Gravitational Wave Burst from Axion Clumps and Possible Dark Fluxes

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Based on PRD 104 (2021), 103009 by Sichun Sun(BIT), Y. L. Zhang R. G. Cai, S. Sun, B. Zhang and Y. L. Zhang, [arXiv:2009.02315]
Dark Fluxes from Accreting Black Holes and Direct Detections
Nov 20@TDLI, Shanghai 2021[Email: zhangyunlong@nao.cas.cn]

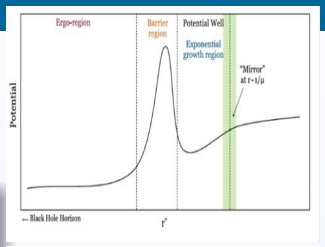
Outline

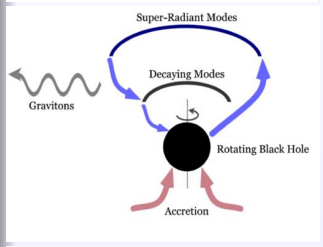
Black Hole Superradiance & GWs

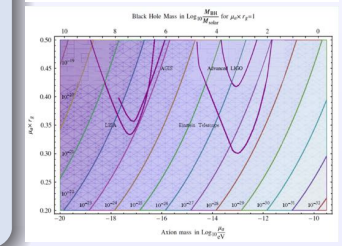
- Axion annihilation $\vartheta + \vartheta \to h$
  Energy transition $\vartheta^+ \to \vartheta^- + h$
- Superradiance $\alpha \equiv \frac{R_{BH}}{\lambda_\vartheta} \simeq \left(\frac{M_{BH}}{M_\odot}\right)\left(\frac{m_\vartheta}{10^{-10}\mathrm{eV}}\right)$
- Fast Radio Burst from Axion $\sim \vartheta F\tilde{F}$ $(\vartheta \to \gamma\gamma)$
- GW burst from Axion $\sim \vartheta R\tilde{R}$ $(\vartheta \to hh)$

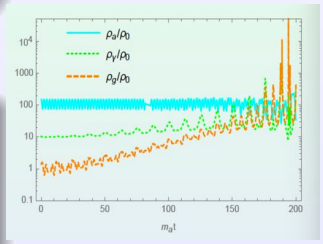
Ultra-light DM and multi band GW detection

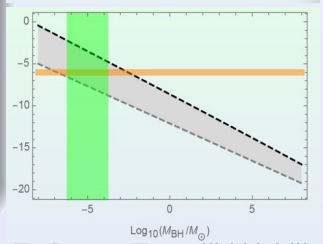
- PTA & SKA : Ultra-light dark matter ($\sim$ nHz)
- LVK & LISA: Superradiance ($\sim$ mHz - kHz)
- Table Lab: Axion star & GW burst ($\sim$ GHz)



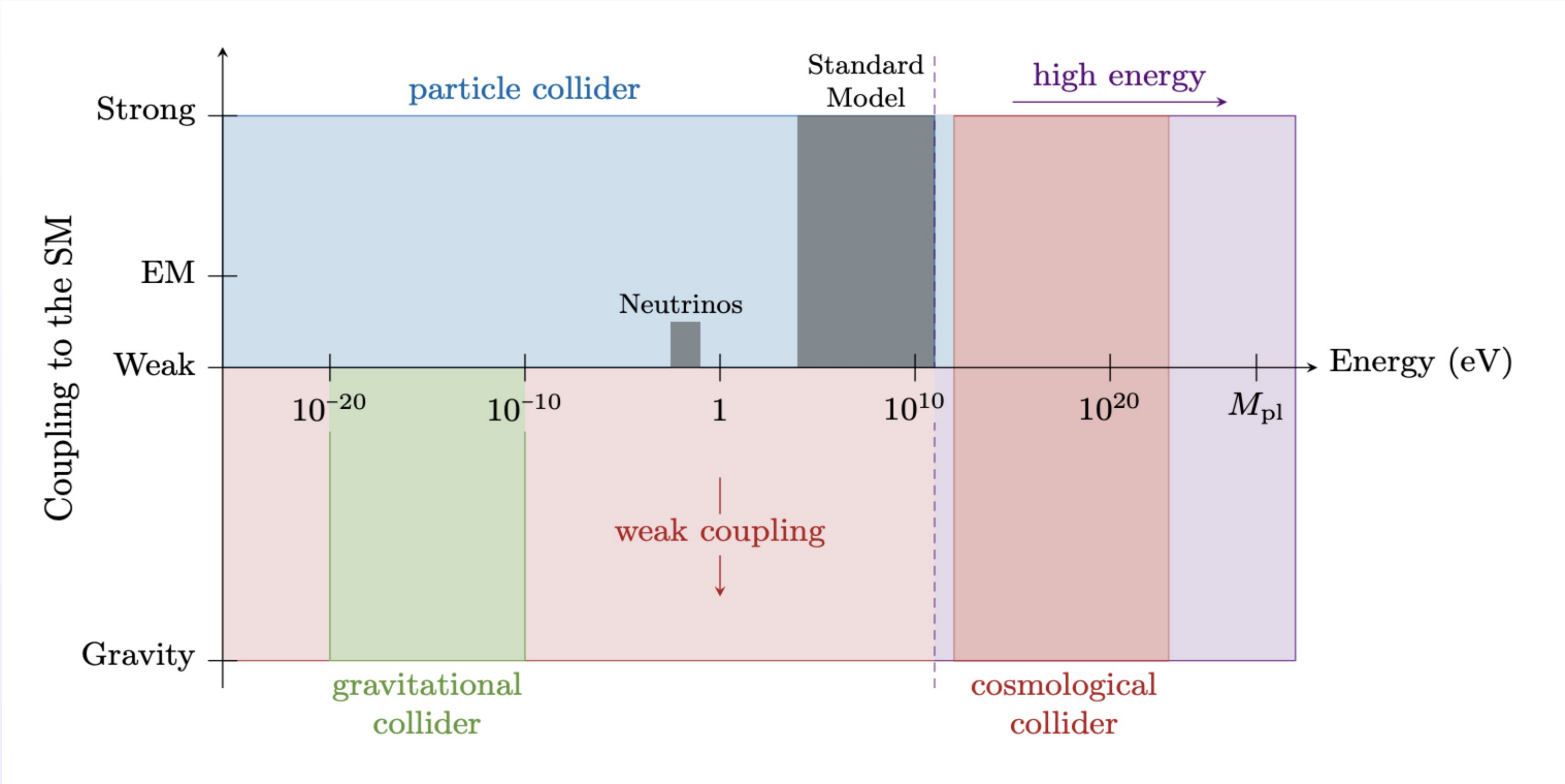




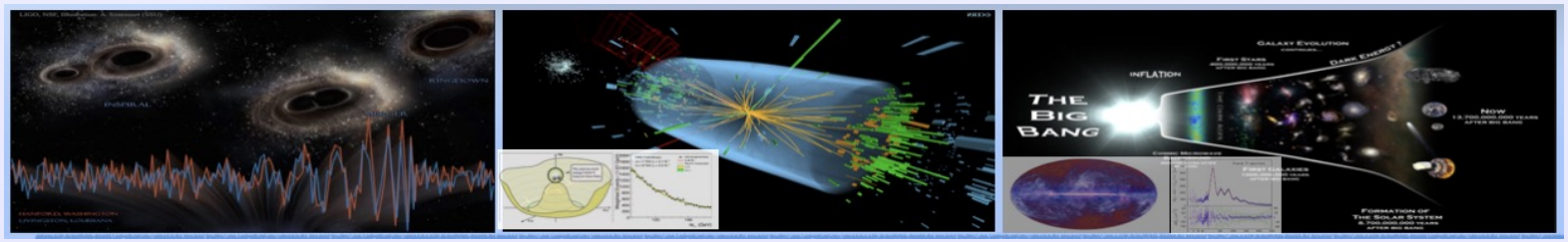




Motivation: Gravitational Collider Physics
New Physics in Ultra-low energy scale



[cf. Baumann-Chia-Porto-Stout, Gravitational Collider Physics, 2019]



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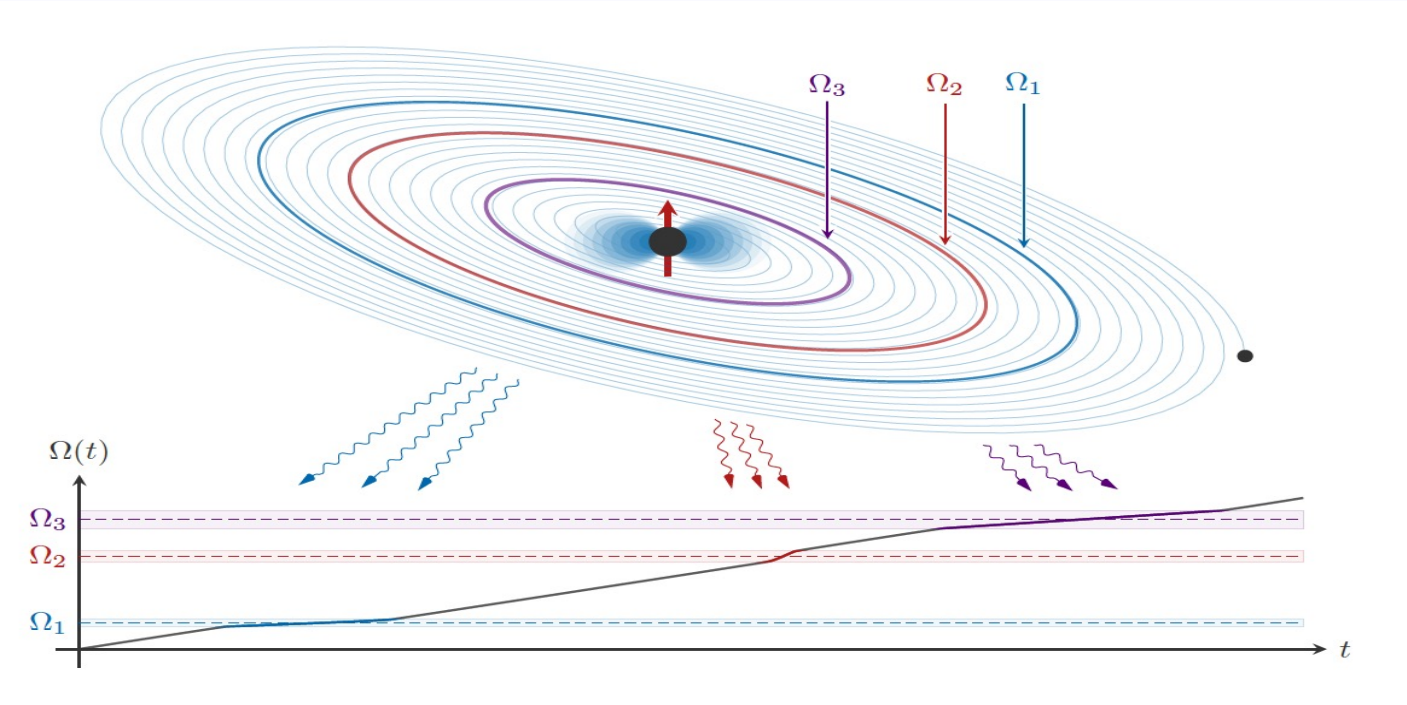
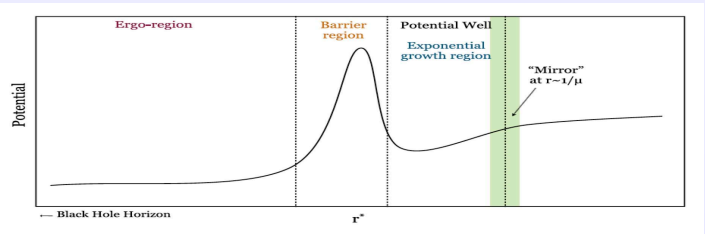
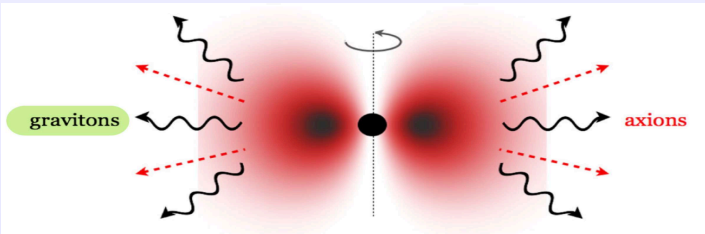


[cf. Baumann-Chia-Porto-Stout, Gravitational Collider Physics(2019)]



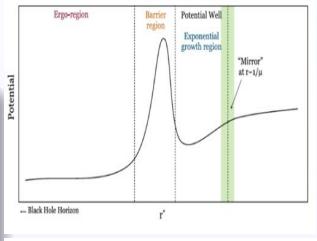


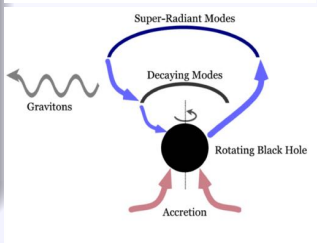
[cf. Arvanitaki-Dubovsky, String Axiverse -2011]

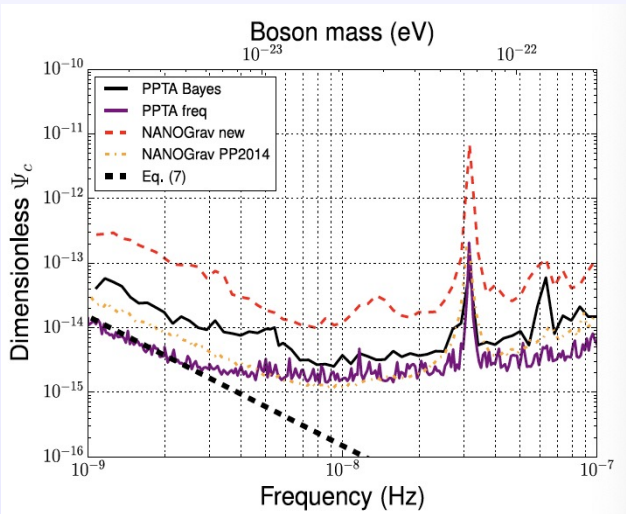
Ultra light dark matter and gravitational waves

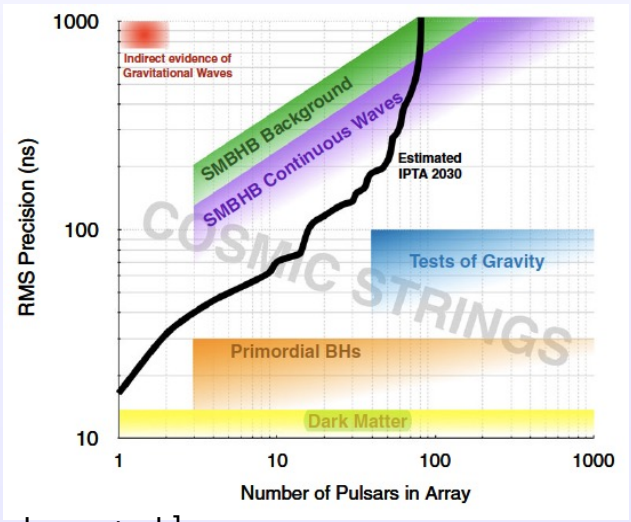
Axion like dark matter and dark energy

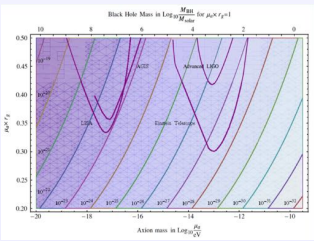
- PTA & FAST& SKA: ultra light DM($\sim$ nHz)
- LISA-Taiji-Tianqin/Ligo-Virgo-Kagra (mHz- kHz)
- Axion star & FRB & GWs ($\sim$ kHz- GHz)

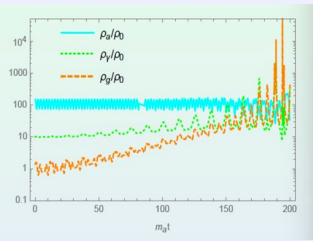




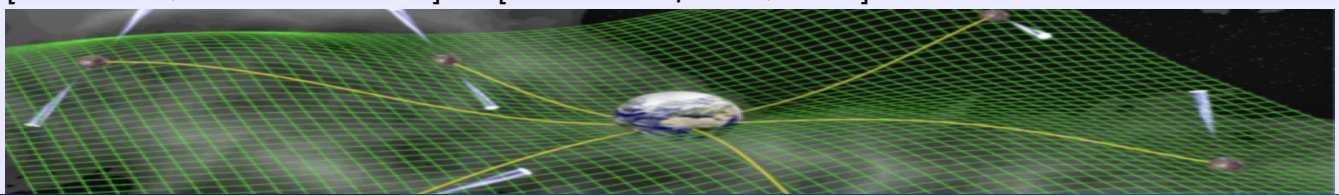


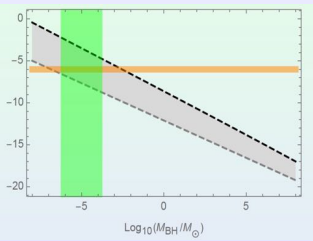






[cf. X. Xue, X. J. Zhu et al.] & [cf. Burke-Spolaor, et al.]





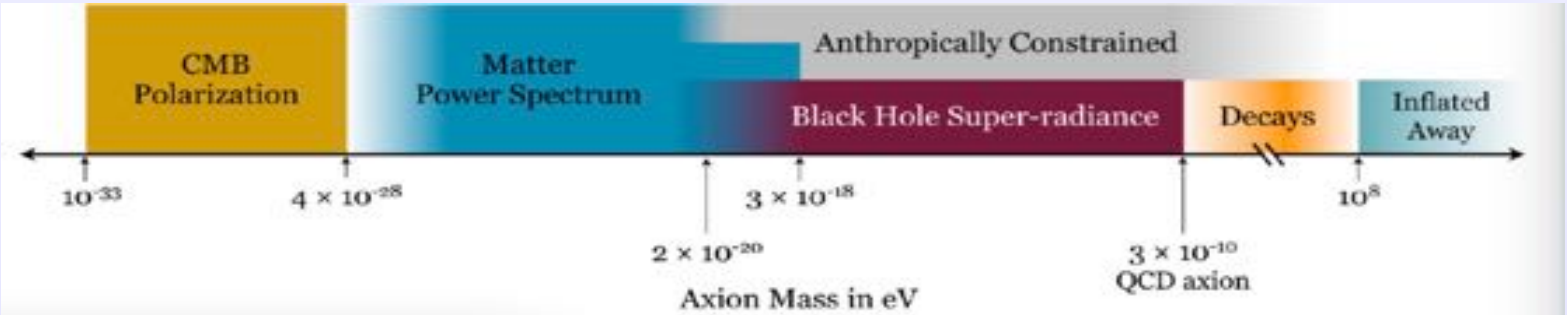
Ultra Light Dark Matter

QCD axion

- $\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} - \alpha\theta F^a_{\mu\nu}\tilde{F}_a^{\mu\nu} + \bar{\psi}\left(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5}\right)\psi$
- Strong CP problem: no CP violation in experiment
- Peccei–Quinn (1977): introduce new pseudoscalar
- Wilczek- Weinberg: relax the CP-violation parameter

Axion-like ultra light dark matter

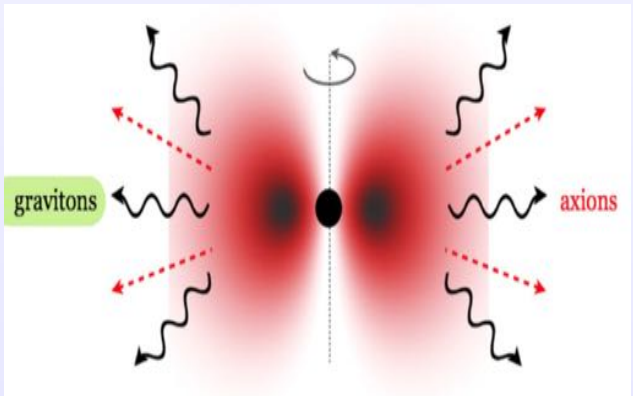
- e.g. Fuzzy Dark Matter [cf. L. Hui, E. Witten, et al]$\sim 10^{-22}$eV

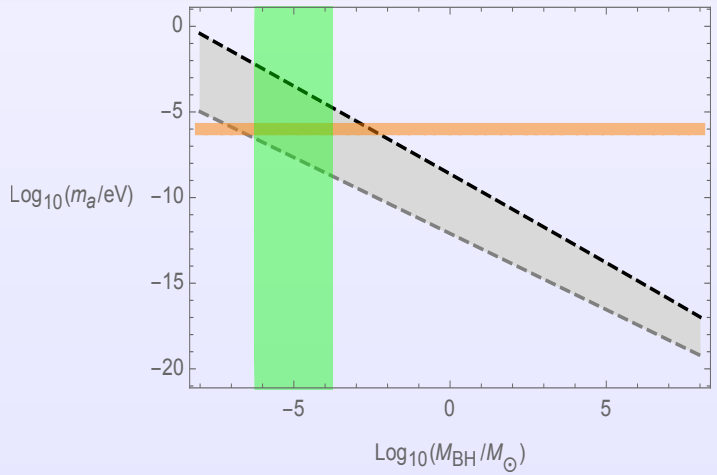


Axion-like Cloud and Black Hole Superradiance

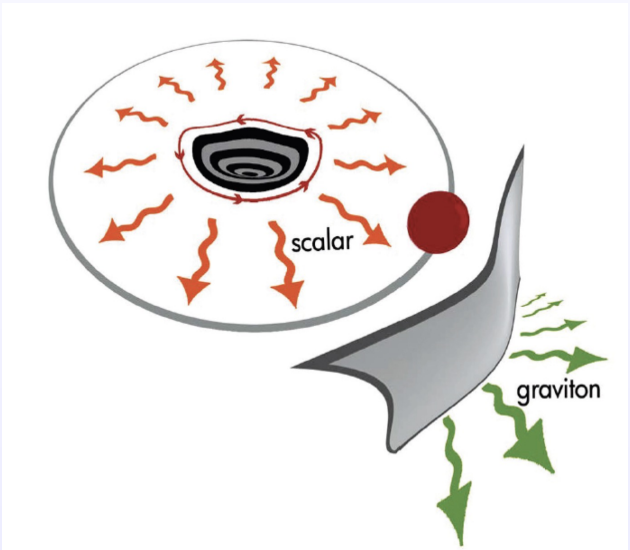
Schwarzschild $R_{BH} = G_N M_{BH}/c^2$, de Broglie wave length $\lambda_\vartheta = \hbar/(m_\vartheta v_\vartheta)$

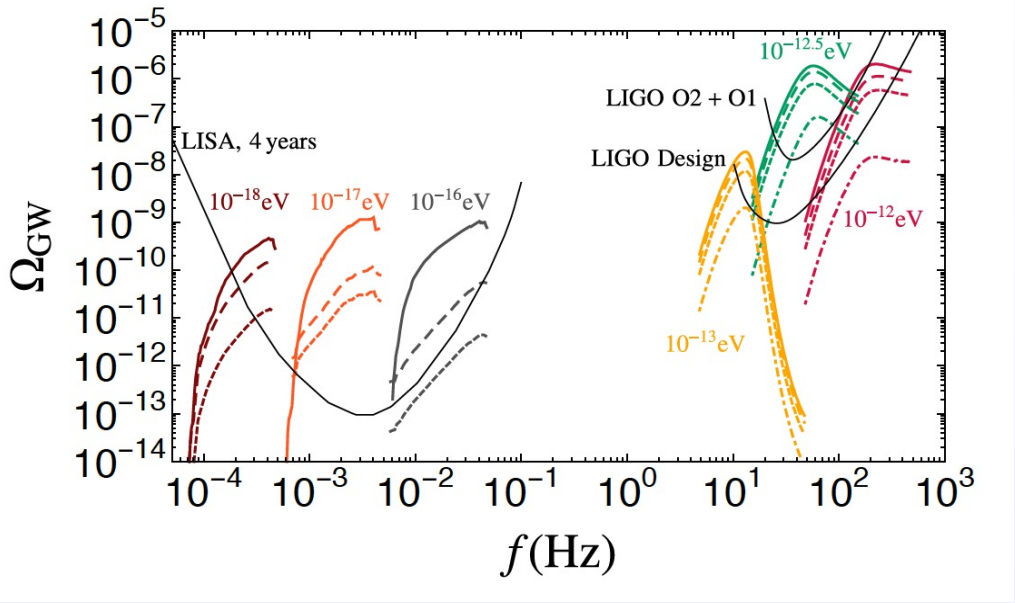
- Characteristic $\alpha \equiv \frac{R_{BH}}{\lambda_\vartheta} \simeq \left(\frac{M_{BH}}{M_\odot}\right)\left(\frac{m_\vartheta}{10^{-10}\mathrm{eV}}\right)\left(\frac{v_\theta}{c}\right)$.
- Formation time τ_ϑ¡ Universe's age $\tau_U \simeq 10^{23}\left(\frac{M_\odot}{M_{BH}}\right) R_{BH}$
- $\tau_{\vartheta\uparrow} \simeq 10^7 e^{1.84\alpha} R_{BH},\ \alpha \gg 1, \quad \tau_{\vartheta\downarrow} \simeq 24\,\alpha^{-9} R_{BH},\ \alpha \ll 1.$





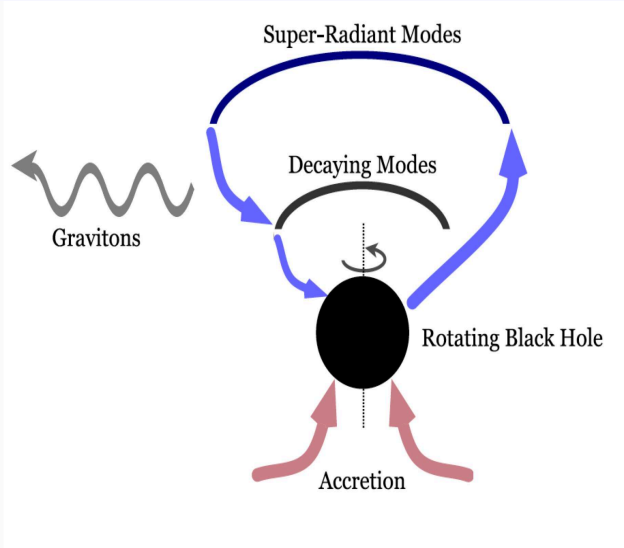
Axion annihilation and GWs

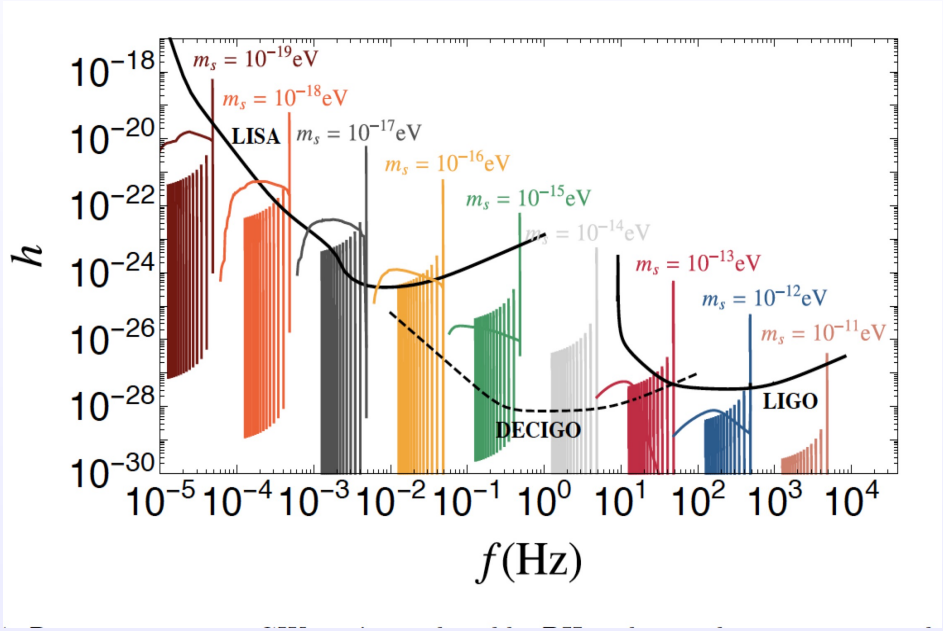




- Axion annihilation $\vartheta + \vartheta \to h$, Strain $h \sim 10^{-21} - 10^{-32}$.
- Stochastic GW [cf. Brito-Cardoso-Pani, Superradiance 2020]

Energy level transition and GWs





- Energy transition $\vartheta^+ \to \vartheta^- + h$, Strain $h \sim 10^{-19} - 10^{-27}$
- Monochromic GW [cf. Brito-Cardoso-Pani, Superradiance 2020]

Axion-photon coupling ($\vartheta \to \gamma\gamma$)

Interaction

- The interaction
  $S_{EM} = \int d^4x\sqrt{-g}\left(-\frac{1}{4}F^2 + \mathcal{L}_\vartheta + \mathcal{L}_{\vartheta F\tilde{F}}\right).$
- Axion term $\mathcal{L}_\vartheta = -\frac{1}{2}(\partial\vartheta)^2 - m_\vartheta^2 f_\vartheta^2\left(1-\cos\frac{\vartheta}{f_\vartheta}\right).$
- Interaction $\mathcal{L}_{\vartheta F\tilde{F}} = -\frac{\alpha_\gamma}{4}\vartheta F_{\mu\nu}\tilde{F}^{\mu\nu},\ \ \tilde{F}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\lambda\rho}F_{\lambda\rho}.$

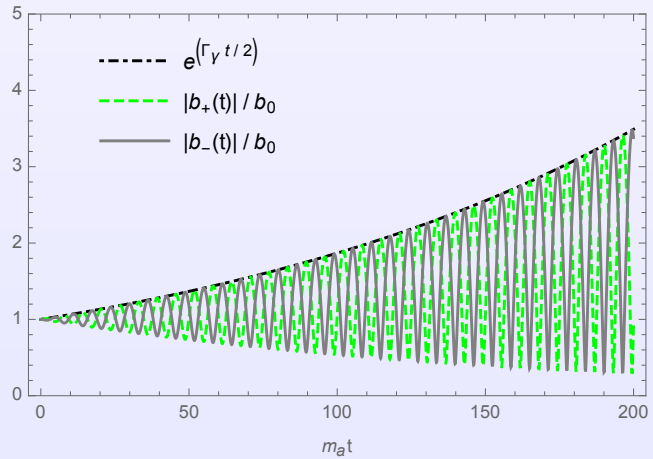
Equation of motion

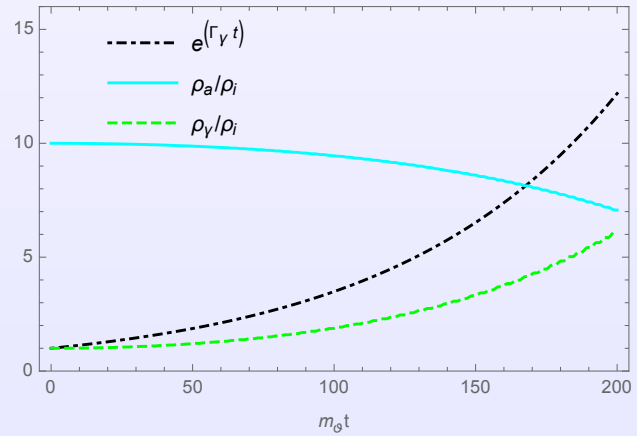
- $(\partial_\mu\partial^\mu - m_\vartheta^2)\vartheta = \frac{\alpha_\gamma}{4}F\tilde{F},\ \ \partial_\mu F^{\mu\nu} = -\alpha_\gamma\tilde{F}^{\mu\nu}\partial_\mu\vartheta$
- Axion like field $\langle\vartheta\rangle = \bar{\vartheta}(t) = \vartheta_0\sin\left(m_\vartheta t + \phi_0\right),$
- Electromagnetic field $A_\pm(t,z) \equiv [A_x(t,z) \pm iA_y(t,z)]/\sqrt{2}$

Mathieu equation and parametric resonance

$\left[-\partial_t^2+\partial_z^2 \mp i\alpha_\gamma \dot{\bar{\vartheta}}(t)\partial_z\right]A_\pm(t,z)=0,\ A_\pm(t,z)=b_\pm(t)e^{ikz}.$

- In momentum space $\ddot{b}_\pm(t)+\left[k^2 \mp \alpha_\gamma k\dot{\bar{\vartheta}}\right]b_\pm(t)=0.$
- Amplification factor $e^{\Gamma_\gamma t_\gamma}$, $\Gamma_\gamma=\alpha_\gamma\vartheta_0\frac{m_\vartheta}{2}$, $\quad t_\gamma\simeq\frac{1}{m_\vartheta v_\vartheta c}$.
- Time evolution of energy density: photon ρ_γ & axion ρ_ϑ.





Fast Radio Burst(GHz) & Gamma Ray Burst

FRBs vs. GRBs

- Physical connection??
- Cultural connection between the two fields

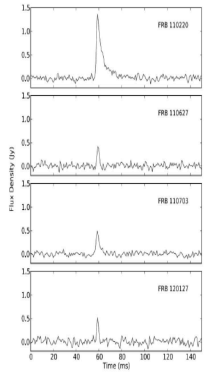
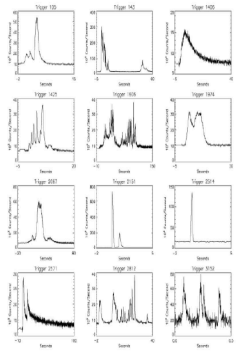


Fig. 1. The frequency-integrated flux densities for the four FRBs. The time resolutions match the level of dispersive smearing in the central frequency channel (0.8, 0.6, 0.9, and 0.5 milliseconds, respectively).



FRBs vs. GRBs

	GRBs	FRBs
Step one: Are they astrophysical?	1967 – 1973	2007 – 2015
Step two: Where are they (distance)?	1973 – 1997 – 2004 (Afterglow counterpart, host galaxy)	2016 (VLBI localization of first repeater, direct localizations with ASKAP, host galaxy)
Step three: What make them?	1998 – 2017 (SN Ic, GW)	??? (young magnetars? pulsars? massive black holes? ...)

- [cf. slides credit: from Bing Zhang]

Axion gravitation coupling ($\vartheta \to hh$)

Gravitational interaction

- Action $S_{GW} = \int d^4x\sqrt{-g}\left(\frac{1}{2\kappa_4}R + \mathcal{L}_\vartheta + \mathcal{L}_{\vartheta R\tilde{R}}\right)$.
- Axion like field $\mathcal{L}_\vartheta = -\frac{1}{2}(\partial\vartheta)^2 - \frac{1}{2}m_\vartheta^2\vartheta^2$.
- Chern-Simons term
  $\mathcal{L}_{\vartheta R\tilde{R}} = \frac{\alpha_g}{4}\vartheta R^\beta{}_{\alpha\gamma\delta}\tilde{R}^{\alpha\ \gamma\delta}_{\ \beta}$, $\tilde{R}^{\alpha\ \gamma\delta}_{\ \beta} \equiv \frac{1}{2}\epsilon^{\gamma\delta\mu\nu}R^\alpha{}_{\beta\mu\nu}$.

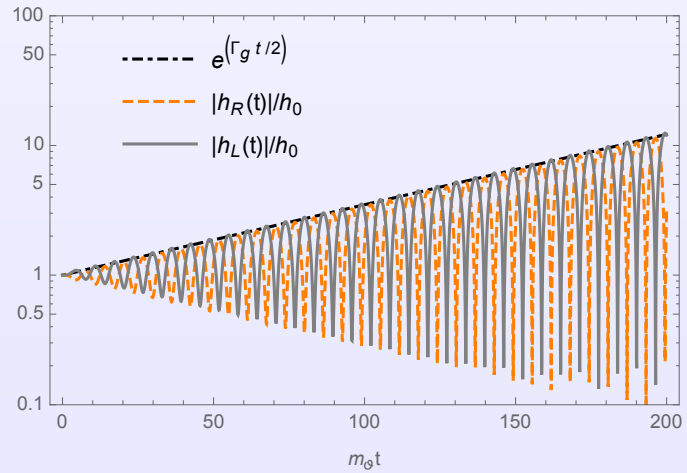
Equation of motion

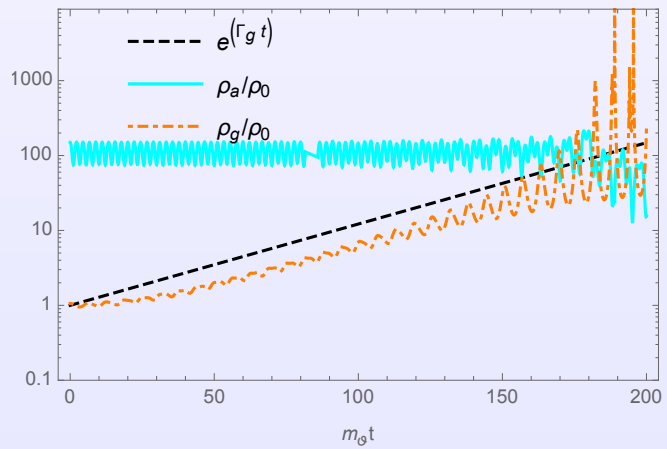
- GWs: $\Box h_{ij} = \kappa_4\alpha_g\tilde{\epsilon}^{pk}{}_{(i}\left[\dot{\vartheta}(\partial_p\Box h_{j)k}) - \ddot{\vartheta}(\partial_p\partial_t h_{j)k})\right]$,
- Axion like field: $(\Box - m_\vartheta^2)\vartheta = -\frac{\alpha_g}{4}R\tilde{R}$,
- Polarization: $h_{ij}(t,z) = \left[h_R(t)e^R_{ij} + h_L(t)e^L_{ij}\right]e^{ikz} + \text{h.c.}$

Parametric Resonance and GW Amplification

E.O.M. of gravitational wave ($I = L, R$)

- $\left[\ddot{h}_I(t) + k^2 h_I(t)\right]\left[1 - \varepsilon_I \kappa_4 \alpha_g k\dot{\vartheta}(t)\right] = \varepsilon_I \kappa_4 \alpha_g k\ddot{\vartheta}(t)\dot{h}_I(t).$
- Factor $e^{\Gamma_g t_g}$, & $\frac{\Gamma_g}{m_\vartheta} \sim \left(\frac{\kappa_4 \alpha_g}{1\mathrm{eV}^{-3}}\right)\left(\frac{m_\vartheta}{10^{-9}\mathrm{eV}}\right)^2\left(\frac{\vartheta_0}{10^9\mathrm{GeV}}\right)$.
- Time evolution of gravitational field ρ_g & axion field ρ_ϑ.





[cf. S. Sun, Y. L. Zhang, Gravitational Wave Burst from Axion Clumps, PRD'21]

Joint analysis & Branch Ratio ($\vartheta \to \gamma\gamma,\ \vartheta \to hh$)

The interaction

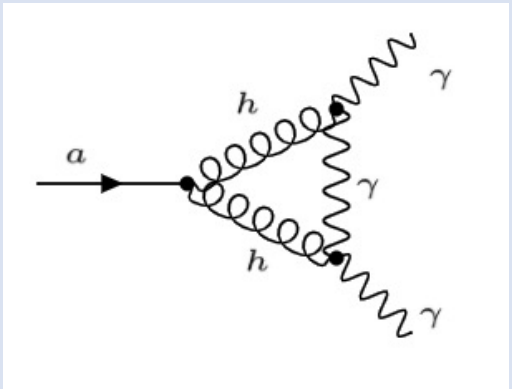
- $S_{total} = \int d^4x\sqrt{-g}\left(\frac{1}{2\kappa_4}R - \frac{1}{4}F^2 + \mathcal{L}_\vartheta + \mathcal{L}_{\vartheta F\tilde{F}} + \mathcal{L}_{\vartheta R\tilde{R}}\right)$
- EM field $\mathcal{L}_\vartheta = -\frac{1}{2}(\partial\vartheta)^2 - \frac{1}{2}m_\vartheta^2\vartheta^2$.
- $\mathcal{L}_{\vartheta F\tilde{F}} = -\frac{\alpha_\gamma}{4}\vartheta F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\mathcal{L}_{\vartheta R\tilde{R}} = \frac{\alpha_g}{4}\vartheta R^{\beta}{}_{\alpha\gamma\delta}\tilde{R}^{\alpha}{}_{\beta}{}^{\gamma\delta}$.

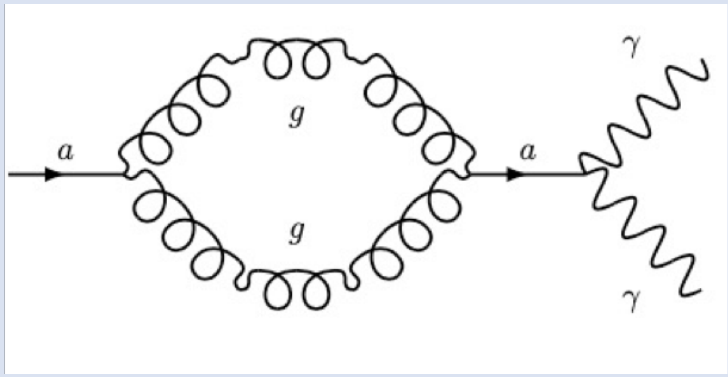
Equation of motion

- $\Box h_{ij} = \kappa_4\alpha_g\tilde{\epsilon}^{pk}{}_{(i}\left[\dot{\bar{\vartheta}}(\partial_p\Box h_{j)k}) - \ddot{\bar{\vartheta}}(\partial_p\partial_t h_{j)k})\right] - 2\kappa_4\left(T^{(\gamma)}_{ij} + T^{(\vartheta)}_{ij}\right)$
- axion like field $(\Box - m_\vartheta^2)\vartheta = \frac{\alpha_\gamma}{4}F\tilde{F} - \frac{\alpha_g}{4}R\tilde{R}$
- Polarization $\nabla_\mu F^{\mu\nu} = -\alpha_\gamma\partial_\mu\vartheta\tilde{F}^{\mu\nu}$

Branch Ratio and Triangle Feynman Diagram

- The triangle Feynman diagram, where the axion-photon coupling is generated from CS gravity coupling.
- $\mathcal{L}_{\vartheta F\tilde{F}} = -\frac{\alpha_\gamma}{4}\vartheta F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad \mathcal{L}_{\vartheta R\tilde{R}} = \frac{\alpha_g}{4}\vartheta R^{\beta}{}_{\alpha\gamma\delta}\tilde{R}^{\alpha}{}_{\beta}{}^{\gamma\delta}.$





- This diagram is quadratically divergent, with 4 extra powers of momentum from 3 vertices in the loop and two powers of M_{pl} from $h_{\mu\nu}T^{\mu\nu}$ coupling
- It is evaluated as $\alpha_\gamma \sim \alpha_g(\Lambda/M_{pl})^4$, where Λ is the cut-off for Chern-Simons theory.

Parameter resonance and GW amplification

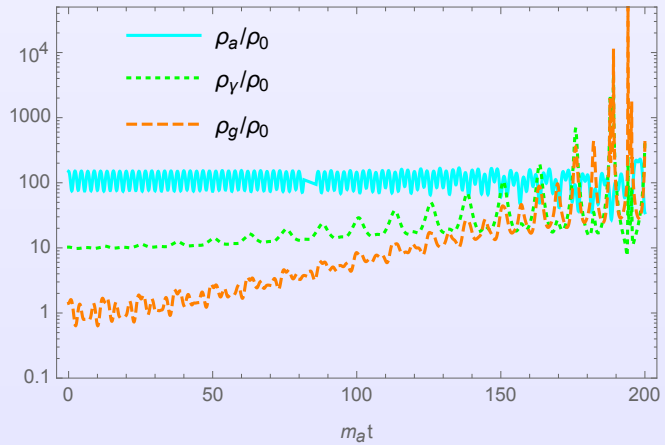
Branch Ratio and GWs

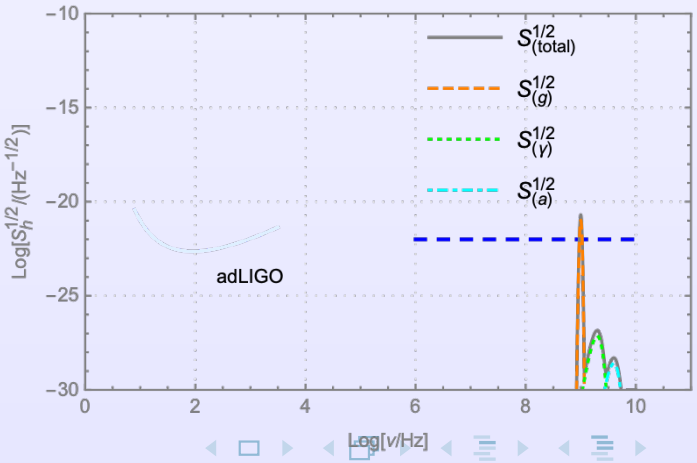
- $\frac{\mathrm{Br}(\vartheta\to gg)}{\mathrm{Br}(\vartheta\to\gamma\gamma)} \simeq \frac{\alpha_g^2}{\alpha_\gamma^2}$, (Power of FRB $P_{(\gamma)} \sim 10^{42}$ergs/s).
- High frequency band

$$h_{(g)} \sim 10^{-23}\left(\frac{1\mathrm{GHz}}{\nu}\right)\left(\frac{P_{(g)}}{P_{(\gamma)}}\right)^{1/2}\left(\frac{1\mathrm{kpc}}{L}\right)$$

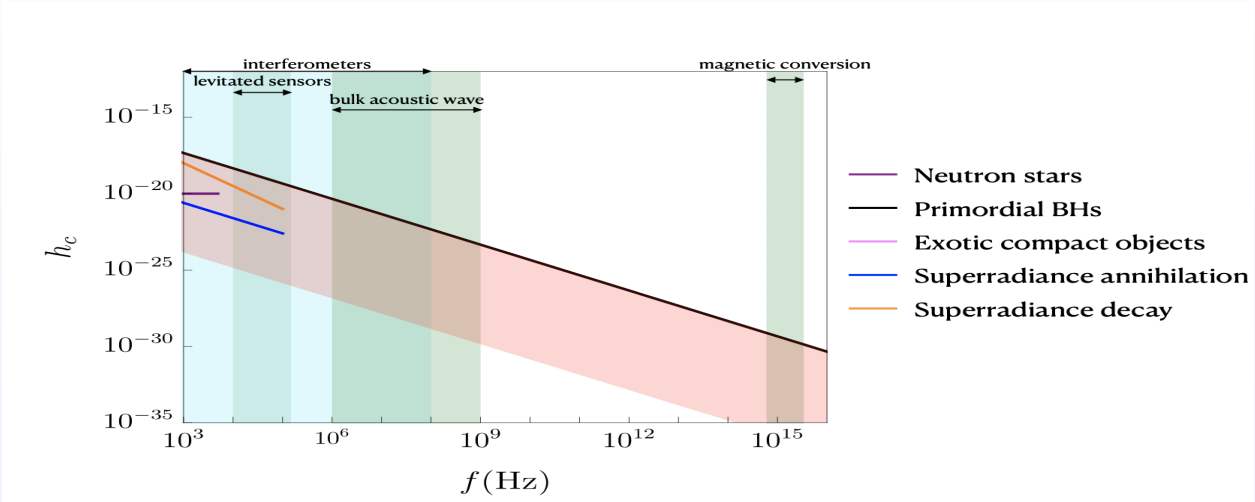
- Low frequency band

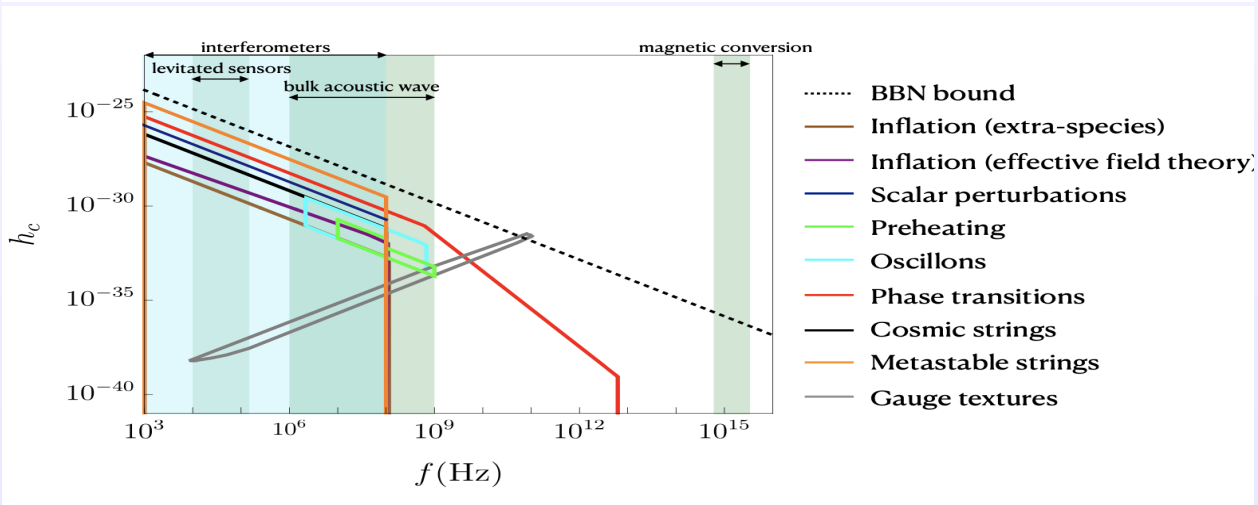
$$h_{(g)} \sim 10^{-21}\left(\frac{10^{-2}\mathrm{Hz}}{\nu}\right)^{1/2}\left(\frac{M_{\mathrm{BH}}}{10^7 M_\odot}\right)^{1/2}\left(\frac{1\mathrm{kpc}}{L}\right).$$





GW searches from kHz to GHz Frequencies

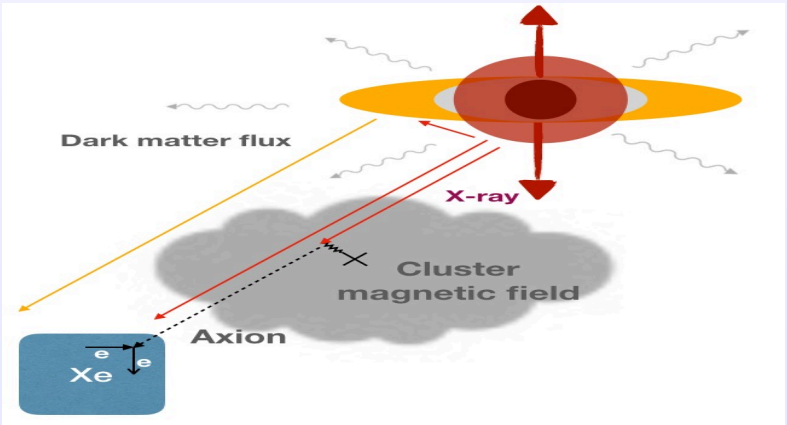


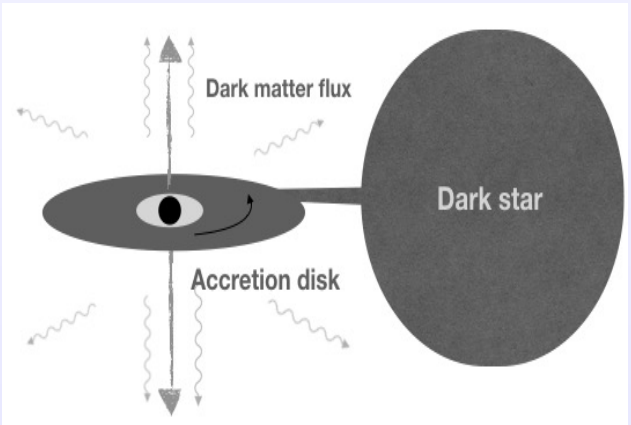


[cf. N. Aggarwal *et al.*, "Challenges and Opportunities of Gravitational Wave Searches at MHz to GHz Frequencies"]

Dark Fluxes from Accreting Black Holes

- keV light dark matter flux: several mechanisms from the accreting black hole systems.
- X-Ray sources: Coronal thermal plasmas around supermassive black holes in active galactic nuclei (AGNs),
- X-Ray sources: Accretion disks of stellar-mass black hole binaries (BHBs).



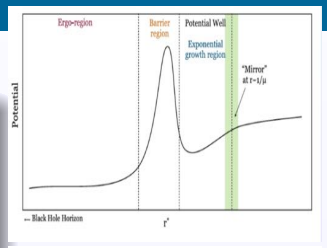


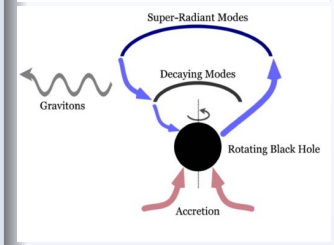
[cf. R. G. Cai, S. Sun, B. Zhang and Y. L. Zhang, arXiv:2009.02315.]

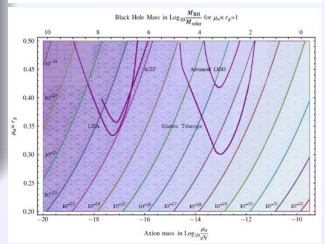
Summary and Outlook

Black Hole Superradiance & GWs

- Superradiance $\alpha \equiv \frac{R_{BH}}{\lambda_\vartheta} \simeq \left(\frac{M_{BH}}{M_\odot}\right)\left(\frac{m_\vartheta}{10^{-10}\mathrm{eV}}\right)$
- Energy transition $\vartheta^+ \to \vartheta^- + h$ (monochromic)
  Axion annihilation $\vartheta + \vartheta \to h$ (stochastic)
- Fast Radio Burst from Axion $\sim \vartheta F\tilde{F}$ $(\vartheta \to \gamma\gamma)$
- GW burst from Axion $\sim \vartheta R\tilde{R}$ $(\vartheta \to hh)$

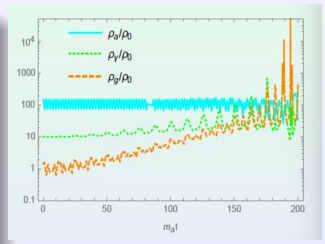


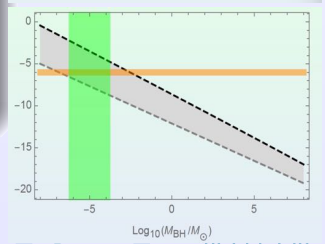




Outlook: Ultra-light DM and multi band GW detection

- PTA & SKA : Ultra-light dark matter ($\sim$ nHz)
- LVK & LISA-TT: Superradiance ($\sim$ mHz - kHz)
- Table Lab: Axion star & GW burst ($\sim$ GHz)





Thanks a lot for your attention!