Fast Gravitational Wave Burst from Axion Clumps

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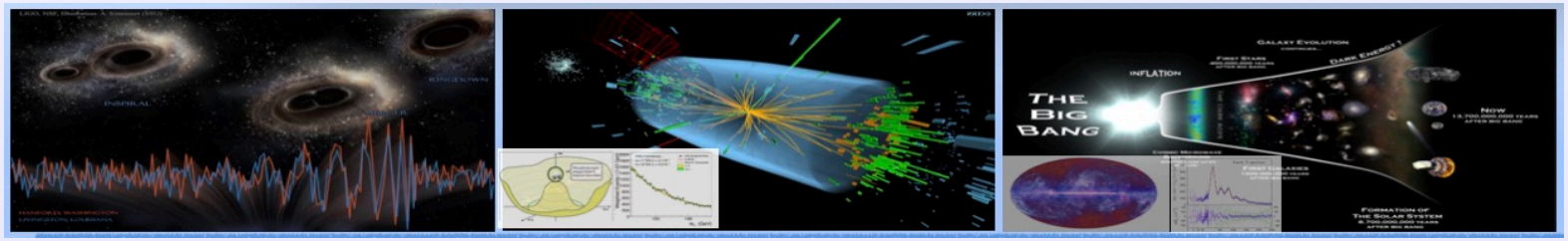
Aug 17, 2021 @13th 粒子物理学术会议
based on 2003.10527 with Sichun Sun (BIT)



引力波天体物理团组
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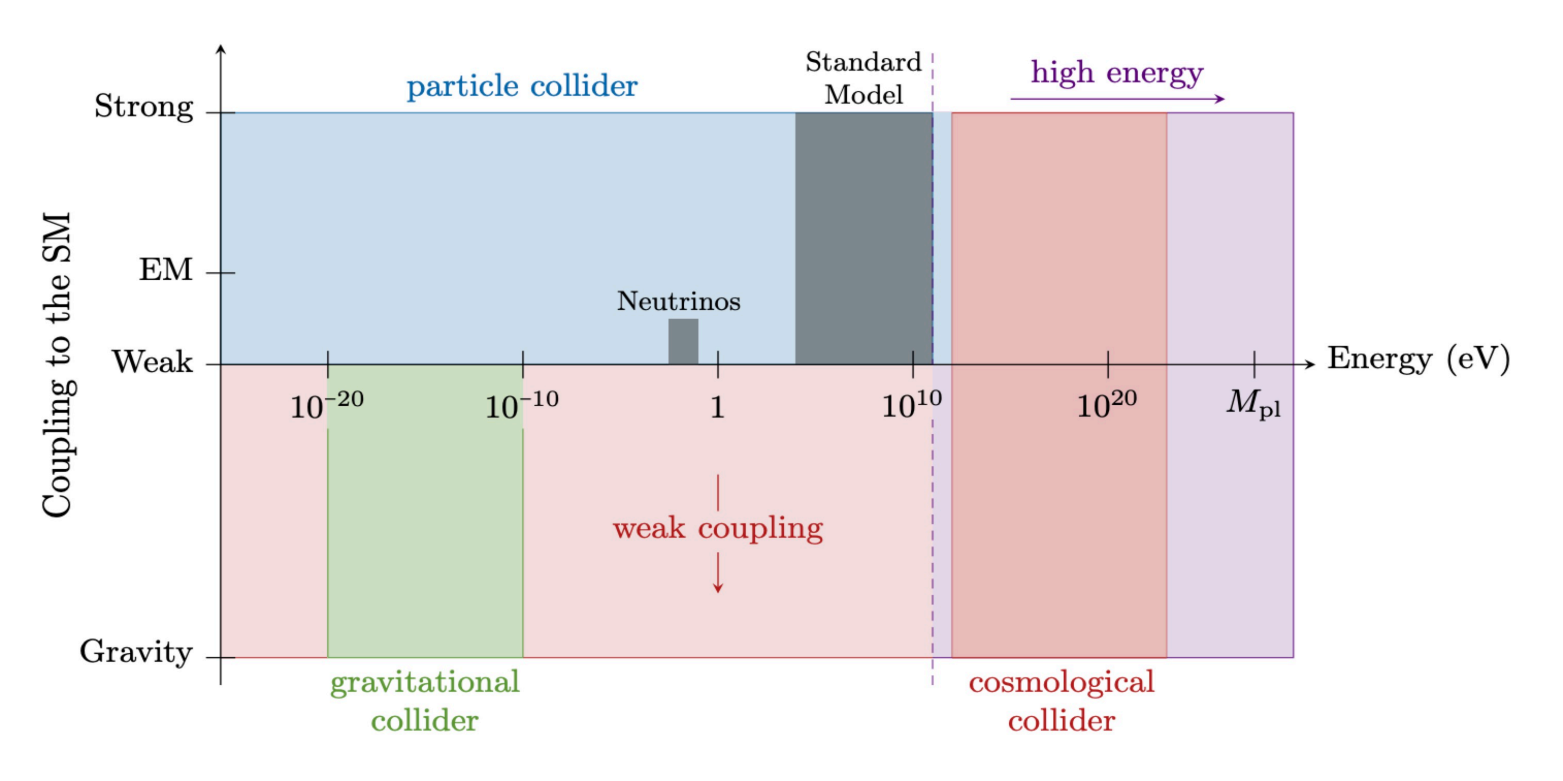
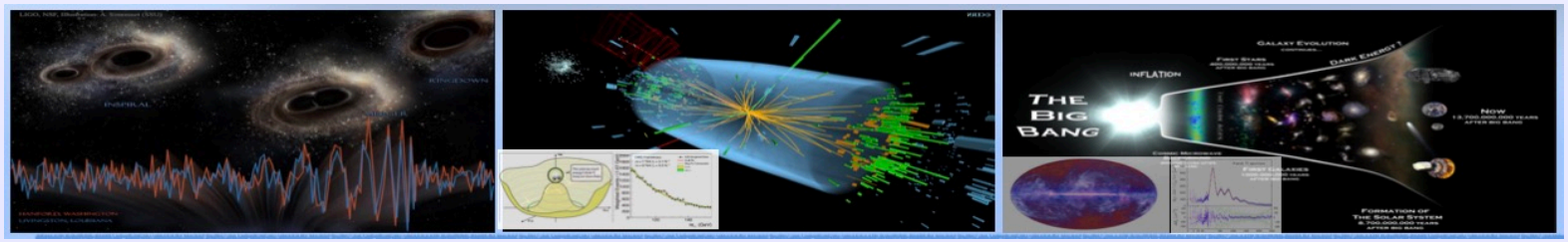
引力对撞机和超低能标的新物理效应



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



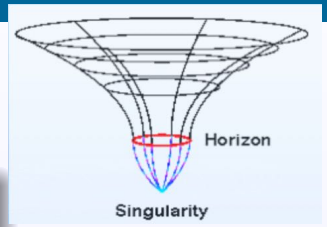
报告目录

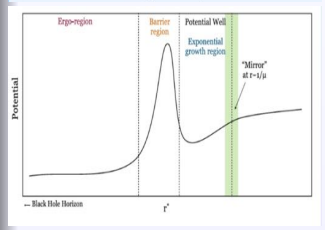
黑洞的超辐射和引力波效应

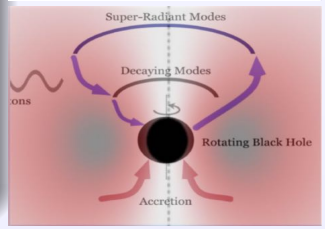
- 超辐射和轴子云：$\alpha \equiv \frac{R_{BH}}{\lambda_\vartheta} \simeq \left(\frac{M_{BH}}{M_\odot}\right)\left(\frac{m_\vartheta}{10^{-10}\mathrm{eV}}\right)$
- 能级跃迁：$\vartheta^+ \to \vartheta^- + h$，轴子湮灭：$\vartheta + \vartheta \to h$
- 轴子诱导的快速射电暴：$\sim \vartheta F\tilde{F}\ (\vartheta \to \gamma\gamma)$
- 轴子诱导的引力波暴：$\sim \vartheta R\tilde{R}\ (\vartheta \to hh)$

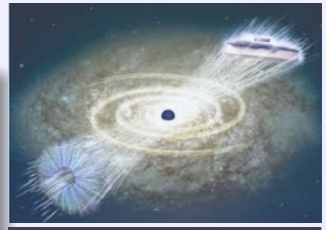
超轻暗物质的多波段引力波探测

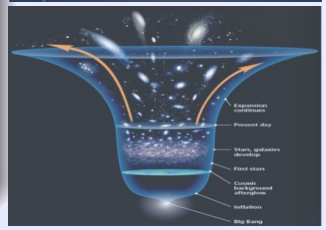
- PTA & SKA 脉冲星计时：超轻暗物质 ($\sim$ nHz)
- LISA-Taiji-Tianqin & Ligo-Virgo-Kagra ($\sim$ mHz - kHz)
- Table Lab 轴子星 & 射电暴引力波等 ($\sim$ GHz)











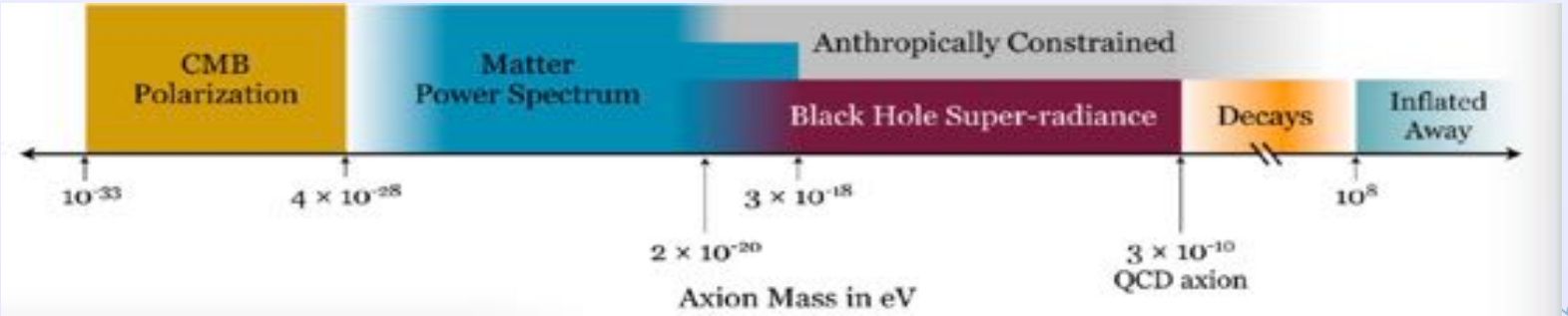
超轻暗物质

量子色动力学 (QCD 轴子)

- $\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a - \alpha\theta F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a + \bar{\psi}\left(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5}\right)\psi$
- 强 CP 问题：电荷共轭 C 和宇称 P 变换下没有破缺
- Peccei–Quinn (1977)：引入新的赝标量粒子
- Wilczek- Weinberg：有效 ϑ 参数可以自然选取为零

类轴子型超轻暗物质

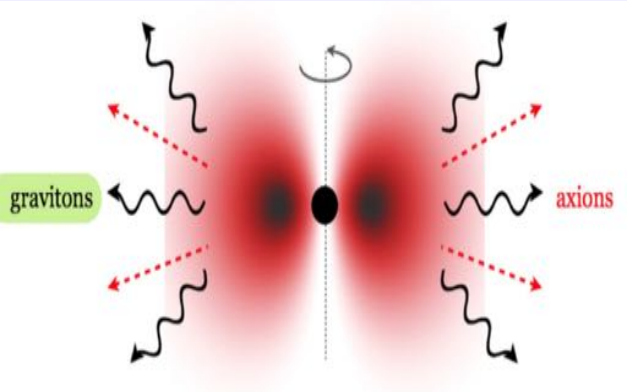
- e.g. Fuzzy Dark Matter (L. Hui, E. Witten, et al 2015) $\sim 10^{-22}$eV

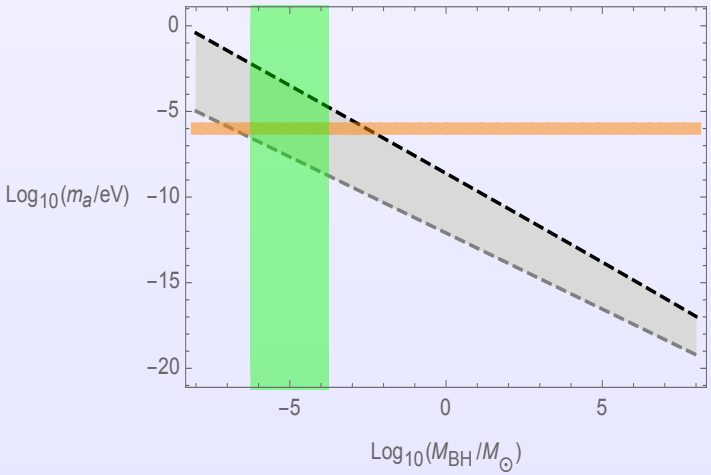


轴子云和黑洞超辐射

黑洞尺度 $R_{BH} = G_N M_{BH}/c^2$, 轴子德布罗意波长 $\lambda_\vartheta = \hbar/(m_\vartheta v_\vartheta)$

- 特征参数 $\alpha \equiv \frac{R_{BH}}{\lambda_\vartheta} \simeq \left(\frac{M_{BH}}{M_\odot}\right)\left(\frac{m_\vartheta}{10^{-10}\mathrm{eV}}\right)\left(\frac{v_\theta}{c}\right)$.
- 轴子云形成时间 $\tau_\vartheta <$ 宇宙年龄 $\tau_U \simeq 10^{23}\left(\frac{M_\odot}{M_{BH}}\right) R_{BH}$
- $\tau_{\vartheta\uparrow} \simeq 10^7 e^{1.84\alpha} R_{BH},\ \alpha \gg 1, \quad \tau_{\vartheta\downarrow} \simeq 24\,\alpha^{-9} R_{BH},\ \alpha \ll 1.$

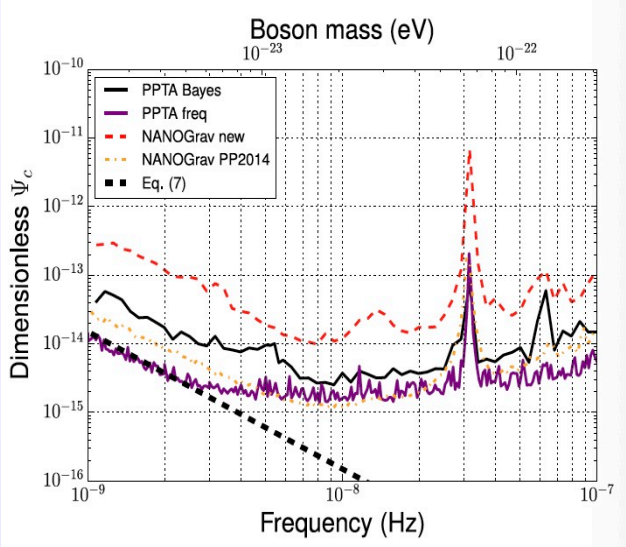


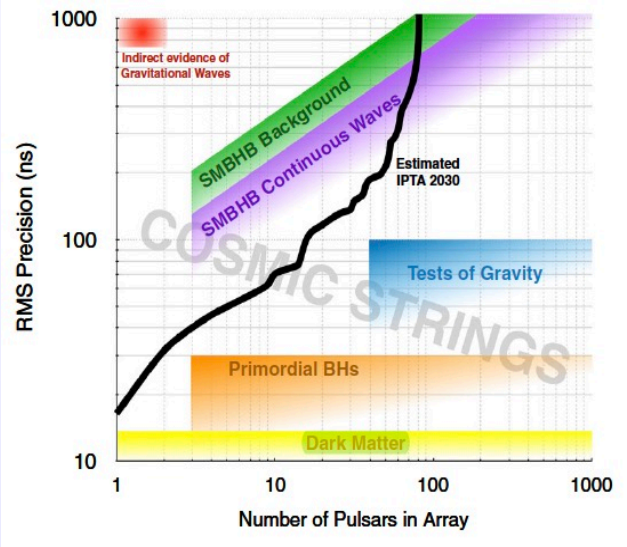


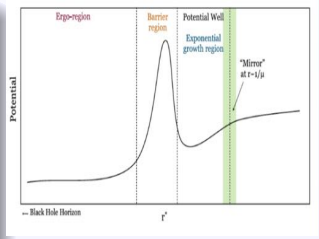
超轻暗物质和多波段引力波探测

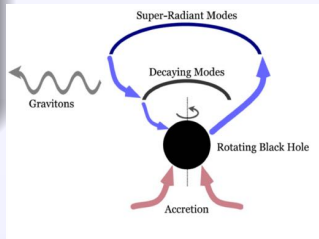
类轴子型超轻暗物质模型和参数空间

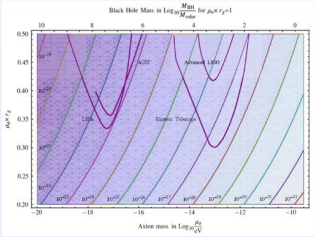
- PTA & SKA 波段：超轻 Fuzzy 暗物质 (∼ nHz)
- LISA-Taiji-Tianqin & Ligo-Virgo-Kagra (∼ mHz - kHz)
- 轴子星 & 快速射电暴 & 引力波暴等 (∼ GHz)

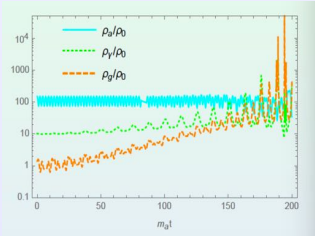


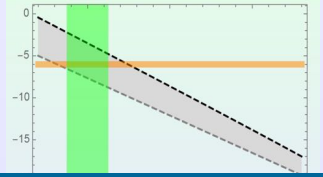




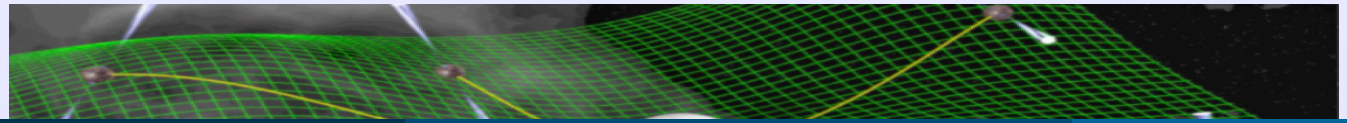




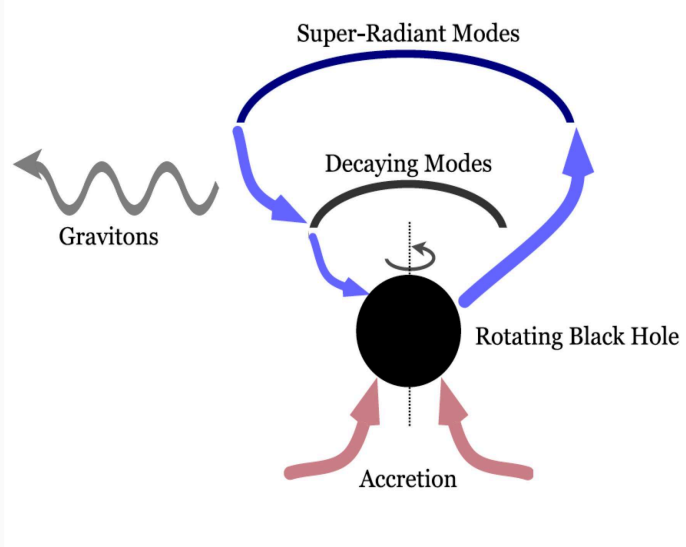


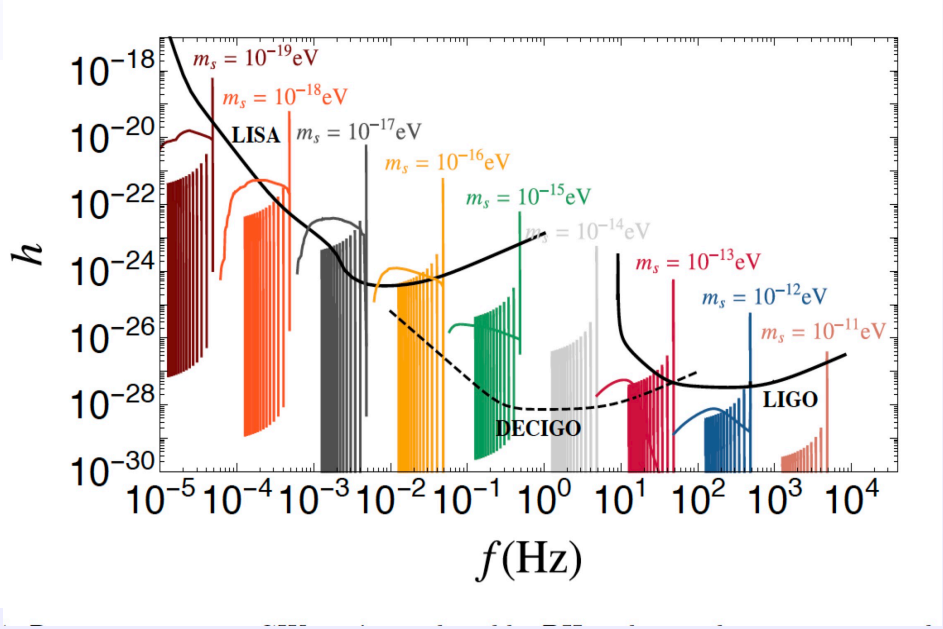


[cf. X. J. Zhu et al, 2018] Parkes PTA constraints on ultralight scalar-field dark matter



能级跃迁和引力波效应

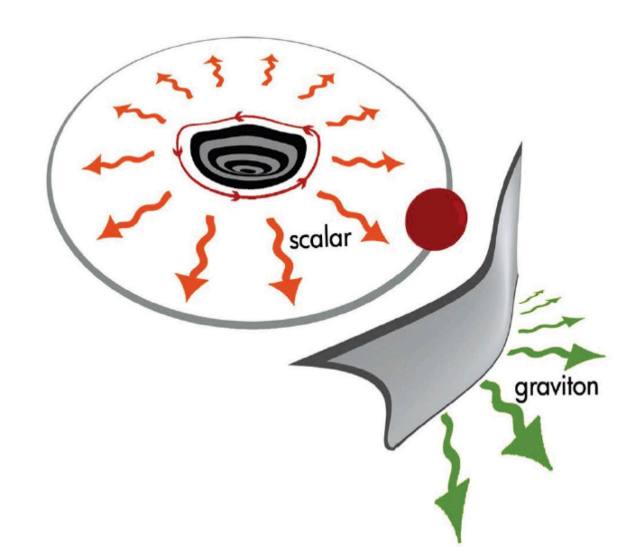


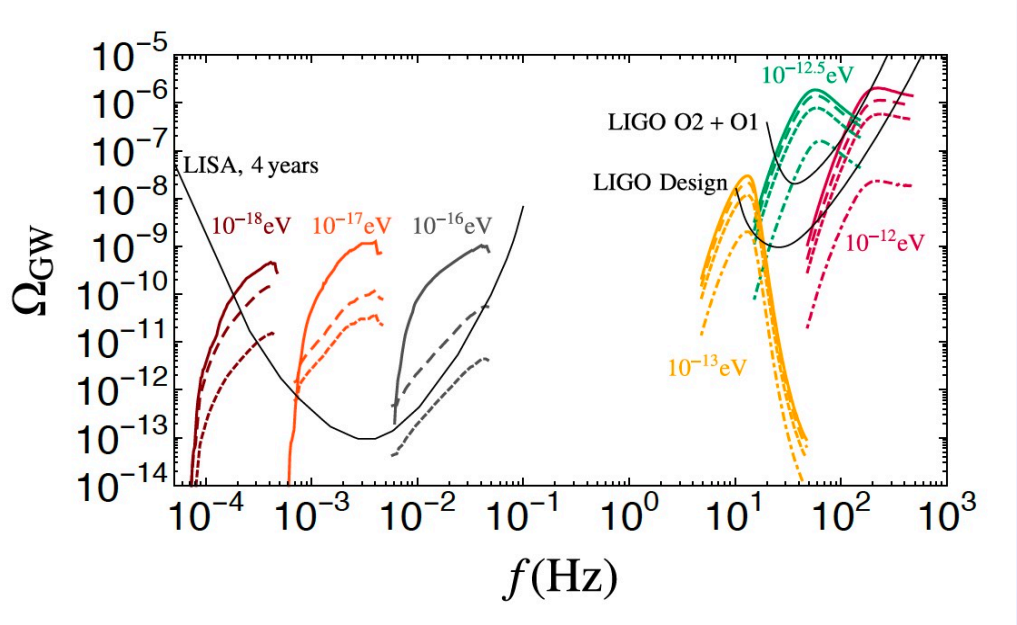


黑洞尺度 $R_{BH} = G_N M_{BH}/c^2$, 轴子康普顿波长 $\lambda_\vartheta = \hbar/(m_\vartheta c)$

- 能级跃迁 $\vartheta^+ \to \vartheta^- + h$, 信号 $h \sim 10^{-19} - 10^{-27}$
- [cf. Brito-Cardoso-Pani, Superradiance 2020]

轴子湮灭和引力波效应





- 轴子湮灭 $\vartheta + \vartheta \to h$, 信号 $h \sim 10^{-21} - 10^{-32}$.
- [cf. Brito-Cardoso-Pani, Superradiance 2020]

轴子光子耦合 ($\vartheta \to \gamma\gamma$)

相互作用量

- 电磁作用量 $S_{EM} = \int d^4x\sqrt{-g}\left(-\frac{1}{4}F^2 + \mathcal{L}_\vartheta + \mathcal{L}_{\vartheta F\tilde{F}}\right)$.
- 类轴子场 $\mathcal{L}_\vartheta = -\frac{1}{2}(\partial\vartheta)^2 - m_\vartheta^2 f_\vartheta^2\left(1 - \cos\frac{\vartheta}{f_\vartheta}\right)$.
- 相互作用 $\mathcal{L}_{\vartheta F\tilde{F}} = -\frac{\alpha_\gamma}{4}\vartheta F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\tilde{F}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\lambda\rho}F_{\lambda\rho}$..

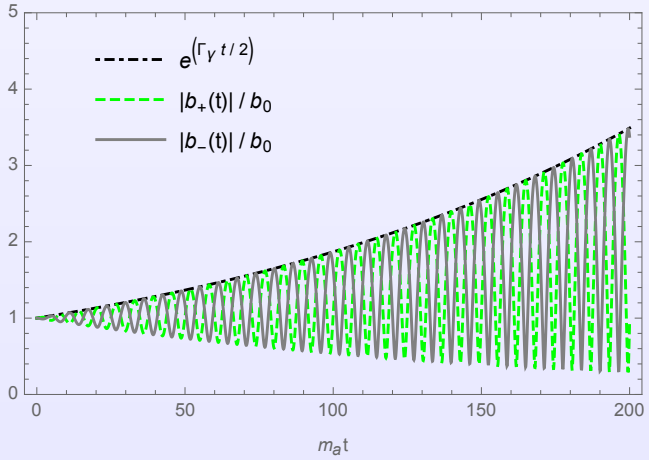
运动方程

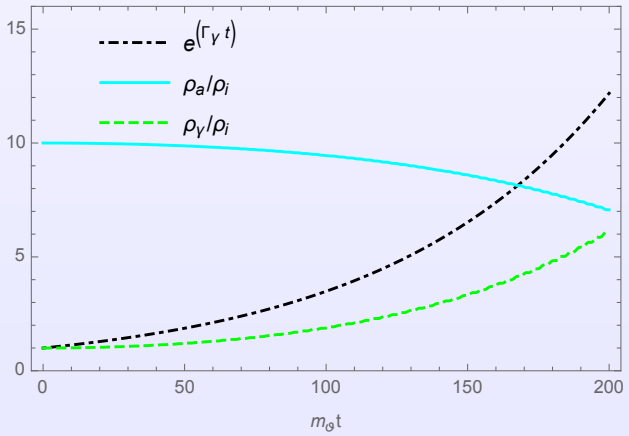
- $(\partial_\mu\partial^\mu - m_\vartheta^2)\vartheta = \frac{\alpha_\gamma}{4}F\tilde{F}$, $\partial_\mu F^{\mu\nu} = -\alpha_\gamma\tilde{F}^{\mu\nu}\partial_\mu\vartheta$.
- 类轴子场 $\langle\vartheta\rangle = \bar{\vartheta}(t) = \vartheta_0\sin(m_\vartheta t + \phi_0)$,
- 电磁场 $A_\pm(t,z) \equiv [A_x(t,z) \pm iA_y(t,z)]/\sqrt{2}$

Mathieu 方程和参数共振

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

- 动量空间 $\ddot{b}_\pm(t)+\left[k^2\mp\alpha_\gamma k\dot{\vartheta}\right]b_\pm(t)=0.$
- 指数增长因子 $e^{\Gamma_\gamma t_\gamma}$，其中 $\Gamma_\gamma=\alpha_\gamma\vartheta_0\frac{m_\vartheta}{2},\quad t_\gamma\simeq\frac{1}{m_\vartheta v_\vartheta c}.$
- 光子和轴子场的能量密度 ρ_γ 和 ρ_ϑ 随时间的变化





快速射电暴和轴子云

- 轴子云超辐射 ($10^{-6}eV$) $\rightarrow$ 快速射电暴 (@GHz)
- 原初黑洞 ($10^{-5}M_{\odot}$) 附近的轴子云 (10^{42}erg/s)

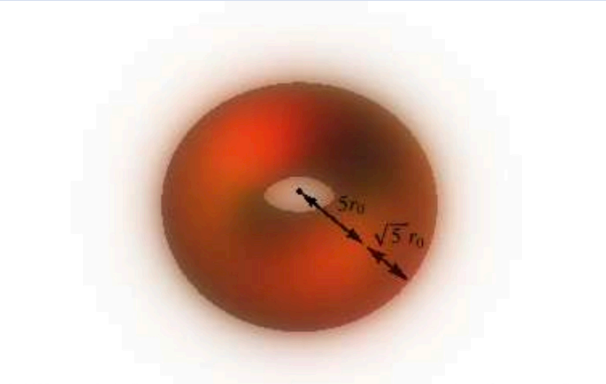
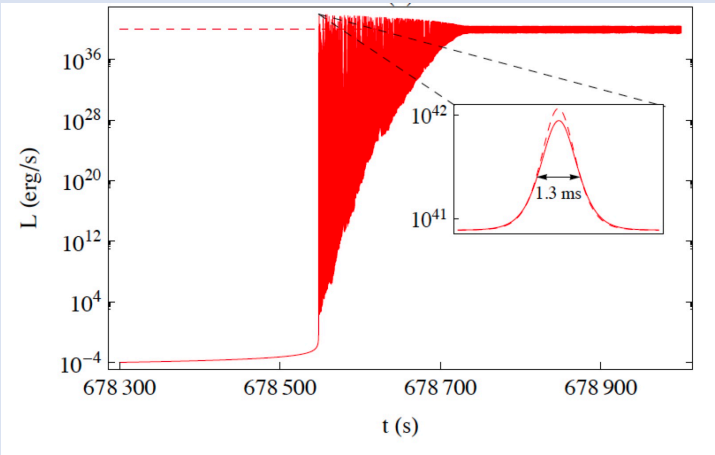


FIG. 1. Model of the superradiant $2p$-axion cloud around a central Kerr black hole.



- $\left[-\partial_t^2+\partial_z^2\mp i\alpha_\gamma\dot{\bar{\vartheta}}(t)\partial_z\right]A_\pm(t,z)=0,\ A_\pm(t,z)=b_\pm(t)e^{ikz}$
- [cf. J. Rosa-T. Kephart , PRL(2018)]

轴子引力子耦合 ($\vartheta \to hh$)

相互作用量

- 引力作用量 $S_{GW} = \int d^4x\sqrt{-g}\left(\frac{1}{2\kappa_4}R + \mathcal{L}_\vartheta + \mathcal{L}_{\vartheta R\tilde{R}}\right)$.
- 类轴子场 $\mathcal{L}_\vartheta = -\frac{1}{2}(\partial\vartheta)^2 - \frac{1}{2}m_\vartheta^2\vartheta^2$.
- 相互作用 $\mathcal{L}_{\vartheta R\tilde{R}} = \frac{\alpha_{\mathrm{g}}}{4}\vartheta R^\beta{}_{\alpha\gamma\delta}\tilde{R}^\alpha{}_\beta{}^{\gamma\delta}$, $\tilde{R}^\alpha{}_\beta{}^{\gamma\delta} \equiv \frac{1}{2}\epsilon^{\gamma\delta\mu\nu}R^\alpha{}_{\beta\mu\nu}$.

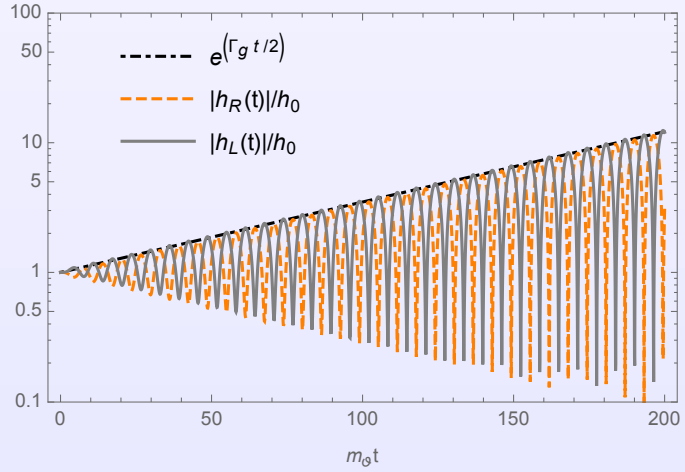
运动方程

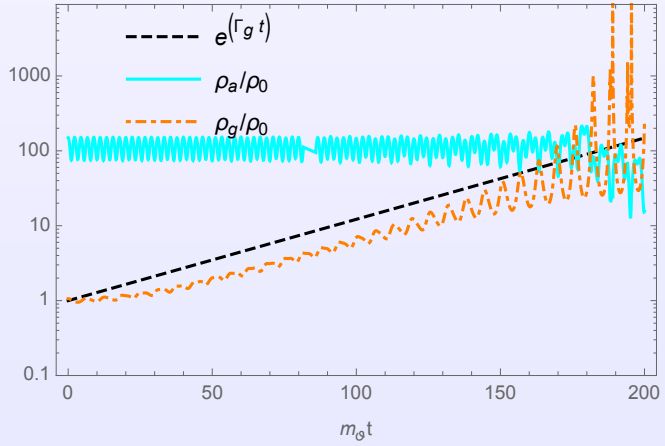
- 引力波 $\Box h_{ij} = \kappa_4\alpha_{\mathrm{g}}\tilde{\epsilon}^{pk}{}_{(i}\left[\dot{\vartheta}(\partial_p\Box h_{j)k}) - \ddot{\vartheta}(\partial_p\partial_t h_{j)k})\right]$,
- 类轴子场 $(\Box - m_\vartheta^2)\vartheta = -\frac{\alpha_{\mathrm{g}}}{4}R\tilde{R}$,
- 极化模式 $h_{ij}(t,z) = \left[h_R(t)e_{ij}^R + h_L(t)e_{ij}^L\right]e^{ikz} + \mathrm{h.c.}$

参数共振和引力波信号放大

引力波动方程 ($I = L, R$)

- $\left[\ddot{h}_I(t) + k^2 h_I(t)\right]\left[1 - \varepsilon_I \kappa_4 \alpha_{\mathbf{g}} k \dot{\vartheta}(t)\right] = \varepsilon_I \kappa_4 \alpha_{\mathbf{g}} k \ddot{\vartheta}(t) \dot{h}_I(t).$
- 指数因子 $e^{\Gamma_{\mathbf{g}} t_{\mathbf{g}}}$, 其中 $\frac{\Gamma_{\mathbf{g}}}{m_\vartheta} \sim \left(\frac{\kappa_4 \alpha_{\mathbf{g}}}{1\mathrm{eV}^{-3}}\right)\left(\frac{m_\vartheta}{10^{-9}\mathrm{eV}}\right)^2\left(\frac{\vartheta_0}{10^9\mathrm{GeV}}\right).$
- 引力场和轴子场的能量密度 ρ_g 和 ρ_ϑ 随时间的变化





c.f. S. Sun, Y. L. Zhang, Gravitational Waves and Possible Fast Radio Bursts from Axion Clumps.

联立求解和分支比例 ($\vartheta \to \gamma\gamma,\ \vartheta \to hh$)

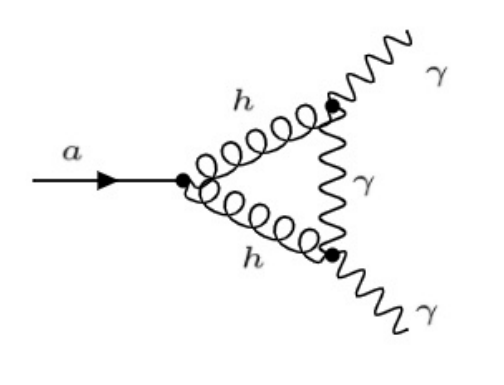
相互作用量

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

运动方程

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

分支比和三角反常费曼图

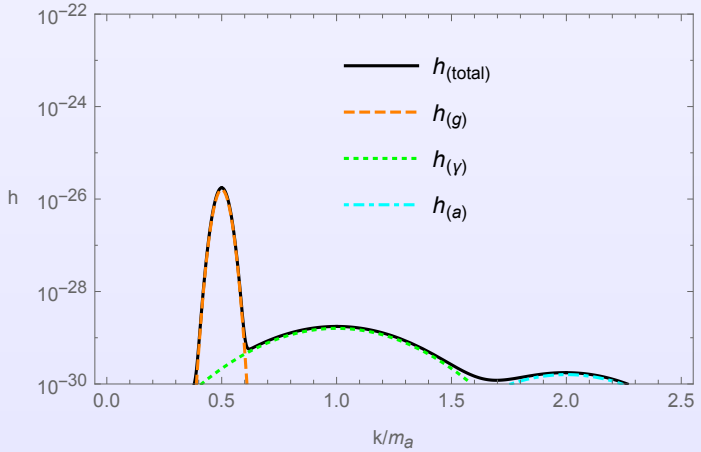
- $\mathcal{L}_{\vartheta F\tilde{F}} = -\frac{\alpha_\gamma}{4}\vartheta F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad \mathcal{L}_{\vartheta R\tilde{R}} = \frac{\alpha_{\mathbf{g}}}{4}\vartheta R^{\beta}{}_{\alpha\gamma\delta}\tilde{R}^{\alpha}{}_{\beta}{}^{\gamma\delta}.$
- 轴子-引力子耦合诱导的轴子-光子耦合
- 

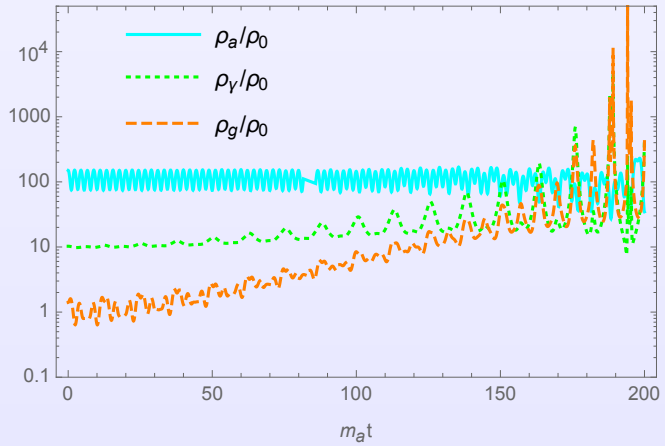
$\Rightarrow \alpha_\gamma \sim \alpha_{\mathbf{g}}(M_c/M_{pl})^4$
- 其中 M_c 是 Chern-Simons 引力的截断能标
- 引力子-光子耦合顶点来自 $\tilde{h}_{\mu\nu}T^{\mu\nu} \sim \frac{1}{M_{pl}}h_{\mu\nu}F^{\mu\lambda}F_\lambda{}^\nu$

参数共振和引力波信号放大

分支比和引力波效应

- $\frac{\mathrm{Br}(\vartheta\to \mathrm{gg})}{\mathrm{Br}(\vartheta\to\gamma\gamma)} \simeq \frac{\alpha_{\mathrm{g}}^2}{\alpha_\gamma^2} \gg 1$, (快速射电暴功率 $P_{(\gamma)} \sim 10^{42}$ergs/s).
- 高频波段 $h_{(\mathrm{g})} \sim 10^{-26}\left(\frac{1\mathrm{GHz}}{\nu}\right)\left(\frac{P_{(\mathrm{g})}}{P_{(\gamma)}}\right)^{1/2}\left(\frac{1\mathrm{kpc}}{L}\right)$
- 低频波段 $\sim 10^{-20}\left(\frac{10^{-2}\mathrm{Hz}}{\nu}\right)^{1/2}\left(\frac{M_{\mathrm{BH}}}{10^7 M_\odot}\right)^{1/2}\left(\frac{1\mathrm{kpc}}{L}\right)$.



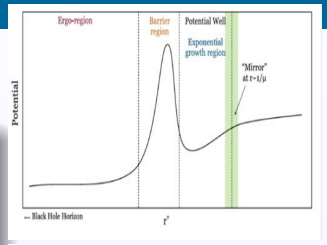
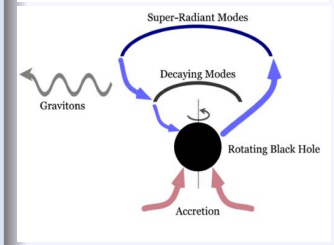
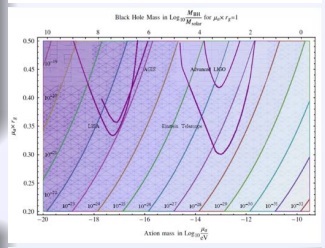
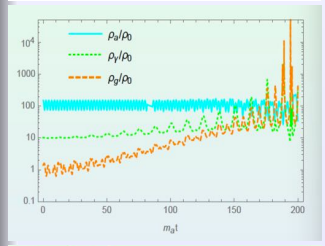
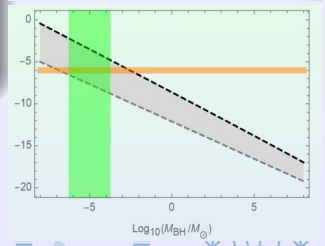


小结和展望

黑洞的超辐射和引力波效应

- 超辐射和轴子云：$\alpha \equiv \frac{R_{BH}}{\lambda_\vartheta} \simeq \left(\frac{M_{BH}}{M_\odot}\right)\left(\frac{m_\vartheta}{10^{-10}\mathrm{eV}}\right)$
- 能级跃迁：$\vartheta^+ \to \vartheta^- + h$，轴子湮灭：$\vartheta + \vartheta \to h$
- 轴子诱导的快速射电暴：$\sim \vartheta F\tilde{F}\ (\vartheta \to \gamma\gamma)$
- 轴子诱导的引力波暴：$\sim \vartheta R\tilde{R}\ (\vartheta \to hh)$

展望：超轻暗物质的多波段引力波探测

- PTA & SKA 脉冲星计时：超轻暗物质 ($\sim$ nHz)
- LISA-Taiji-Tianqin & Ligo-Virgo-Kagra ($\sim$ mHz - kHz)
- 桌面实验 & 轴子星 & 引力波暴 (GHz & mHz)

感谢各位老师同学！