5 > 0$$ → axion decay

B, z 方向一様磁場 around a Sch. BH

$$\boxed{(\Box - \mu^2)\phi = \kappa F_{\mu\nu}\tilde{F}^{\mu\nu}} \quad \& \quad \boxed{\nabla_\mu F^{\mu\nu} = -\kappa \tilde{F}^{\mu\nu}\nabla_\mu \phi}$$

1, BG axion : [n,l,m] = [2,1,1(-1)] に注目

2, odd EM : $\mathcal{D}^A A^o Y_{lm} = \kappa\, m\, B_0 \omega_0 r\, \Phi\, Y_{1\pm1}$ l=1 が励起

even EM : $\mathcal{D}^A A^e Y_{lm} = \kappa\, B_0 \omega_0 r^2\, (\Phi + r\Phi')\, Y_{2\pm1}$ l=2 が励起

3, EM → Axion : $\mathcal{D}^\Phi \delta\phi + 2\omega_0\, \delta\omega\, \Phi = \kappa \left[A^o\, Y_{1\pm1} + A^e\, (Y_{1\pm1} + Y_{3\pm1}) \right]$

$$\mathrm{Im}\,\delta\omega = \kappa^2 B_0^2 \left[(\mathrm{odd})^2 + (\mathrm{even})^2 \right] \propto \frac{\kappa^2 B_0^2}{GM\mu^3} (GM\mu)^8 \mu$$ → axion decay

results

axion cloud decay around a BH with BG magnetic fields

- Superradiant instability (growth of axion cloud)

$$\omega_{sr} \sim (GM\mu)^8 \mu \sim 10^{-17} s^{-1} \left(\mu/10^{-18}[eV]\right)^9 \left(M/10^6 M_\odot\right)^8$$

- axion decay with a monopole magnetic field

$$(\mathrm{Im}\,\omega/\omega_\mathrm{s})_\mathrm{mono} \sim (\kappa^2 q^2/a_0^2)\,(GM\mu)^{-5}$$

a0 : Bohr radius
~ 1/(GMμ²)

- axion decay with a uniform magnetic field

$$(\mathrm{Im}\,\omega/\omega_\mathrm{s})_\mathrm{uni} \sim (a_0^2 \kappa^2 B_0^2)\,(GM\mu)$$

$$\sim \left(\frac{\kappa}{10^{-12}\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B_0}{10^3 G}\right)^2 \left(\frac{\mu}{10^{-18}\mathrm{eV}}\right)^{-3} \left(\frac{M}{10^6 M_\odot}\right)^{-1}$$

summary & discussion

Axion Cloud Decay with background magnetic fields

- We have considered axion cloud decay due to the axion-photon conversion with background magnetic fields

- Axion cloud may decay at the time scale same as that for the superradiant instability around a BH for the uniform M-field while the time scale is extremely large for the monopole M-field
  -> need to consider a realistic configuration of M-fields

- In reality, due to the presence of plasma, photons cannot propagate from a BH -> other decay process ? Alfven wave ??

Thank you
for your attention