



Heating up the Black Hole X-ray Binary Accretion Disk by Superradiance

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Psi Workshop

In collaboration with Antonios Kyriazis (U. Florida) and Siyu Zhou (Notre Dame U.) [2608.18200].

Black hole superradiance

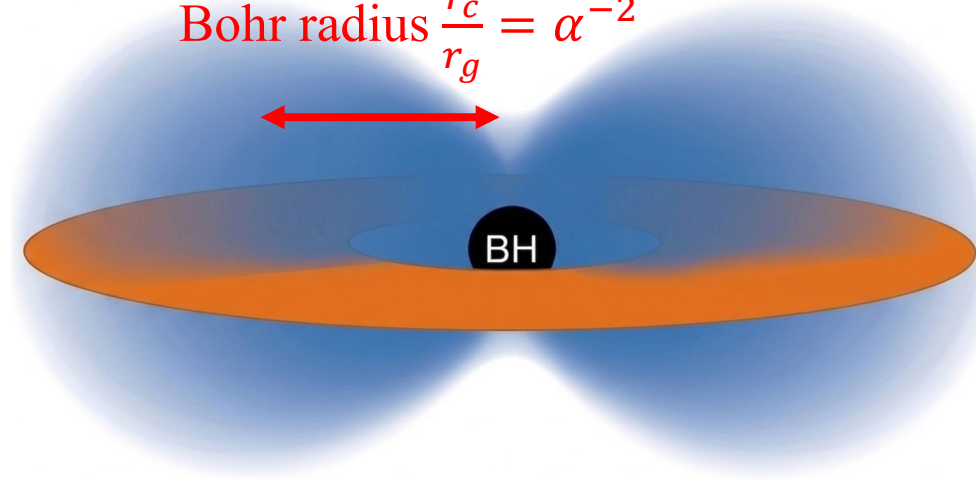
- Superradiance condition, instability $\omega < m\Omega_H$
- Axion cloud can form around BH

Detweiler 1980

Review: *Superradiance* by Brito, Cardoso, Pani

$$\bar{n}_a \simeq 3 \times 10^{50} \text{cm}^{-3} \left(\frac{q_c}{0.1} \right) \left(\frac{\alpha}{0.1} \right)^5 \left(\frac{M_\odot}{M} \right)$$

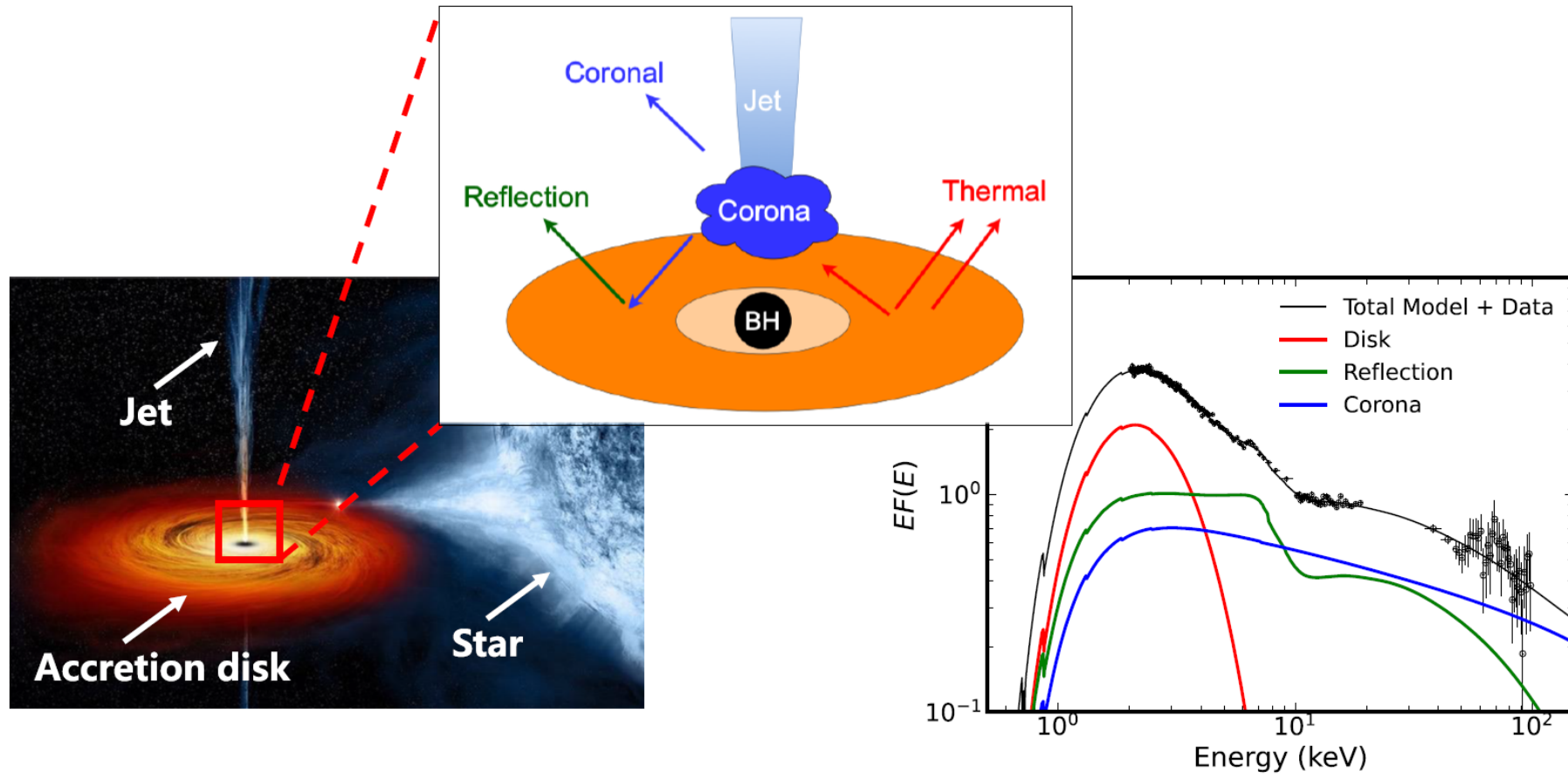
Bohr radius $\frac{r_c}{r_g} = \alpha^{-2}$



Gravitational fine-structure constant $\alpha \equiv GMm_a$

- Axion-photon coupling, self interactions.
- Axion-fermion coupling?

Black hole X-ray binary

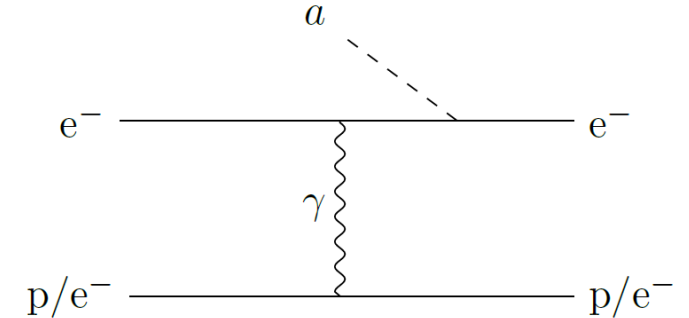
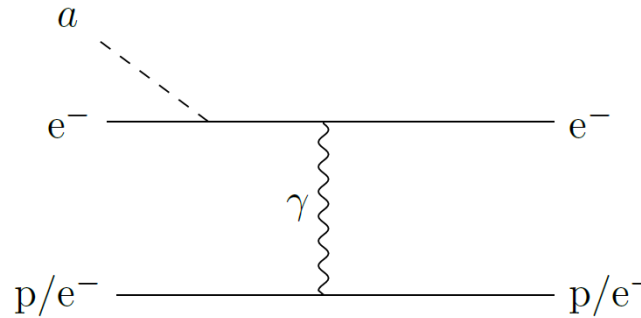


credits to 2026 Liu [2603.00833]

Axion heating via net absorption

Inverse bremsstrahlung

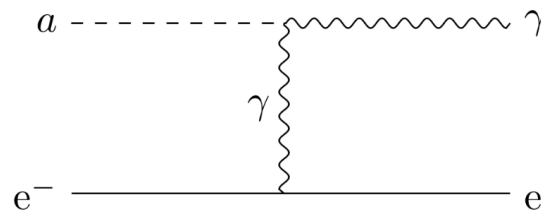
p: proton or ion (consider protons only)



Compton scattering



Inverse Primakoff



*Neglect plasma effect first.

**Inverse processes are also possible.

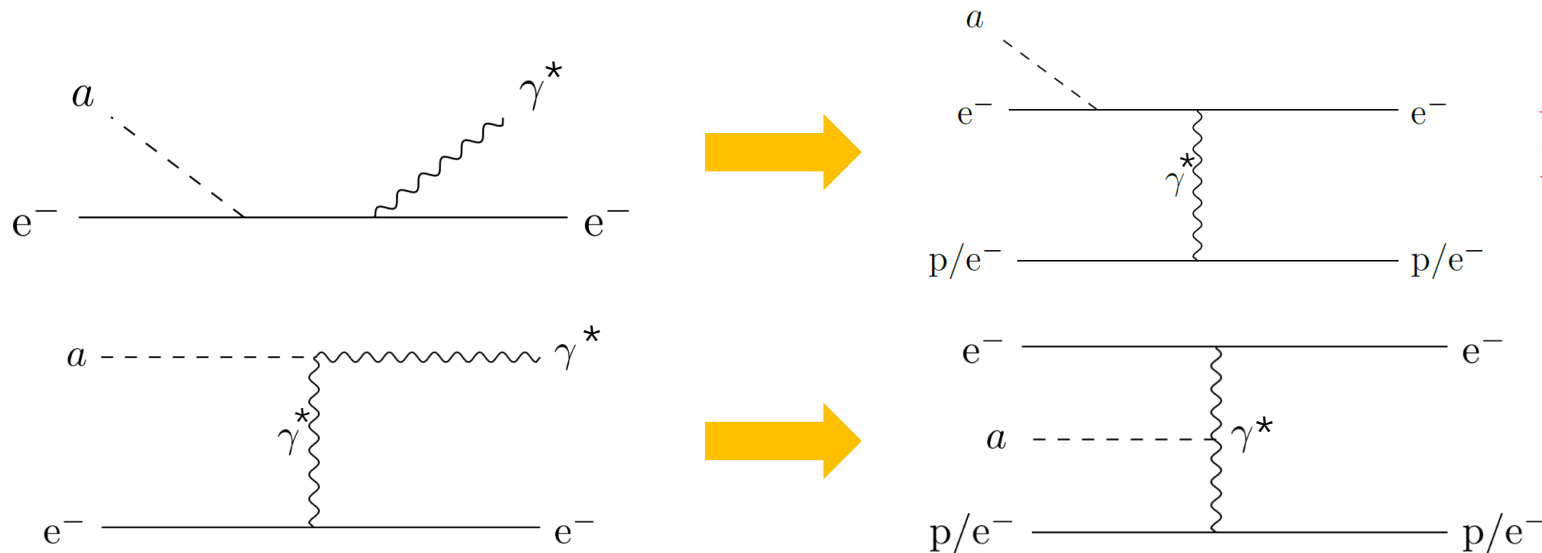
Plasma effect

Plasma frequency: $\omega_{\text{eff}} = \sqrt{\frac{e^2 n_e}{m_e}} = 3.7 \text{ eV} \left(\frac{n_e}{10^{22} \text{ cm}^{-3}} \right)^{1/2} \gg m_a \in [10^{-12}, 10^{-11}] \text{ eV}$

Photons obtain effective mass in plasma $m_{\gamma^*} \simeq \omega_{\text{eff}}$.

Final-state photons with $E_{\gamma^*} < \omega_{\text{eff}}$ are kinematically forbidden.

➔ Compton scattering and inverse Primakoff processes are kinematically forbidden, rendering them to $3 \rightarrow 2$ processes with photon being a propagator.



Note: same as “inverse bremsstrahlung”.

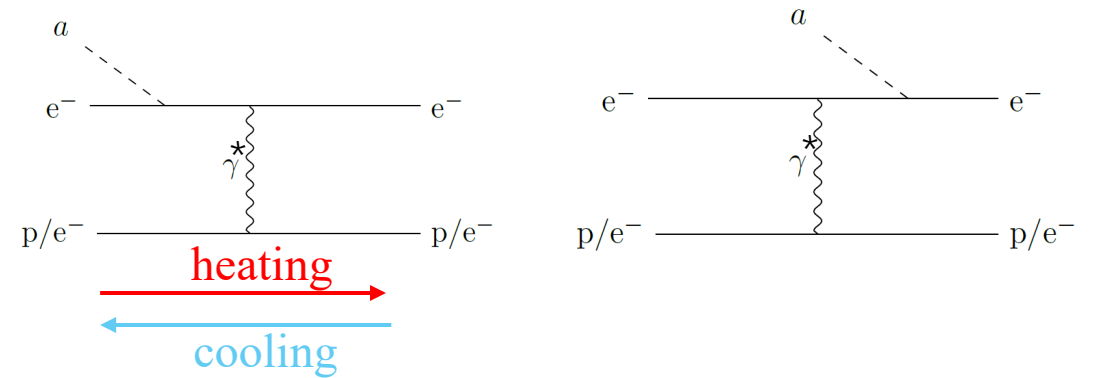
Axion heating

$$\mathcal{L}_{\text{int}} = \frac{g_{ae}}{2m_e} \partial_\mu a \bar{\psi}_e \gamma^\mu \gamma^5 \psi_e$$

$$\frac{1}{4} \sum_{\text{spins}} |\mathcal{M}_{ep}|^2 \simeq \frac{4e^4 g_{ae}^2 m_p^2 |\mathbf{q}|^2}{m_e^2 (|\mathbf{q}|^2 + \omega_{\text{eff}}^2)^2}$$

momentum transfer

$$\frac{1}{2} \frac{1}{4} \sum_{\text{spins}} |\mathcal{M}_{ee}|^2 \simeq \frac{4e^4 g_{ae}^2 |\mathbf{q}|^2}{(|\mathbf{q}|^2 + \omega_{\text{eff}}^2)^2}$$



Emissivity: 1986 G. G. Raffelt

$$\epsilon_a = \int d\Pi_a E_a d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 (2\pi)^4 \delta^{(4)}(p_1 + p_2 + k - p_3 - p_4) |\mathcal{M}|^2 f_a f_1 f_2 (1 - f_3)(1 - f_4) - \int d\Pi_a E_a d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 (2\pi)^4 \delta^{(4)}(p_3 + p_4 + k - p_1 - p_2) |\mathcal{M}|^2 f_3 f_4 (1 - f_1)(1 - f_2)(1 + f_a)$$

Net effect = heating - cooling

Axion heating rate ($a + e + p \rightarrow e + p$):

$$\frac{\epsilon_a}{n_p} = \frac{1}{2} \frac{\text{eV}}{\text{s}} \left(\frac{g_{ae}}{10^{-11}} \right)^2 \frac{E_a n_a}{10^{41} \text{eV cm}^{-3}} \frac{n_e}{10^{22} \text{cm}^{-3}} \left(\frac{10^7 \text{K}}{T} \right)^{\frac{3}{2}} F(\zeta) \quad \text{form factor}$$

$$F(\zeta) = -(1 + \gamma + \ln \zeta) / 2 \quad \text{log dependence on IR cutoff: } \omega_{\text{eff}} \text{ or Debye-Huckel screening scale.}$$

$$\zeta \equiv \omega_{\text{eff}}^2 / (8Tm_e)$$

Accretion disk model

Kerr metric, GR effect included

- Thin disk model: Shakura-Sunyaev (SS) model, Novikov-Thorne (NT) model.
- Plasma density, core temperature, surface density.

middle region: $P_{\text{rad}} < P_{\text{gas}}, \kappa = \kappa_{\text{es}}$ [1104.5499]

$$\rho_{\text{pl}} \simeq 40 \text{ g/cm}^3 \alpha_d^{-\frac{7}{10}} \tilde{m}^{-\frac{7}{10}} \dot{m}^{2/5} \tilde{r}^{-\frac{33}{20}} h_4(x, \tilde{a}),$$

$$T_c \simeq 7 \times 10^8 \text{ K} \alpha_d^{-\frac{1}{5}} \tilde{m}^{-\frac{1}{5}} \dot{m}^{2/5} \tilde{r}^{-\frac{9}{10}} h_5(x, \tilde{a}),$$

$$\Sigma \simeq 9 \times 10^4 \text{ g/cm}^2 \alpha_d^{-4/5} \tilde{m}^{1/5} \dot{m}^{3/5} \tilde{r}^{-3/5} h_6(x, \tilde{a})$$

h 's: auxiliary functions, GR effect, $h \rightarrow 1$ at large radii.

The relevant region = *middle region* where the densest region of the axion cloud is overlapped with the disk.

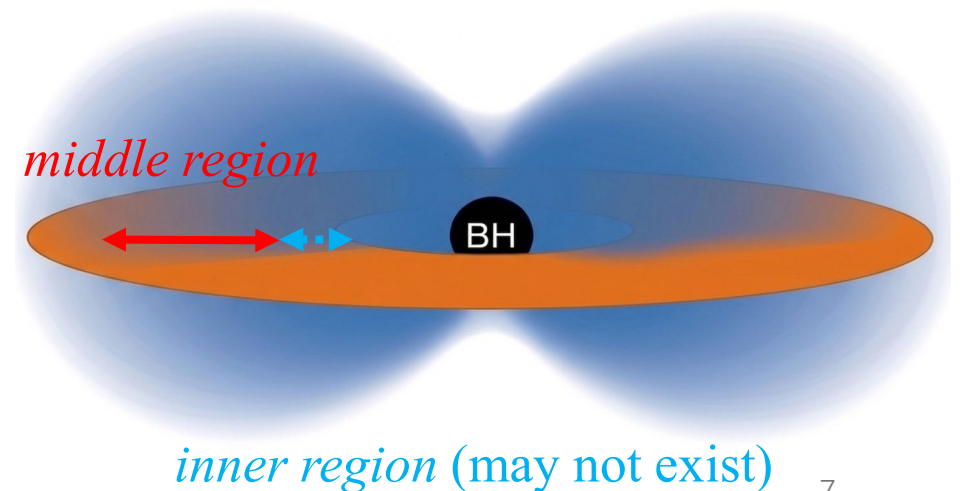
α_d : SS viscosity parameter

$\dot{m} = \frac{\dot{M} c^2}{L_{\text{Edd}}}$: normalized accretion rate

$\tilde{m} = M/M_{\odot}$: normalized BH mass

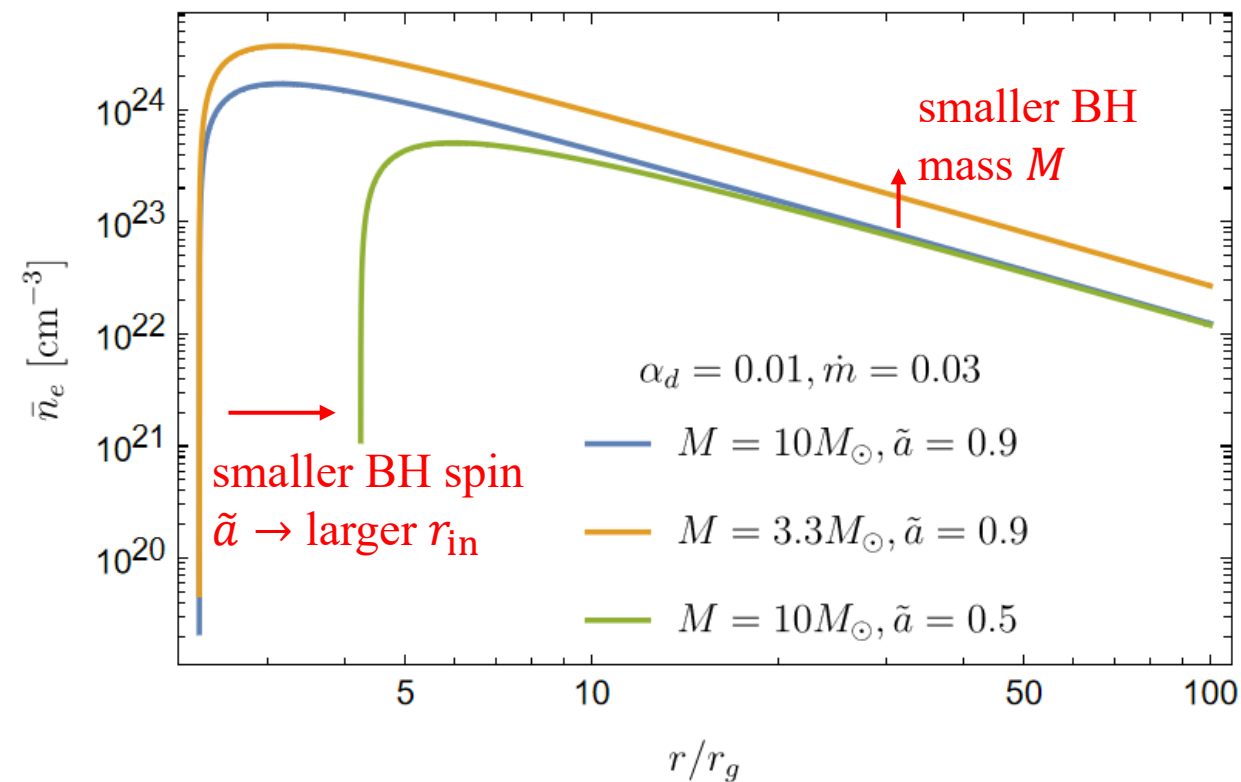
$\tilde{a} = a/M$: dimensionless BH spin

($\tilde{r} = r/r_g, x = \sqrt{\tilde{r}}$)

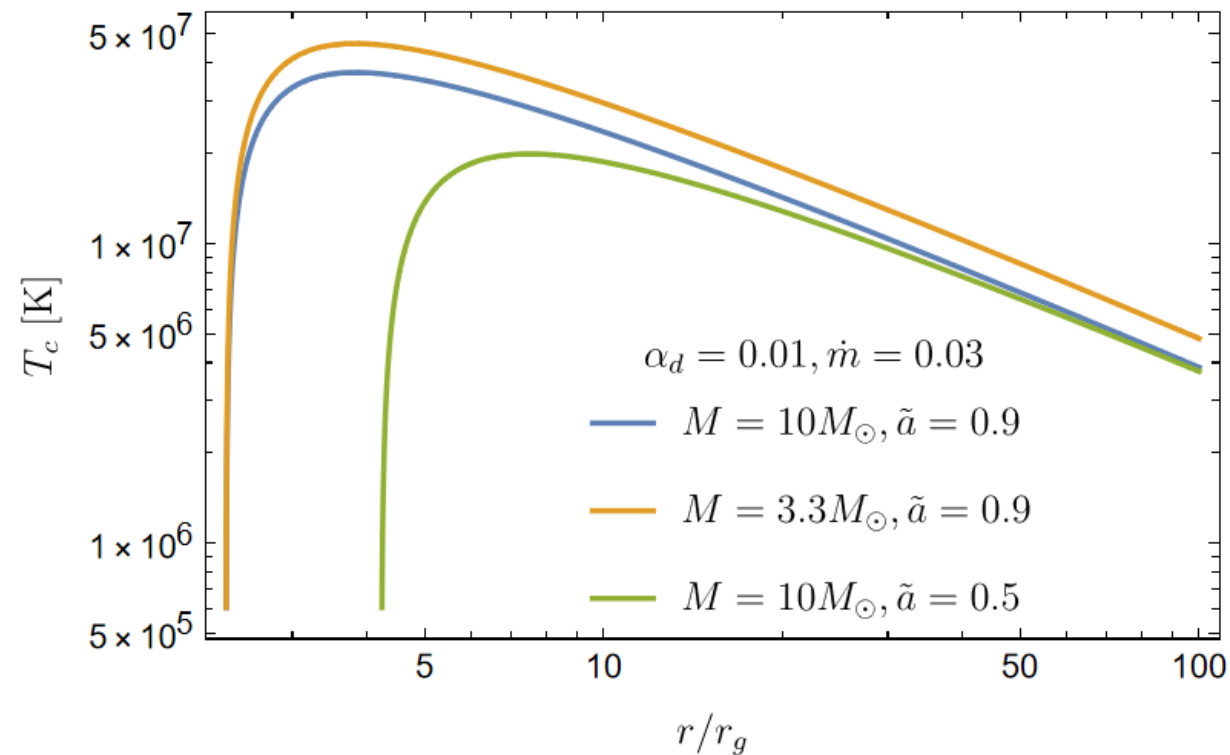


Accretion disk model

electron number density profile



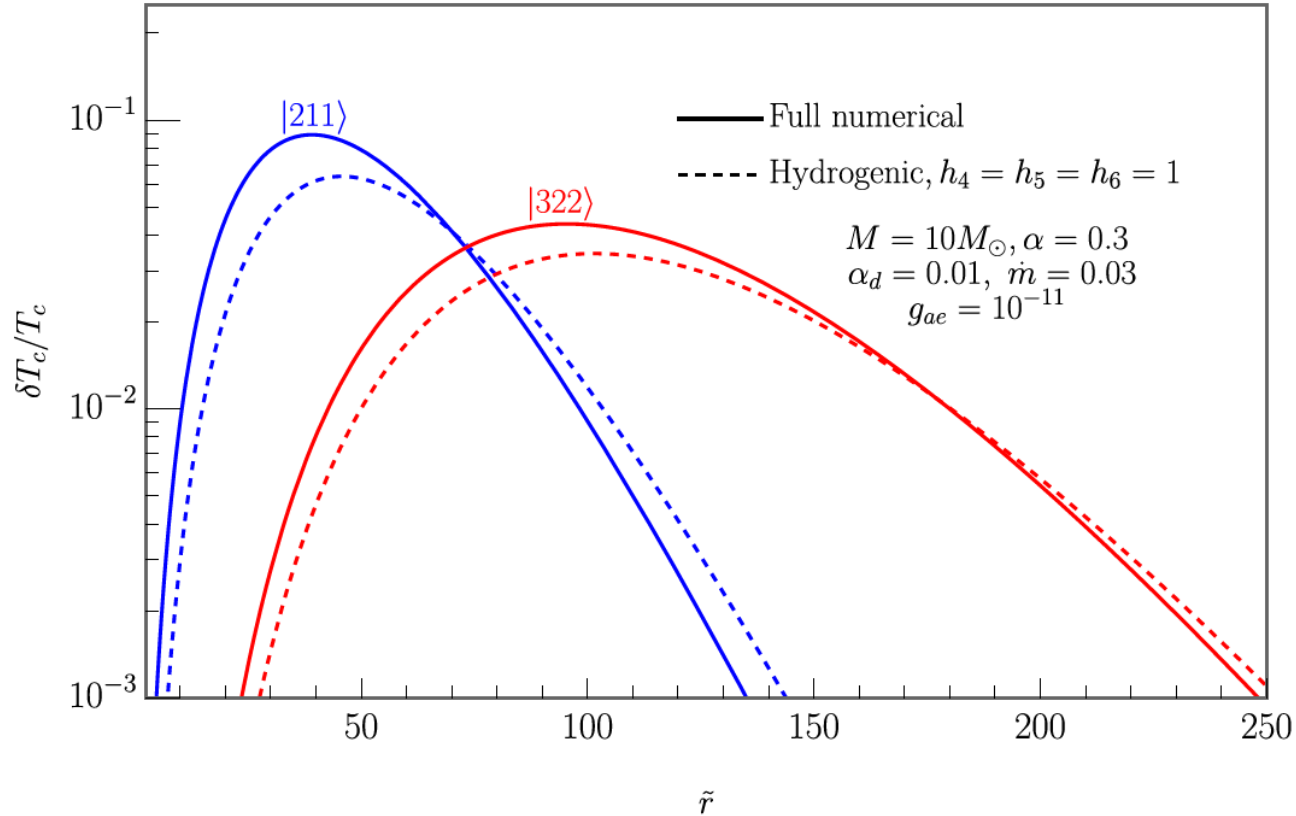
core temperature profile



Temperature fluctuation

Treat axion heating as a perturbative effect:

$$\frac{4}{3\tau}\sigma_{\text{SB}}(T_c + \boxed{\delta T_c})^4 = \underbrace{\frac{3GM\dot{M}}{8\pi r^3}Q'}_{\text{viscosity dissipation}} + \underbrace{\frac{1}{2}\frac{\epsilon_a(T_c)\Sigma(r)}{\rho_{\text{pl}}(r)}}_{\text{axion heating}} \rightarrow \frac{\delta T_c}{T_c} = \frac{3\tau}{32\sigma_{\text{SB}}T_c^4} \left(\frac{\epsilon_a\Sigma}{\rho_{\text{pl}}} \right) \propto q_c g_{ae}^2 \alpha^{\frac{9}{5}} M^{-\frac{6}{5}} \dot{m}^{-\frac{3}{5}} \alpha_d^{-\frac{6}{5}} \quad \text{for } \alpha \leq 0.3$$



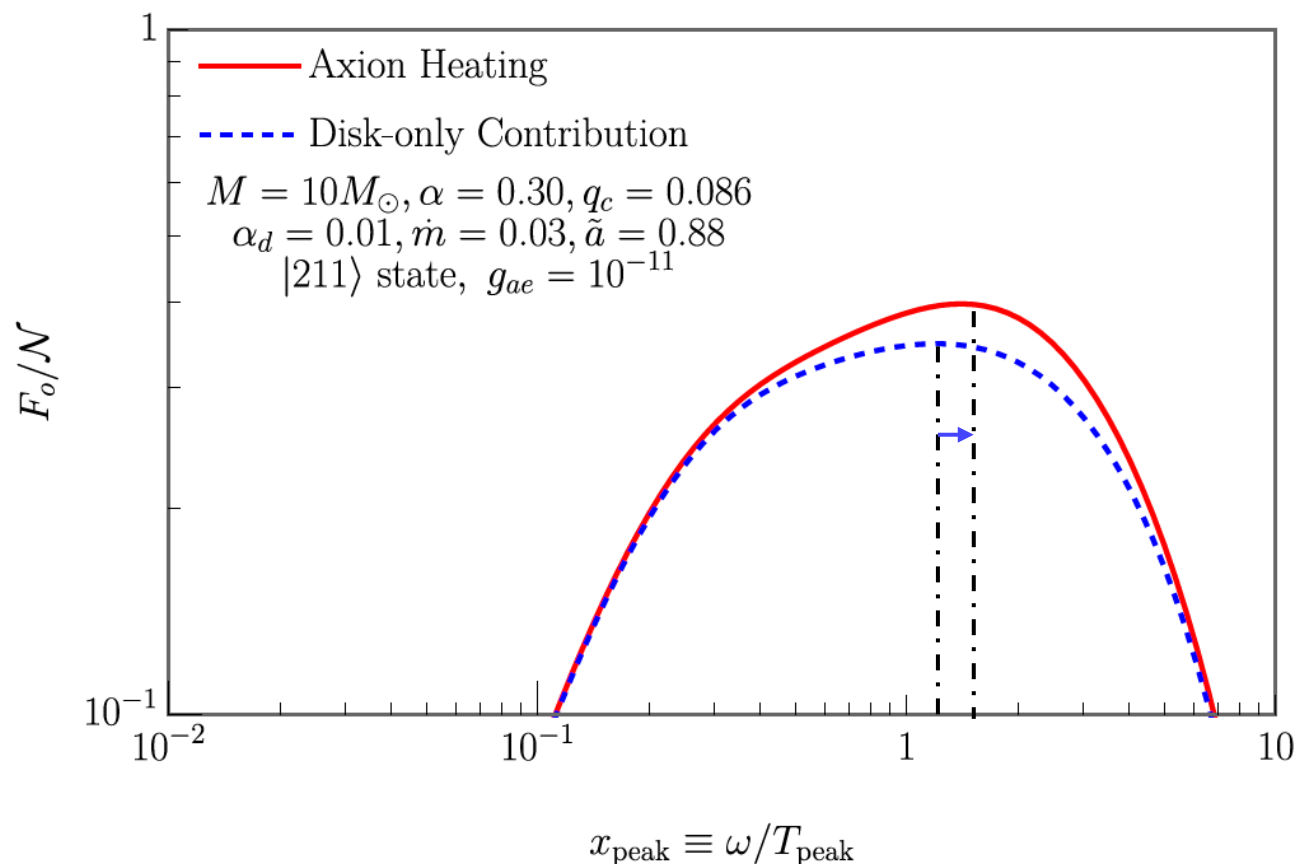
Thermal spectrum

$$F_o(\omega) = \frac{1}{2\pi f_{\text{col}}^4} \int \overset{\text{redshift factor}}{\boxed{g}}^3 \overset{\text{effective surface temperature}}{\boxed{B_{\omega_e}}}(f_{\text{col}}(\boxed{T_{\text{eff}}} + \delta T_{\text{eff}})) d\Omega_{\text{obs}}$$

Blackbody spectrum

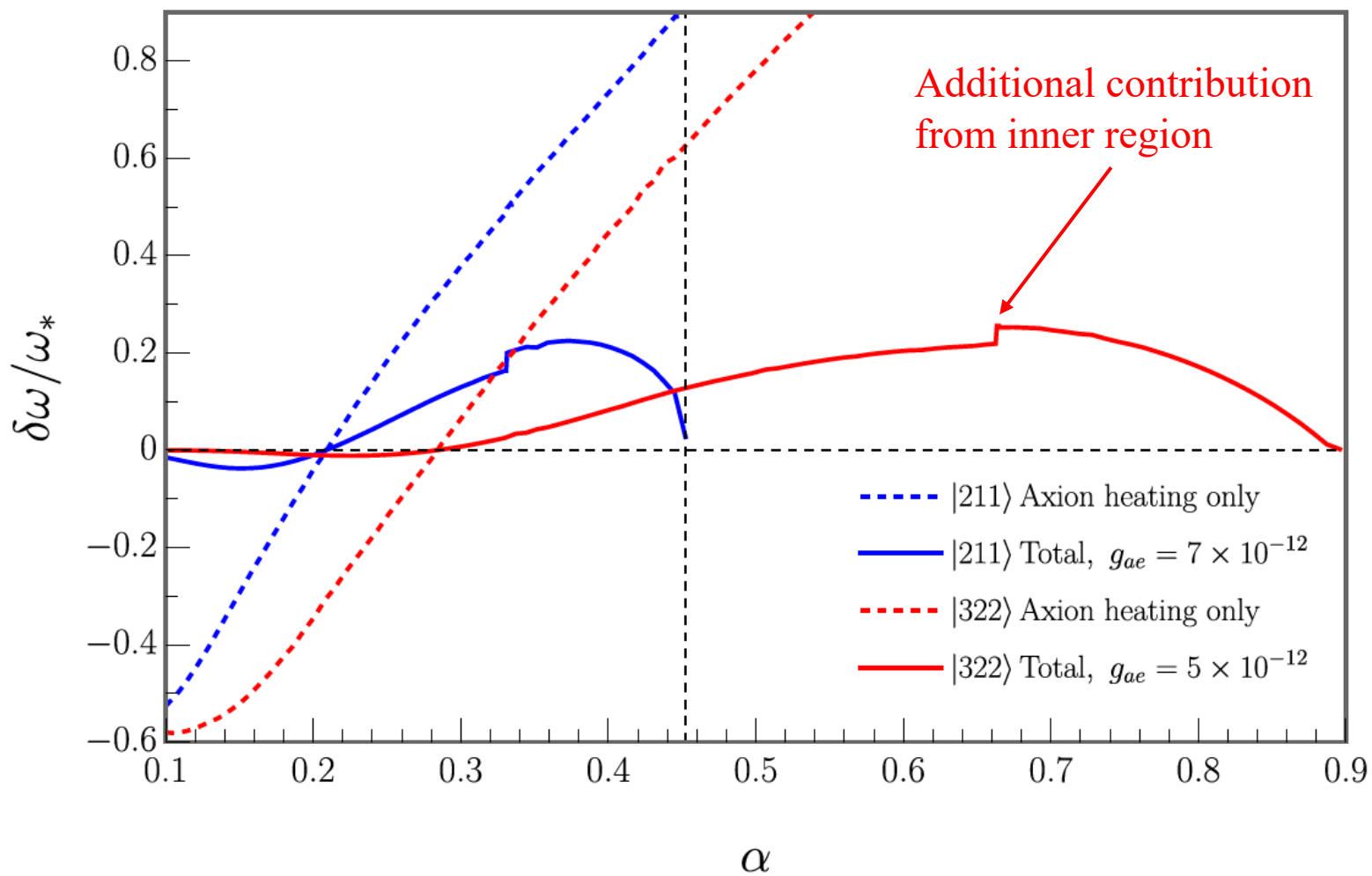
Temperature fluctuation
due to axion heating:

$$\delta T_{\text{eff}} = \left(\frac{4}{3\tau}\right)^{1/4} \delta T_c$$



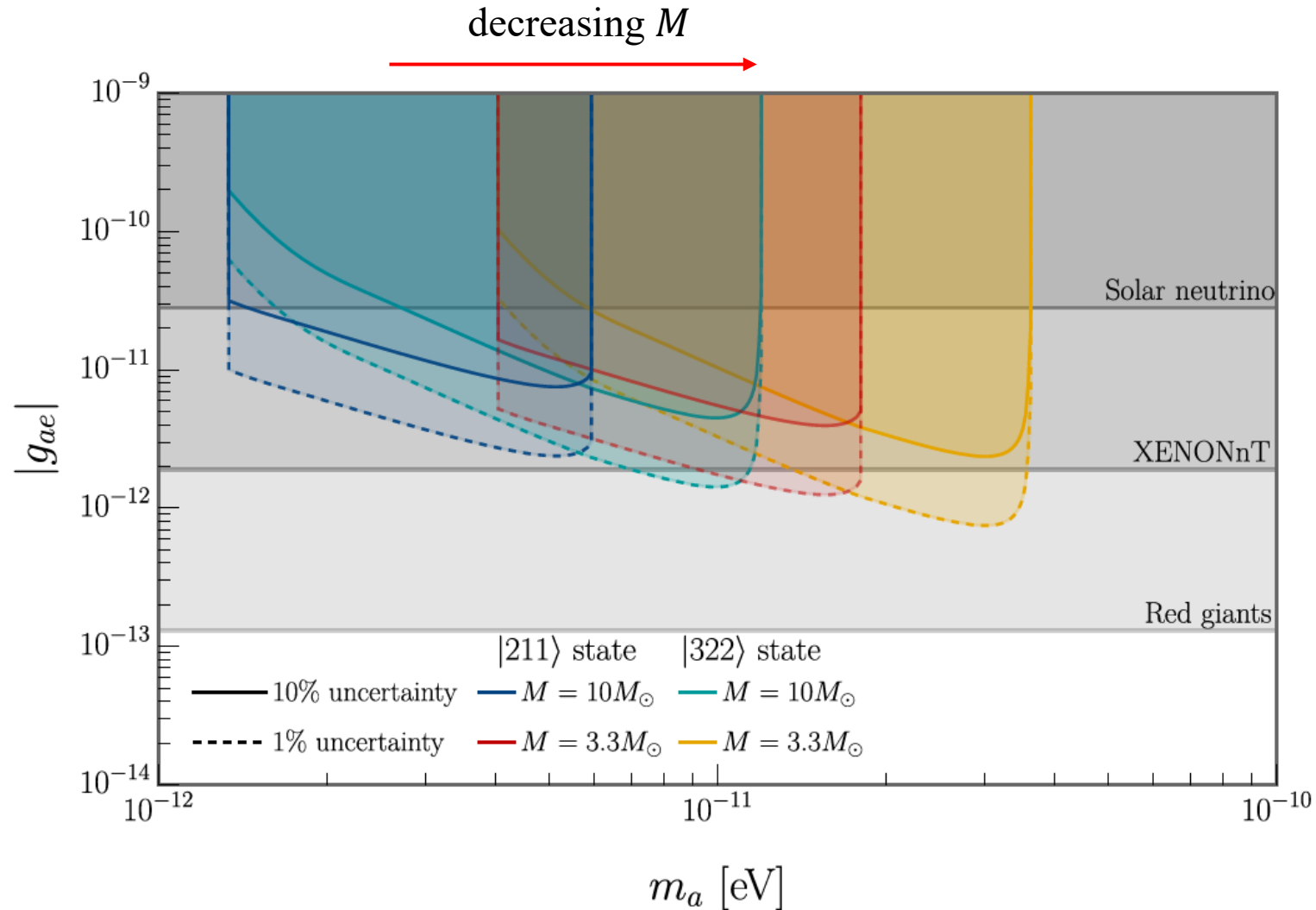
peak frequency
blueshift

Frequency shift



assume saturated BH
spin for each α

Projected sensitivity on g_{ae} vs m_a



1. Smaller BH mass can probe a larger m_a and smaller coupling $|g_{ae}|$.
2. $|322\rangle$ state can cover a broader parameter space due to a larger $\alpha_{\max}$.

Conclusion

- We showed that axion cloud can heat up black hole X-ray binary accretion disk by inverse bremsstrahlung process.
- We studied the effects on the thermal spectrum from the disk.
- We obtained the projected $m_a - g_{ae}$ constraint from axion heating.

Back-up slides

Accretion disk model

Kerr metric, GR effect included

- Thin disk model: Shakura-Sunyaev model, **Novikov-Throne** model.
- Plasma density, core temperature, surface density.

inner region:

$$\rho_{\text{pl}} \simeq 2 \times 10^{-5} \text{ g/cm}^3 \alpha_d^{-1} \tilde{m}^{-1} \dot{m}^{-2} \tilde{r}^{3/2} h_1(x, \tilde{a}),$$

$$P_{\text{rad}} > P_{\text{gas}}, \kappa = \kappa_{\text{es}} \quad T_c \simeq 5 \times 10^7 \text{ K } \alpha_d^{-1/4} \tilde{m}^{-1/4} \tilde{r}^{-3/8} h_2(x, \tilde{a}),$$

$$\Sigma \simeq 5 \text{ g/cm}^2 \alpha_d^{-1} \dot{m}^{-1} \tilde{r}^{3/2} h_3(x, \tilde{a}),$$

middle region:

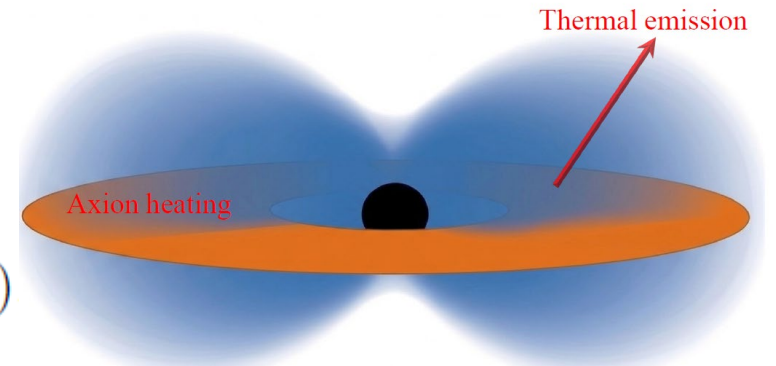
$$\rho_{\text{pl}} \simeq 40 \text{ g/cm}^3 \alpha_d^{-7/10} \tilde{m}^{-7/10} \dot{m}^{2/5} \tilde{r}^{-33/20} h_4(x, \tilde{a}),$$

$$P_{\text{rad}} < P_{\text{gas}}, \kappa = \kappa_{\text{es}} \quad T_c \simeq 7 \times 10^8 \text{ K } \alpha_d^{-1/5} \tilde{m}^{-1/5} \dot{m}^{2/5} \tilde{r}^{-9/10} h_5(x, \tilde{a}),$$

$$\Sigma \simeq 9 \times 10^4 \text{ g/cm}^2 \alpha_d^{-4/5} \tilde{m}^{1/5} \dot{m}^{3/5} \tilde{r}^{-3/5} h_6(x, \tilde{a})$$

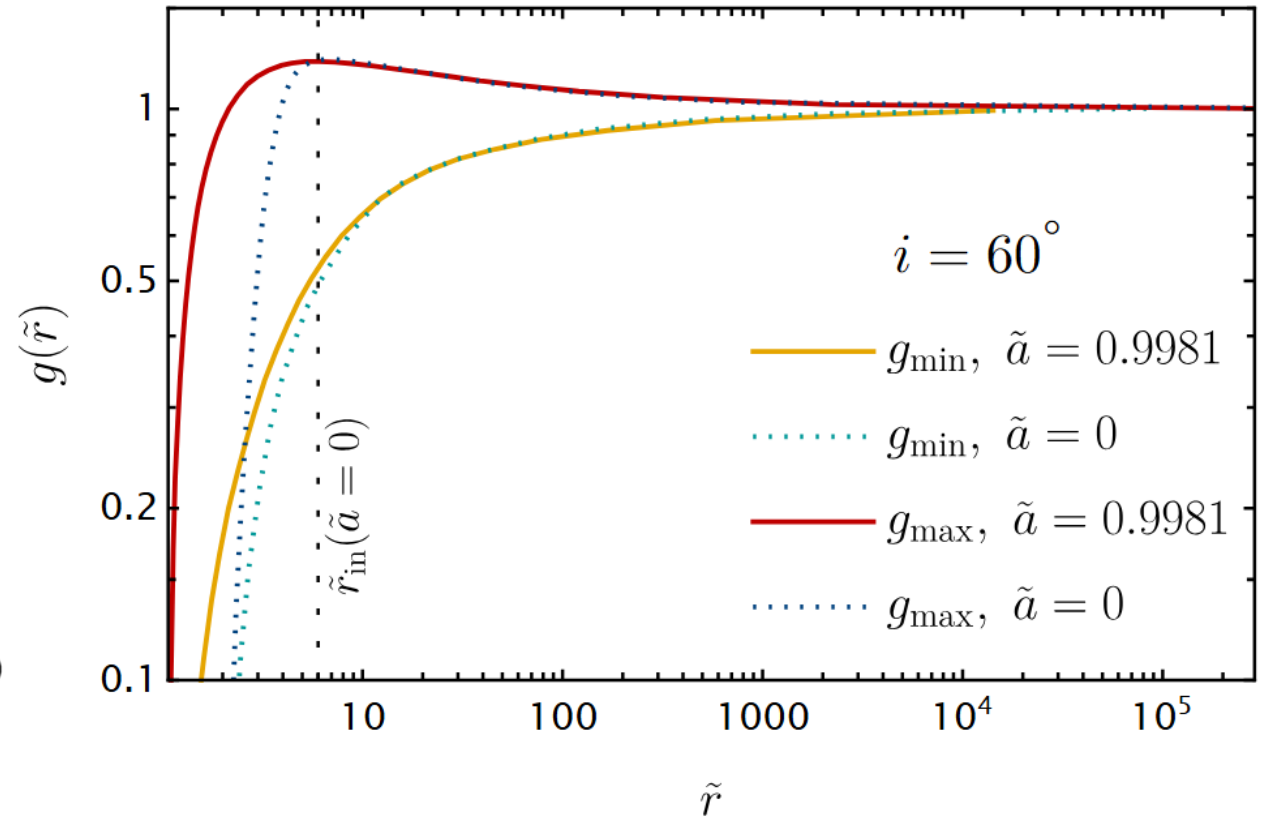
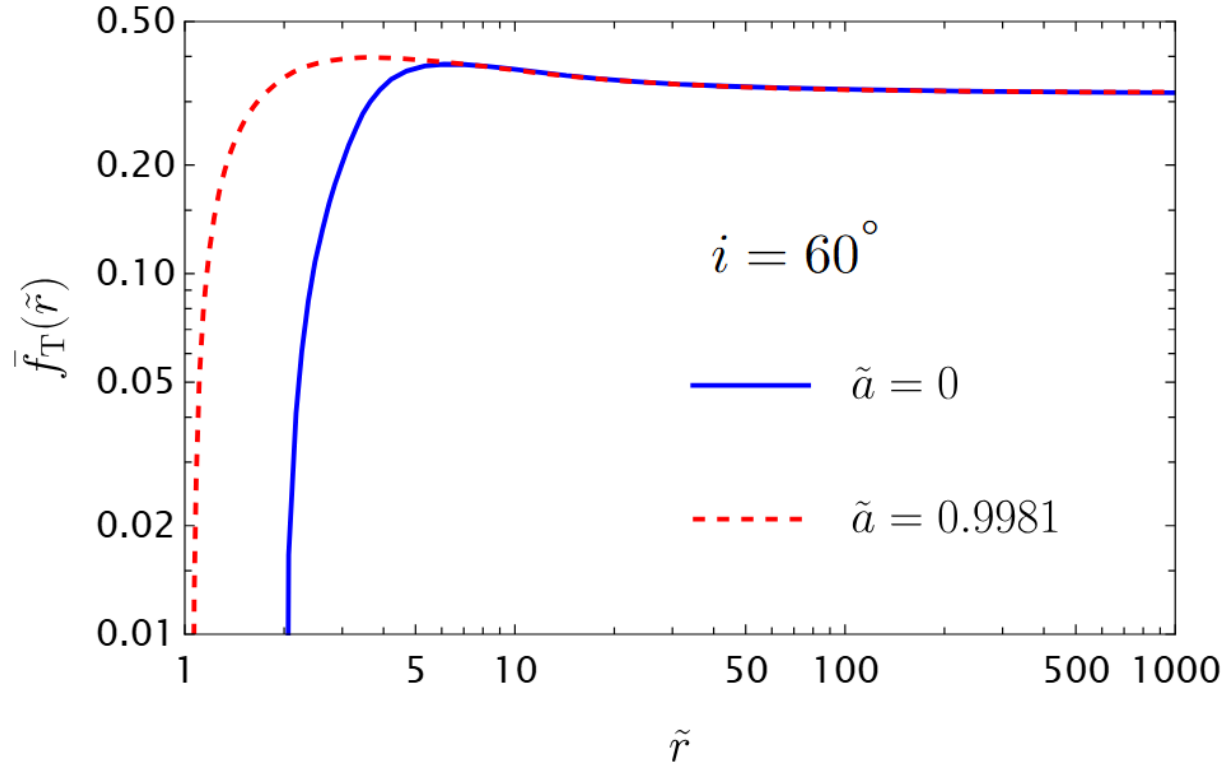
h's: auxiliary functions, including GR effect, and asymptote to unity at large radius.

α_d : Shakura-Sunyaev viscosity parameter
 $\tilde{m} = M/M_{\odot}$: normalized BH mass
 $\dot{m} = \frac{\dot{M}}{M_{\text{Edd}}}$: normalized accretion rate
 $\tilde{r} = r/r_g$: normalized radius; $x = \sqrt{\tilde{r}}$.
 $\tilde{a} = a/M$: dimensionless BH spin



Calculation of the thermal spectrum

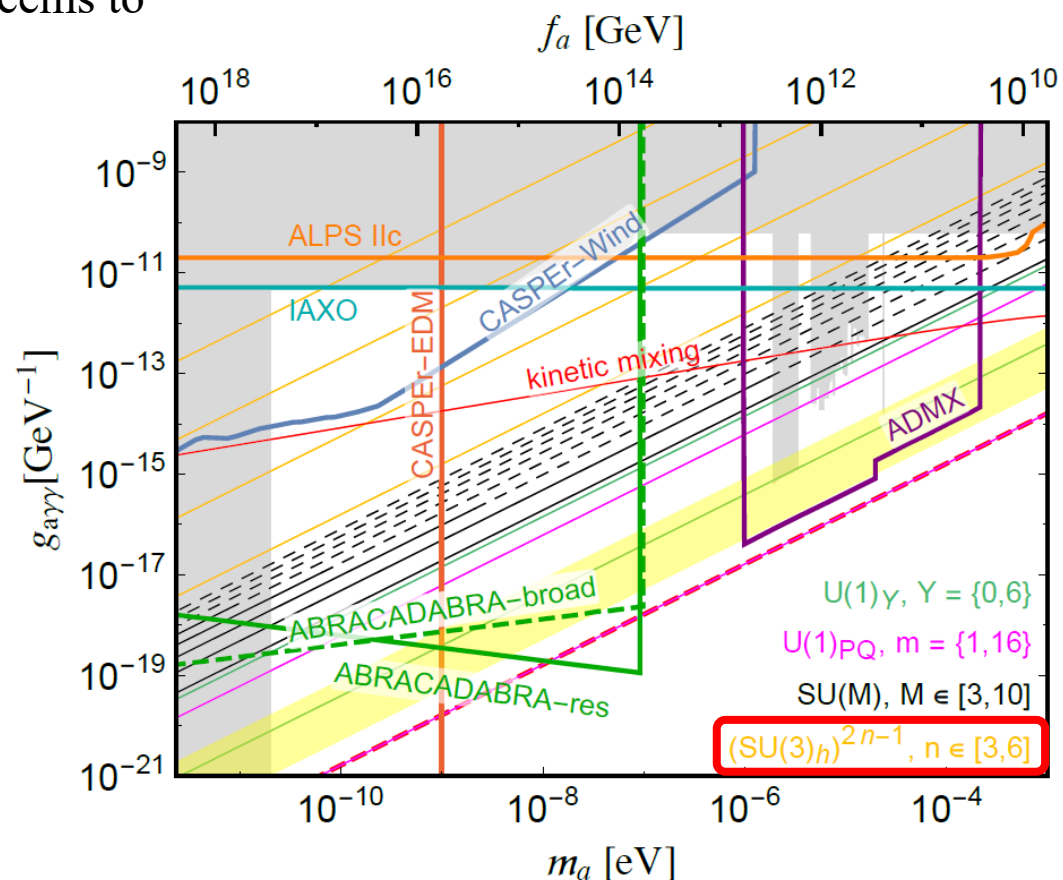
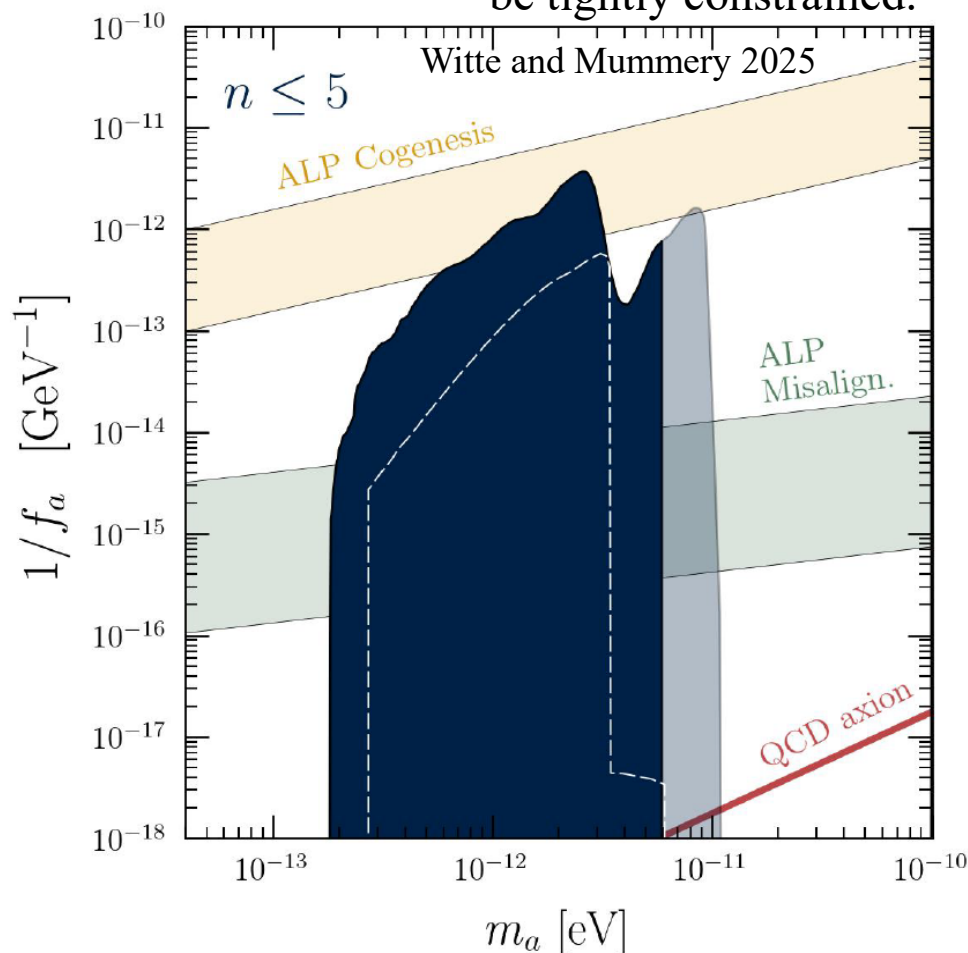
$$d\Omega_{\text{obs}} = \frac{\partial \Omega_{\text{obs}}}{\partial (g_*, r_e)} dg_* dr_e = \frac{\pi r_e}{D^2} \frac{1}{g \sqrt{g_* (1 - g_*)}} f(g_*, r_e, i) dg_* dr_e \quad \text{Cunningham 1975}$$



Comments on axion cloud stability under λ

For a single cosine potential, $V(\Phi) = m_a^2 f_a^2 [1 - \cos(\Phi/f_a)] \Rightarrow \lambda = m_a^2/f_a^2$

$g_{ae} = C m_e/f_a \rightarrow$ The gae bound from ma-1/fa seems to be tightly constrained.



Confinement tower (Agrawal, Fan, Reece, Wang 2017)