Overview of Black Hole Superradiance

Hong Zhang （张宏）
Shandong University, Qingdao

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Outline

- ✧ Introduction
- ✧ The fast-growing cloud
- ✧ Evolution of BH-cloud system
- ✧ Observables
- ✧ Summary

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Kerr Metric

- Describing a rotating black hole

$$ds^2 = \left(1 - \frac{2\,r_g r}{\Sigma}\right) dt^2 + \frac{4\,a\,r_g r}{\Sigma} \sin^2\theta\, dt\, d\varphi - \frac{\Sigma}{\Delta} dr^2$$
$$- \Sigma\, d\theta^2 - \left[(r^2 + a^2)\sin^2\theta + 2\frac{r_g r}{\Sigma} a^2 \sin^4\theta\right] d\varphi^2.$$

with $\quad a = J/M,\; r_g = G\,M$

$$\Delta = r^2 - 2r_g r + a^2$$

$$\Sigma = r^2 + a^2\cos^2\theta$$

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with $\quad a = J/M,\ r_g = G\, M$

$$\Delta = r^2 - 2 r_g r + a^2$$

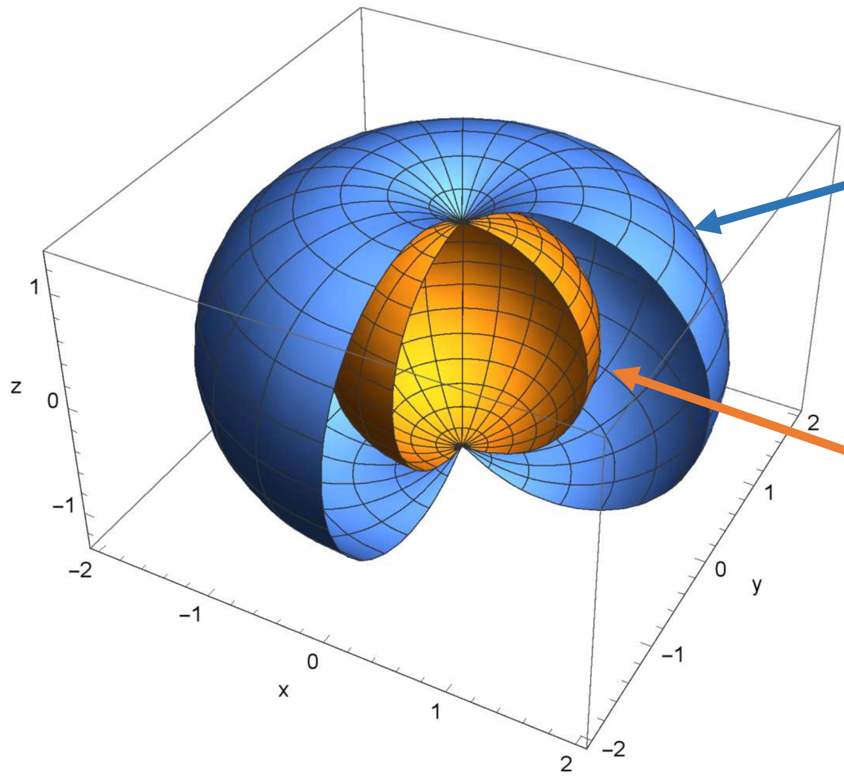
$$\Sigma = r^2 + a^2 \cos^2\theta$$

Horizons: $\quad \Delta = 0 \quad \Longrightarrow \quad r_\pm = r_g \pm \sqrt{r_g^2 - a^2}$

Ergo-sphere: $\quad 1 - \frac{2 r_g r}{\Sigma} = 0 \quad \Longrightarrow \quad r_{\mathrm{E},\pm} = r_g \pm \sqrt{r_g^2 - a^2 \cos\theta^2}$

Ergo-region

- Region between outer horizon and outer ergo-sphere



outer ergosphere

$$r_{\mathrm{E},+} = r_g + \sqrt{r_g^2 - a^2 \cos\theta^2}$$

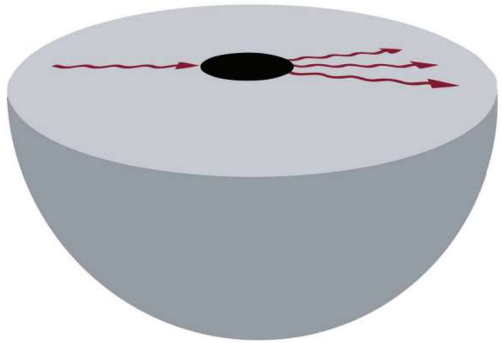
outer horizon

$$r_+ = r_g \pm \sqrt{r_g^2 - a^2}$$

- In the ergoregion, energy can be negative.
- Penrose process: extracting energy and angular mom. From BH

Superradiance

- A wave shining on a Kerr BH could be enhanced in magnitude.



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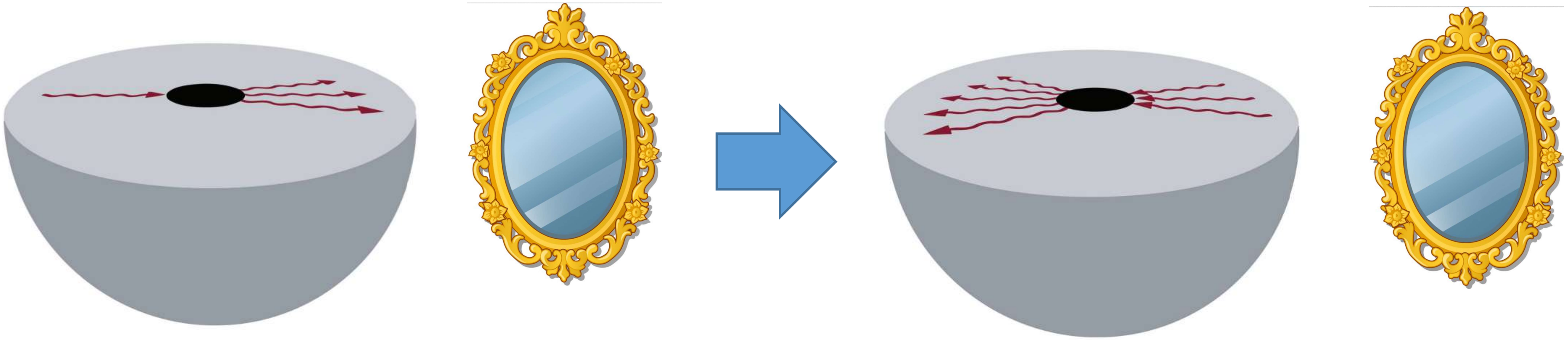

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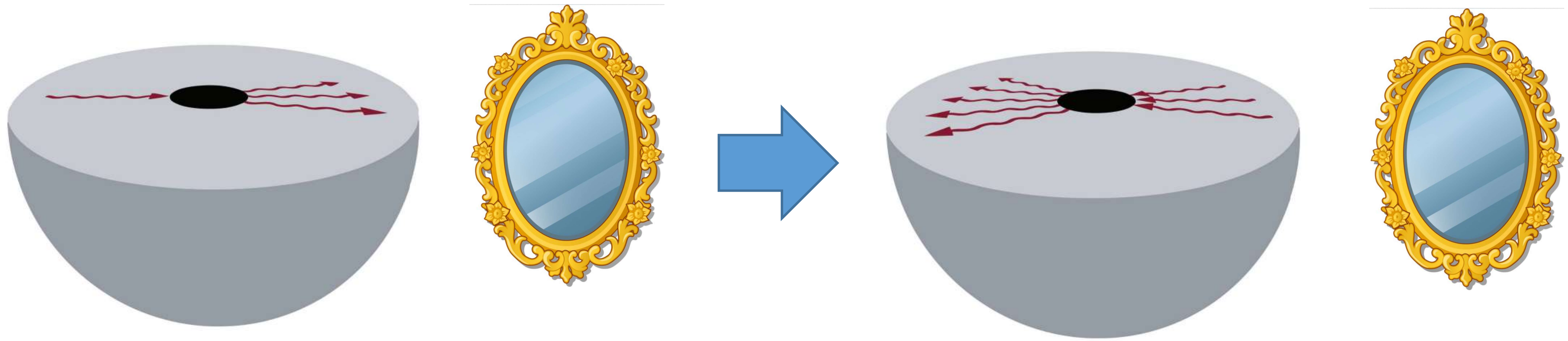
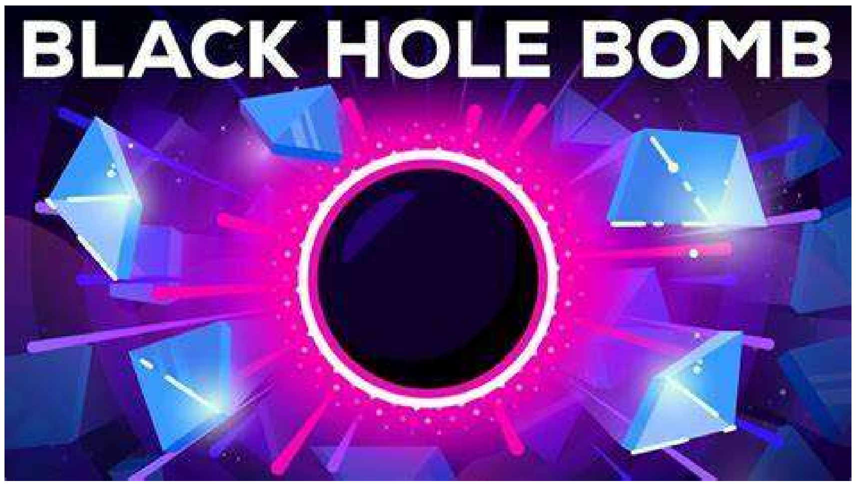


- With a BH wrapped with mirrors, the wave grows exponentially with time, until the mirror breaks.



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Letter | Published: 28 July 1972

Floating Orbits, Superradiant Scattering and the Black-hole Bomb

WILLIAM H. PRESS & SAUL A. TEUKOLSKY

Nature **238**, 211–212 (1972) | Cite this article

Superradiance with a Bound State

- If the wave can from a **bound state** around the BH, the wave cannot propagate to infinity.
  - A natural "mirror".
  - Requires **de Brogile wavelength ≈ BH horizon**
  - Continuously extracting energy and angular mom. from BH.

$M_{\odot} \sim 10^{-10}$ eV

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- Physics at the outer horizon r_+

Use tortoise coordinate, $r_* = r - \frac{r_+ + r_-}{r_+ - r_-}\left[r_- \log\left(\frac{r - r_-}{2M}\right) - r_+ \log\left(\frac{r - r_+}{2M}\right)\right]$

The wave close to the outer horizon is $\propto e^{-i\omega t + i(\omega - m\Omega_H)r_*}$

angular velocity of the outer horizon: $\Omega_H = a/2r_g r_+$

The group velocity and phase velocity are in different direction if $\omega < m\Omega_H$ **Superradiance condition!**

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Non-interacting Real Scalar Field

- Simplest example: non-interacting massive real scalar
- Assume small energy density $\Rightarrow$ can still use Kerr metric
- Klein-Gordon equation in Kerr metric

$$(\nabla^{\nu}\nabla_{\nu} + \mu^2)\Phi = 0$$

μ: scalar mass

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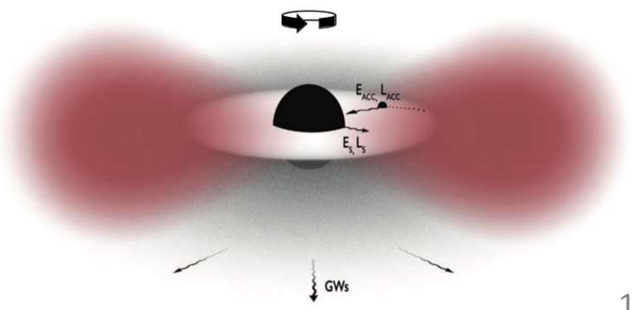
- The bound state eigen-energy is **complex** $\omega_{n\ell m} = \omega_{n\ell m}^{(R)} + i\omega_{n\ell m}^{(I)}$

Three indices: $(n \geq 0, l, m)$, similar to hydrogen atom

- The condensate mass and angular momentum grow exponentially

$$M_s \propto \exp(2\omega_{nlm}^{(I)} t)$$

If $\omega_{nlm}^{(I)} > 0$, called superradiance rate



Superradiance Rate

$$M_s \propto \exp(2\omega_{nlm}^{(I)}\, t)$$

- Analytic approximation at LO of $\alpha = M\mu$

M: BH mass
μ: axion mass

KLEIN-GORDON EQUATION AND ROTATING BLACK HOLES #3

Steven L. Detweiler (Yale U.) (1980)

Published in: *Phys.Rev.D* 22 (1980) 2323-2326

DOI cite claim reference search 559 citations

- Complicated numerical solution

Instability of the massive Klein-Gordon field on the Kerr spacetime #4

Sam R. Dolan (University Coll., Dublin) (May, 2007)

Published in: *Phys.Rev.D* 76 (2007) 084001 • e-Print: 0705.2880 [gr-qc]

pdf DOI cite claim reference search 444 citations

NLO Calculation

- We confirm a mistake in the LO calculation of $\omega_{nlm}^{(I)}$, and calculate the NLO contribution for the first time.

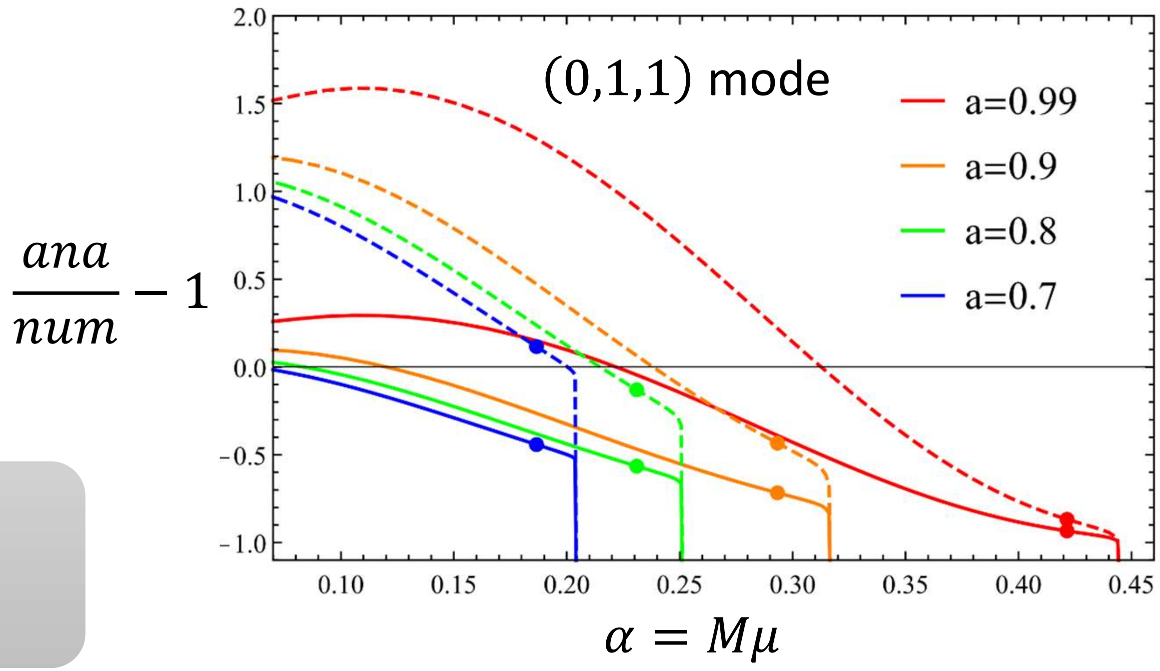
- Leading order

At small α with $a = 0.99$,

Err. of original result $\sim$ 150%

Err. of corrected result $\sim$ 30%

Analytic and numerical results do not converge at $\alpha \to 0$!



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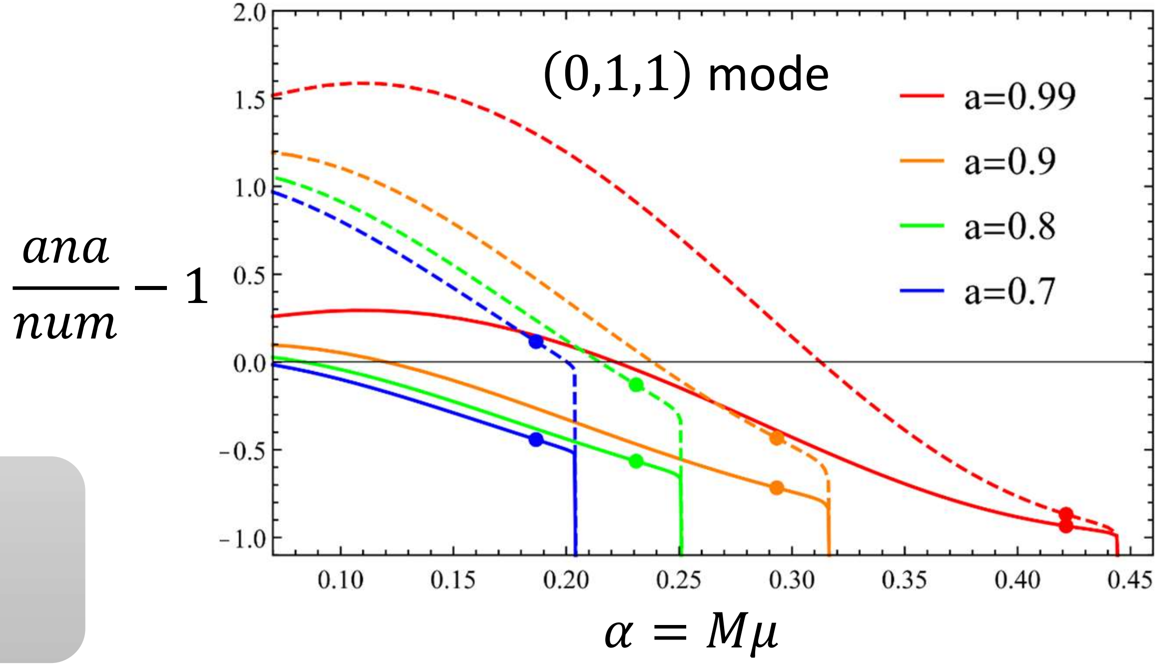
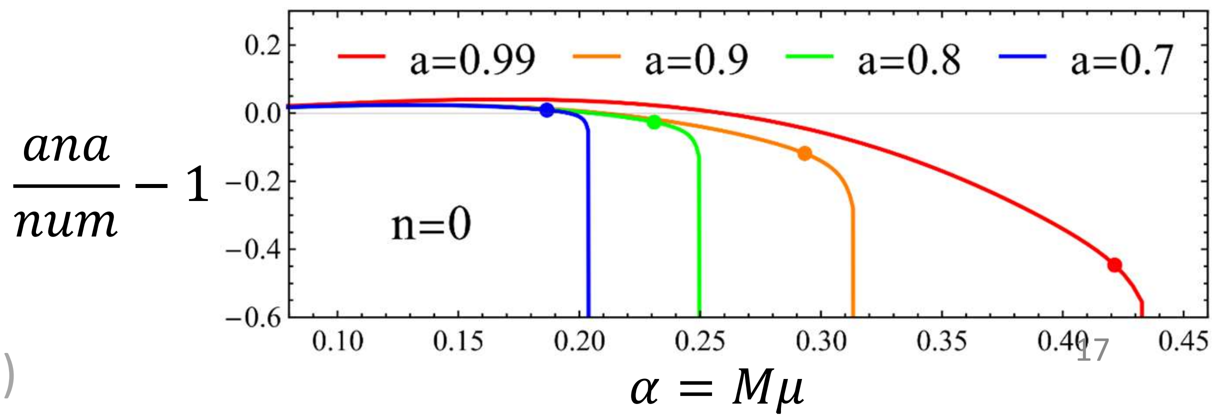


- Next-to-leading order

  At small α, **err.** $<$ **5%**



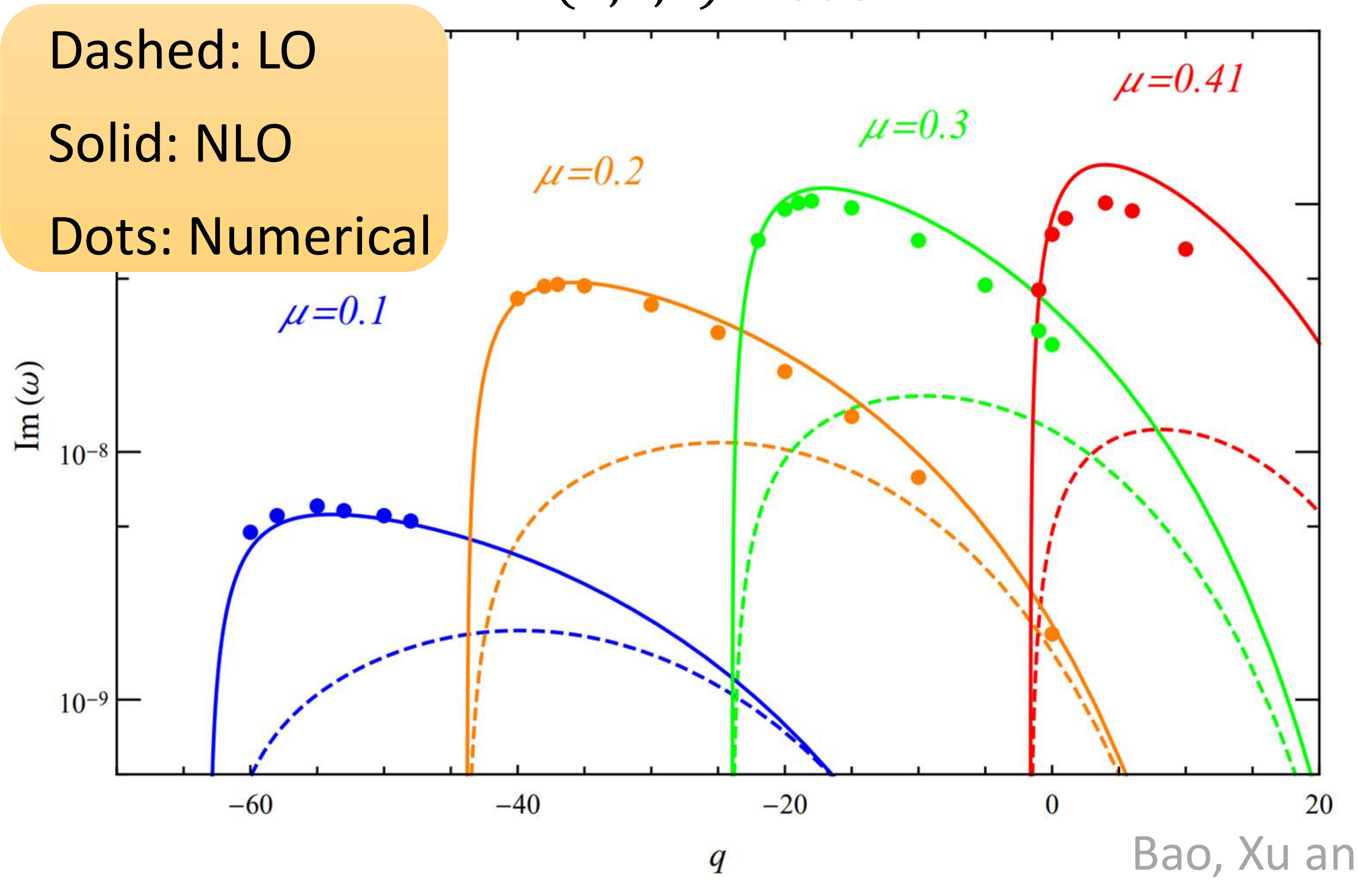
Bao, Xu and **HZ,** PRD (2022)

NLO Sol. of KNBH

- NLO solution greatly improves the precision

BH mass is normalized to 1, BH charge $Q = 0.02$

$(0,1,1)$ mode

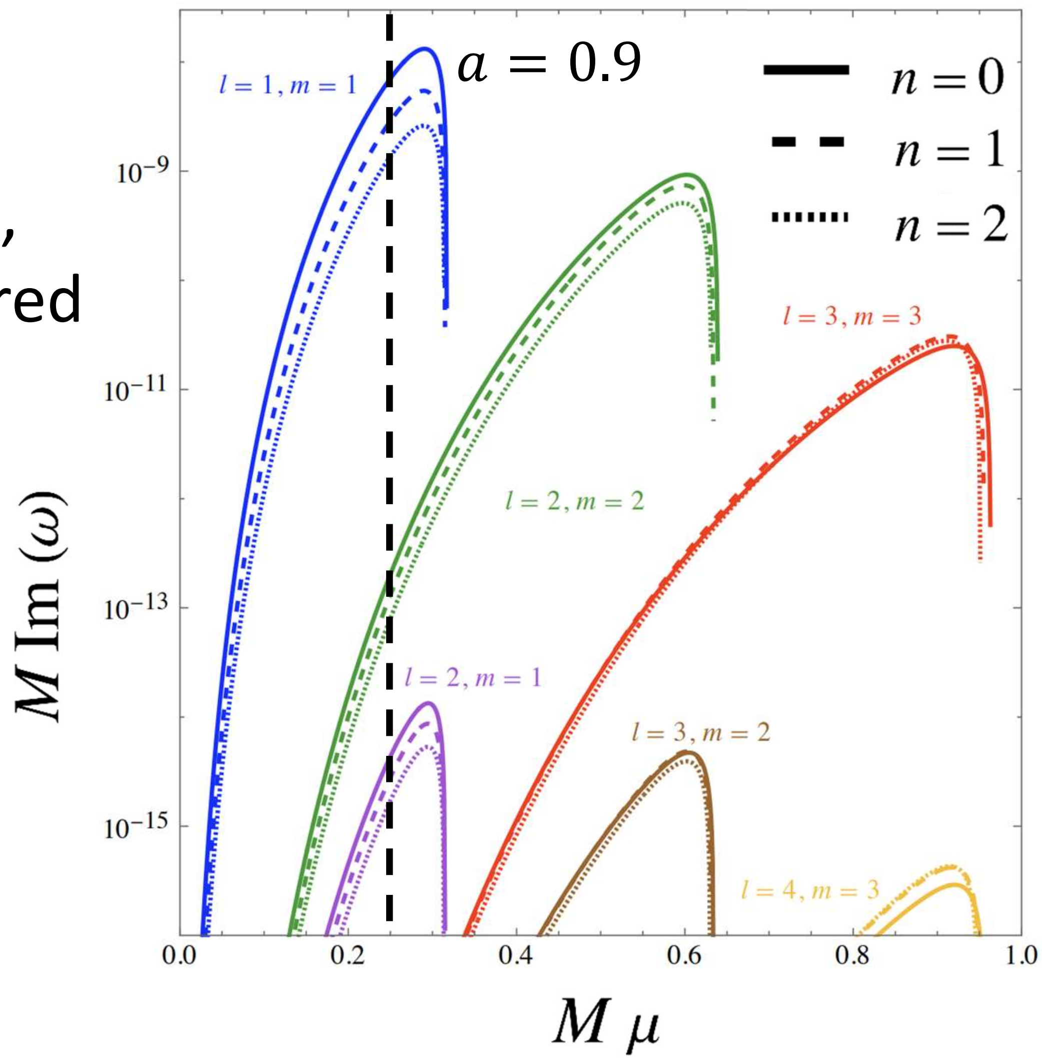


Bao, Xu and **HZ,** PRD (2023)

- In the rest of this part, I focus only on Kerr BH.

Important Modes

- Three indices $(n \geq 0, l, m)$
- (n, l, l) are the most important, modes with $m \neq l$ can be ignored



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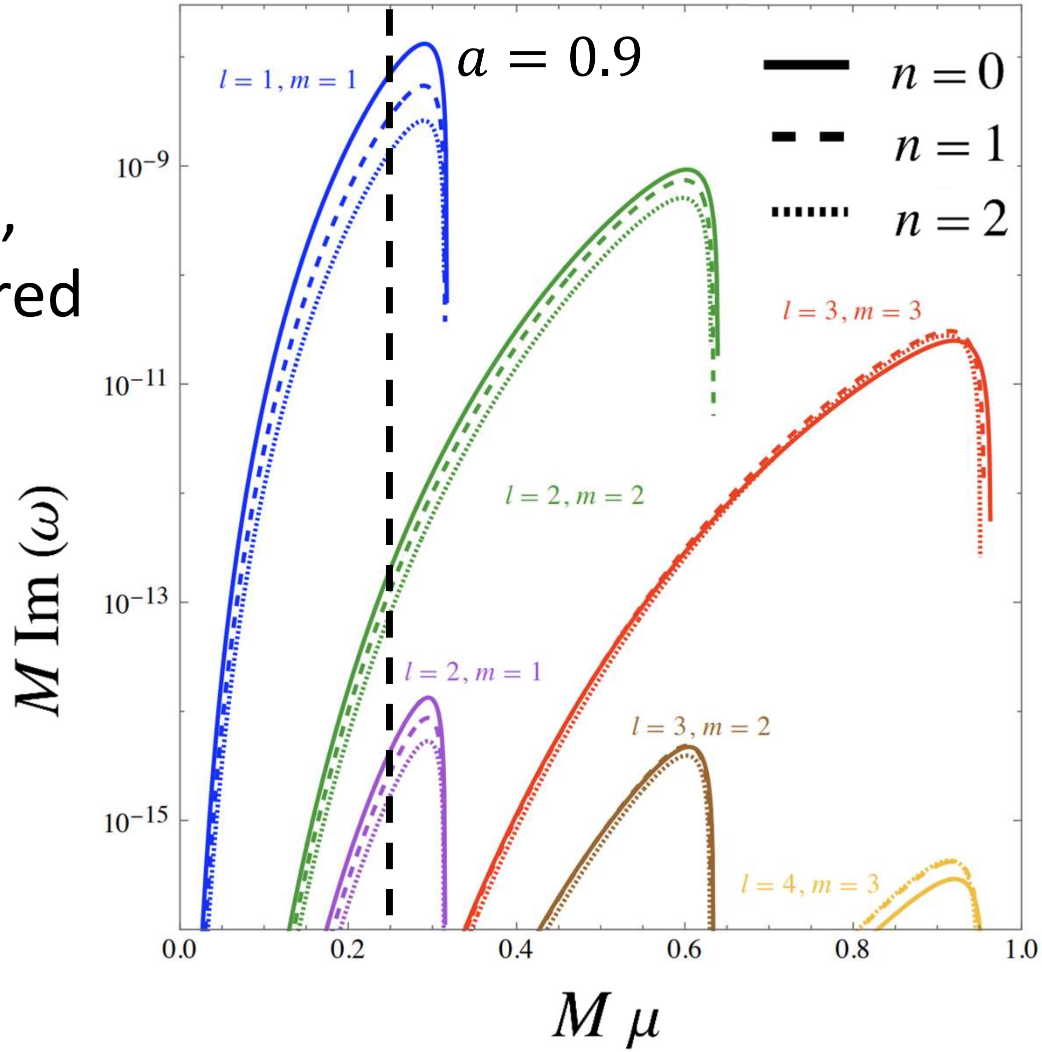
- (n, l, l) modes with different l have very different rates

  ➡ Very different time scales

  Can consider a single l in each time range
- In each l-stage, $(0, l, l)$ is the fastest, followed by $(1, l, l)$



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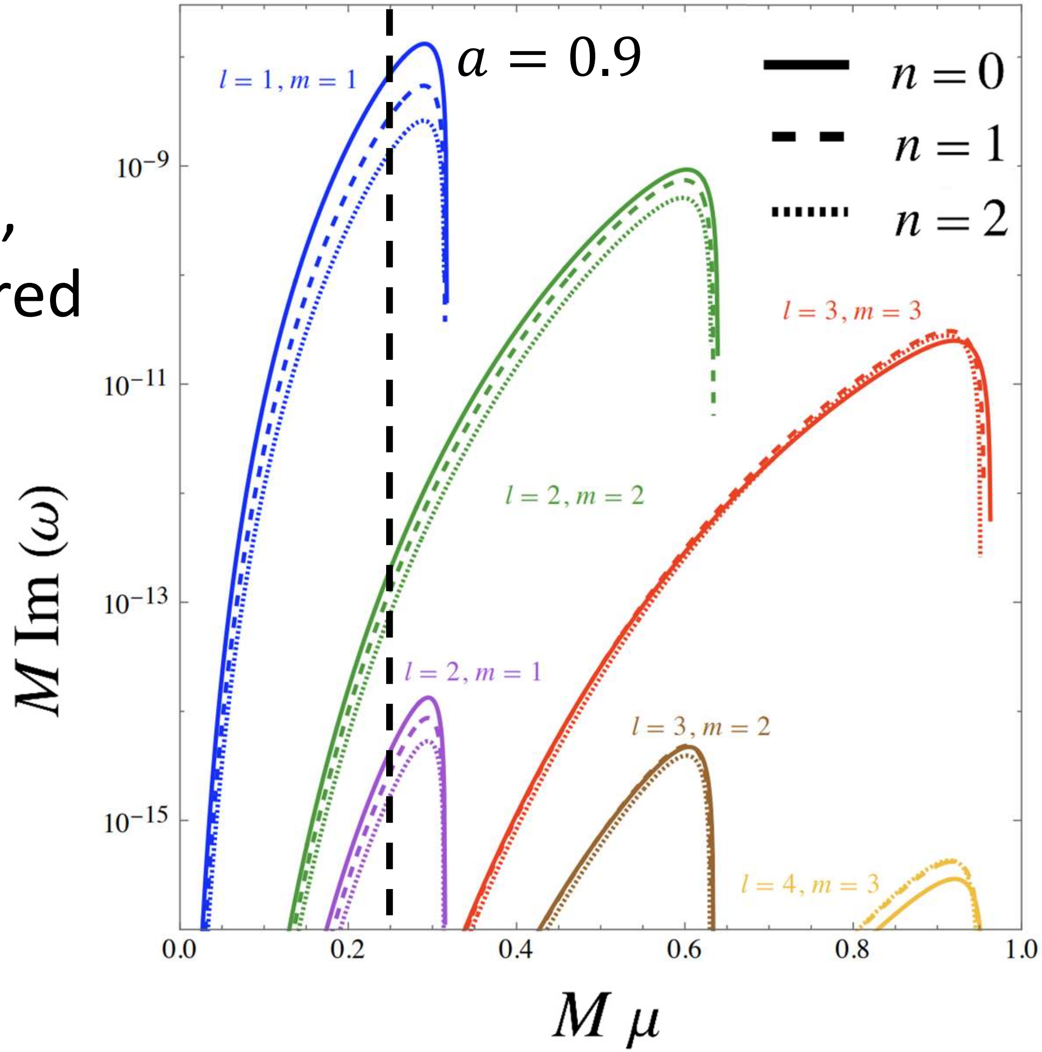

- Superradiance condition $\mu \sim \omega_R < m\,\Omega_H$ gives the max. of $M\mu$

$\Omega_H = a/2r_+$ is the angular velocity of the BH outer horizon.

Fields with Nonzero Spin

$$M_s \propto \exp(2\omega_{nlm}^{(I)}\, t)$$

- Complex scalar: same eigenvalue as the real scalar.

  Strongest mode $\omega^{(I)} \sim \mu(M\mu)^9$

- Fermion: free Dirac field in Kerr metric always have $\omega_{nlm}^{(I)} < 0$

  Iyer, Kumar, Phys. Rev. 1978

  - ➢ No superradiance when cloud density is small!
  - ➢ Not clear with the cloud's contribution to the metric.
  - ➢ Not clear with self-interaction.

- Vector: strongest mode has $\omega^{(I)} \sim \mu(M\mu)^7$ Baumann, Chia, Stout, ter Haar, JCAP 2019

- Rank-2 Tensor: strongest mode has $\omega^{(I)} \sim \mu(M\mu)^3$

  Brito, Cardoso, Pani, PRD 2013

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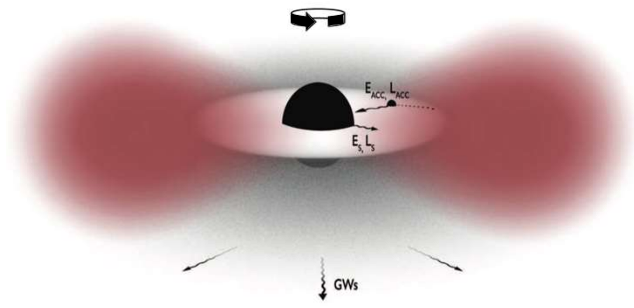
Isolated BH-cloud Evolution

- Consider non-interacting real scalar field in a Kerr metric
- Evolution equation of real scalar field



M: BH mass

J: BH angular mom.

$M_s^{(nlm)}$: mass of mode (nlm)

$J_s^{(nlm)}$: angular mom. of mode (nlm)

$$\dot{M} = -\sum_{nlm} 2M_s^{(nlm)}\omega_I^{(nlm)},$$

$$\dot{J} = -\sum_{nlm} 2mM_s^{(nlm)}\omega_I^{(nlm)}/\omega_R^{(nlm)}$$

$$\dot{M}_s^{(nlm)} = 2M_s^{(nlm)}\omega_I^{(nlm)} - \boxed{\dot{E}_{\rm GW}^{(nlm)}}$$

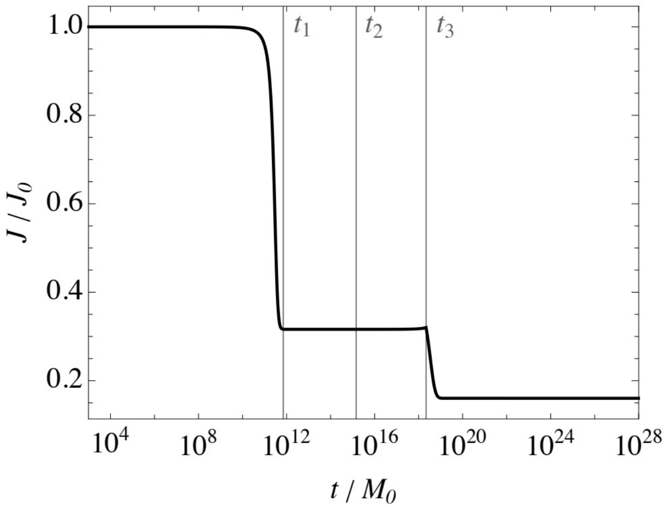
$$\dot{J}_s^{(nlm)} = 2mM_s^{(nlm)}\omega_I^{(nlm)}/\omega_R^{(nlm)} - \boxed{m\dot{E}_{\rm GW}^{(nlm)}/\omega_R^{(nlm)}}$$

Energy and angular mom. radiated by GW

Isolated BH-condesate Evolution

- Keep four $(n, l, m = l)$ modes: $(0,1,1), (1,1,1), (0,2,2), (1,2,2)$
- Evolution can be split into $l = 1$ and $l = 2$ stages

BH angular momentum



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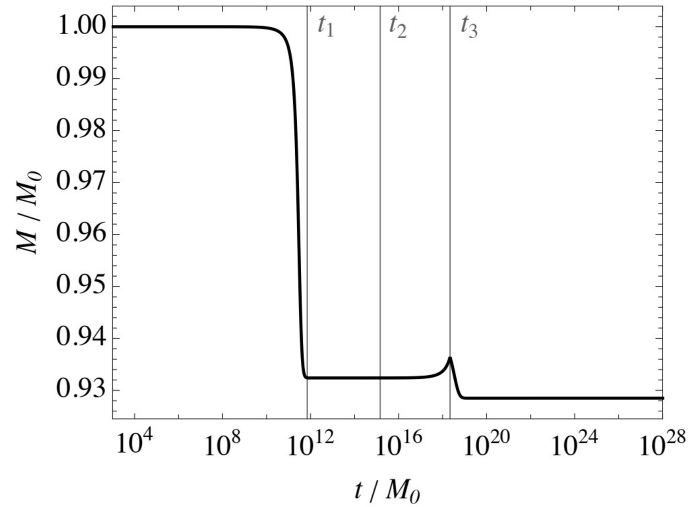
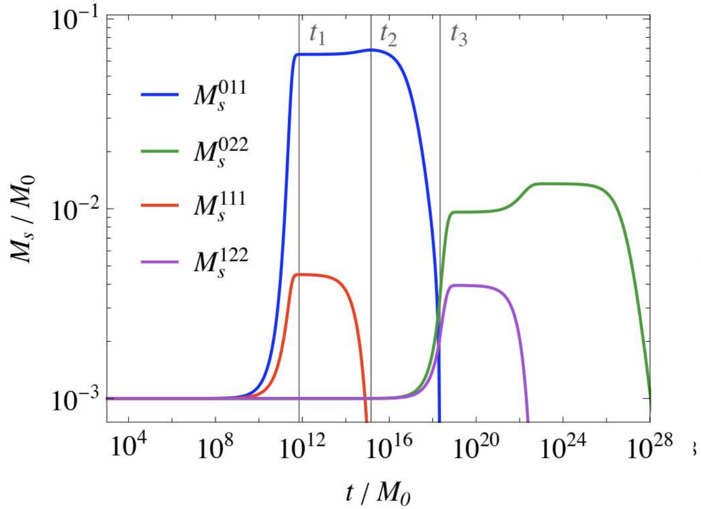
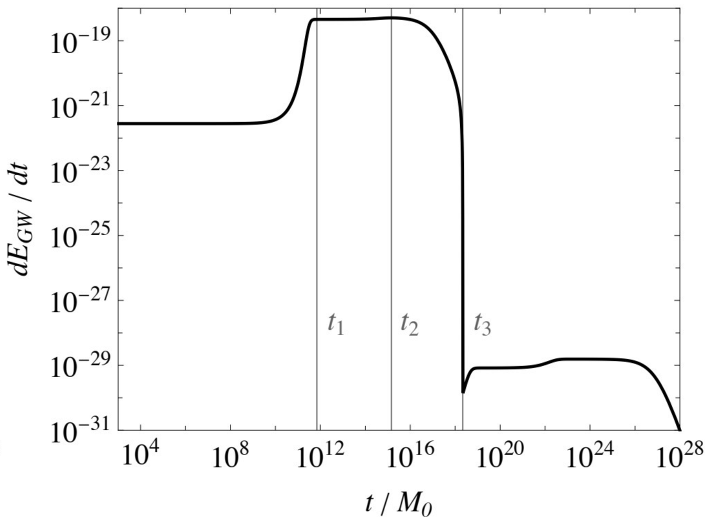


Condensate mass



GW flux



Guo, Bao, and **HZ,** PRD (2023)

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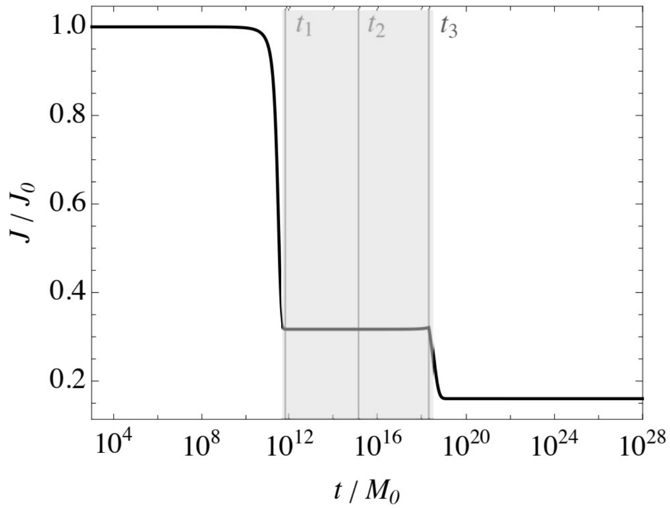

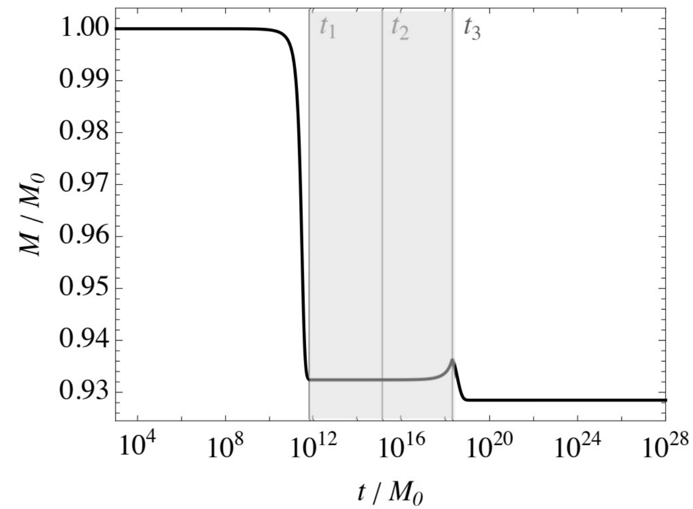

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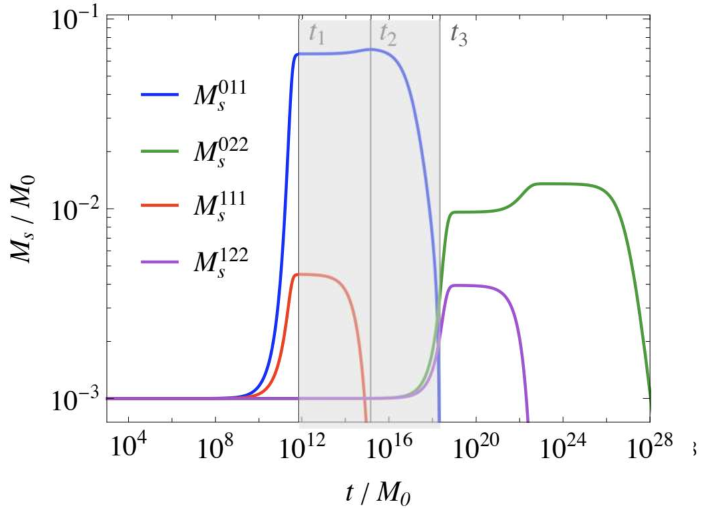

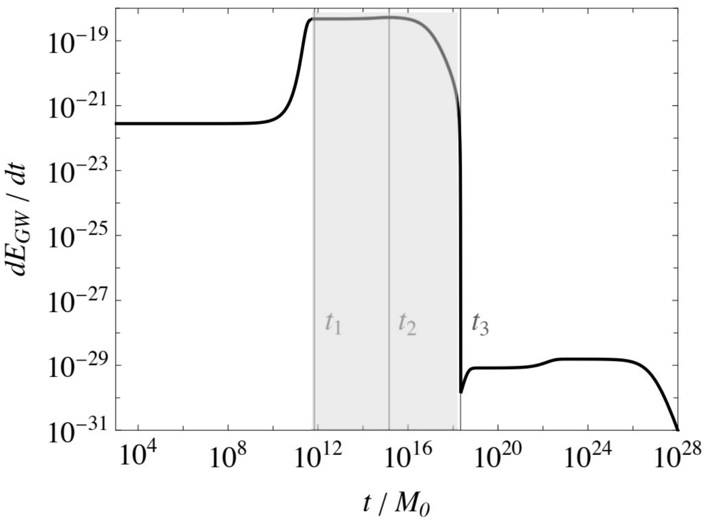

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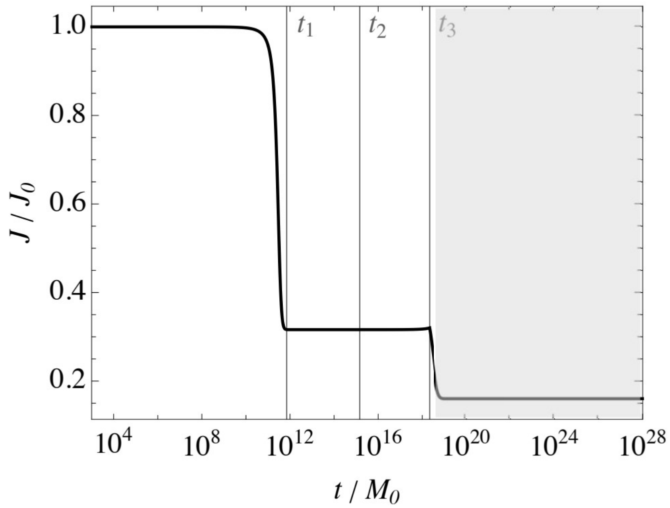

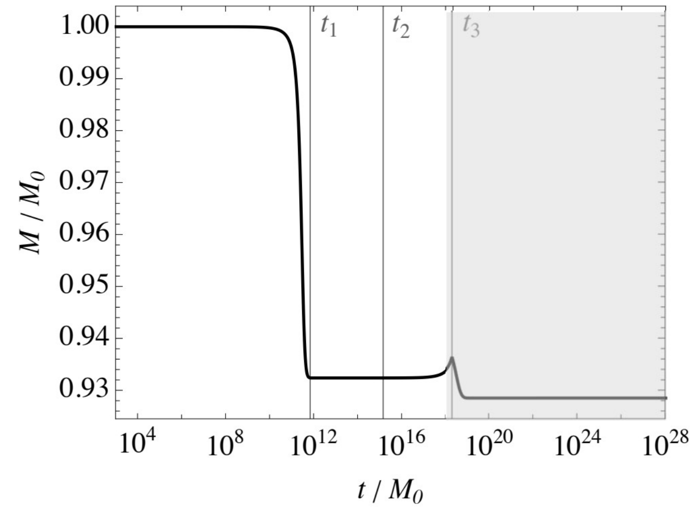

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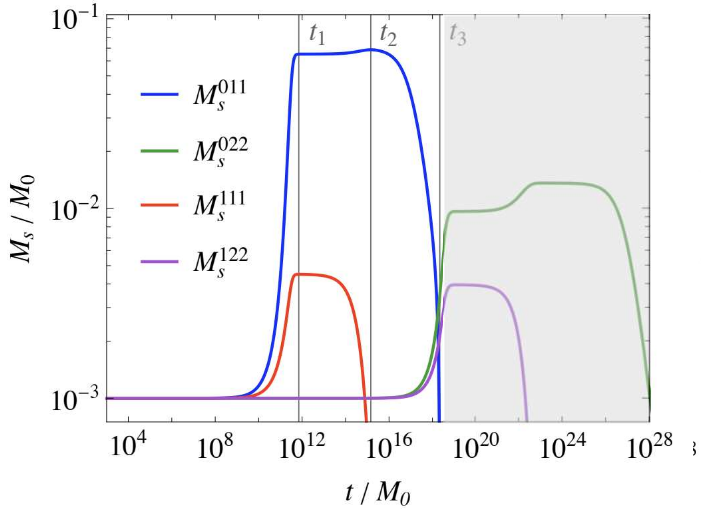

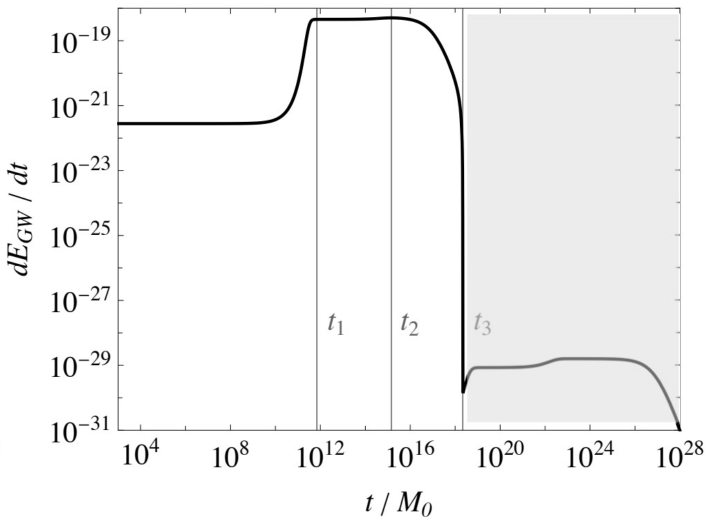

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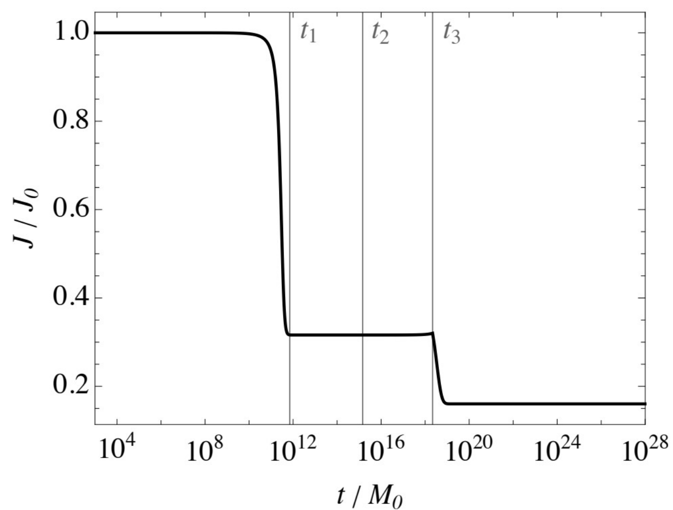
BH Evolution

- When transiting between stages, the **BH spin drops a lot (~50%)** and the BH mass decreases slightly (a few percent)

BH angular mom.



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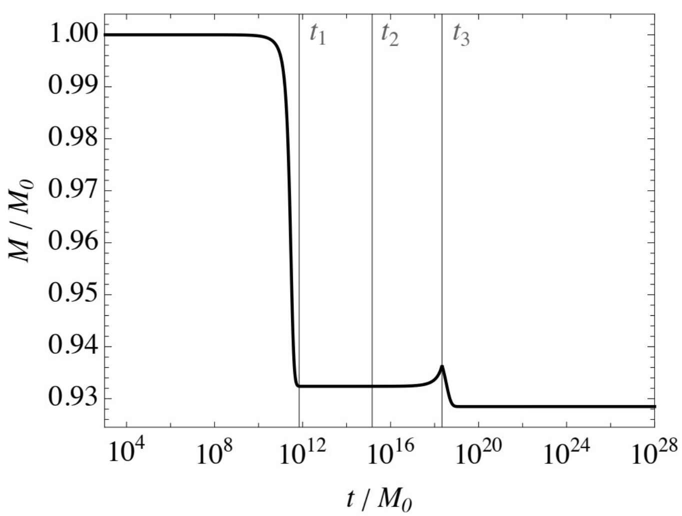

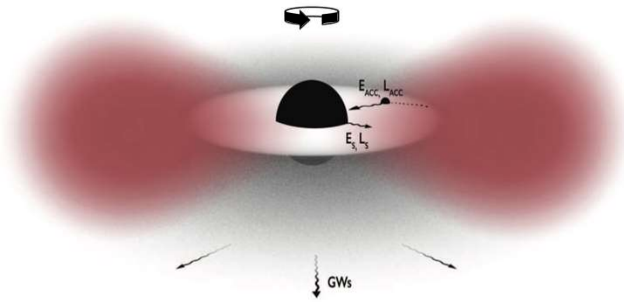

BH Evolution

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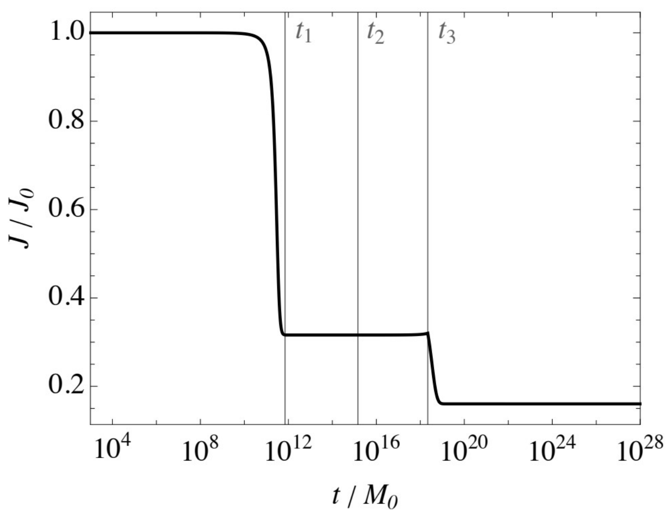
- In each l stage, the BH spin and mass are almost **constants**

If BH spin increases a little, E and J flow from BH to condensate

If BH spin drops a little, E and J flow from condensate to BH

The condensate is a "angular momentum reservoir" ⟹ **Attractor!**

BH angular mom.



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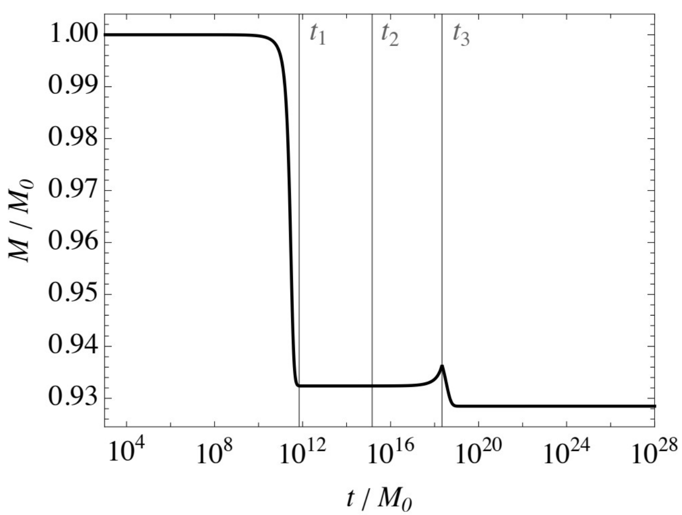
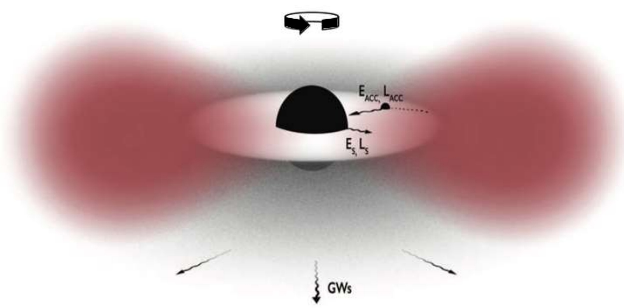
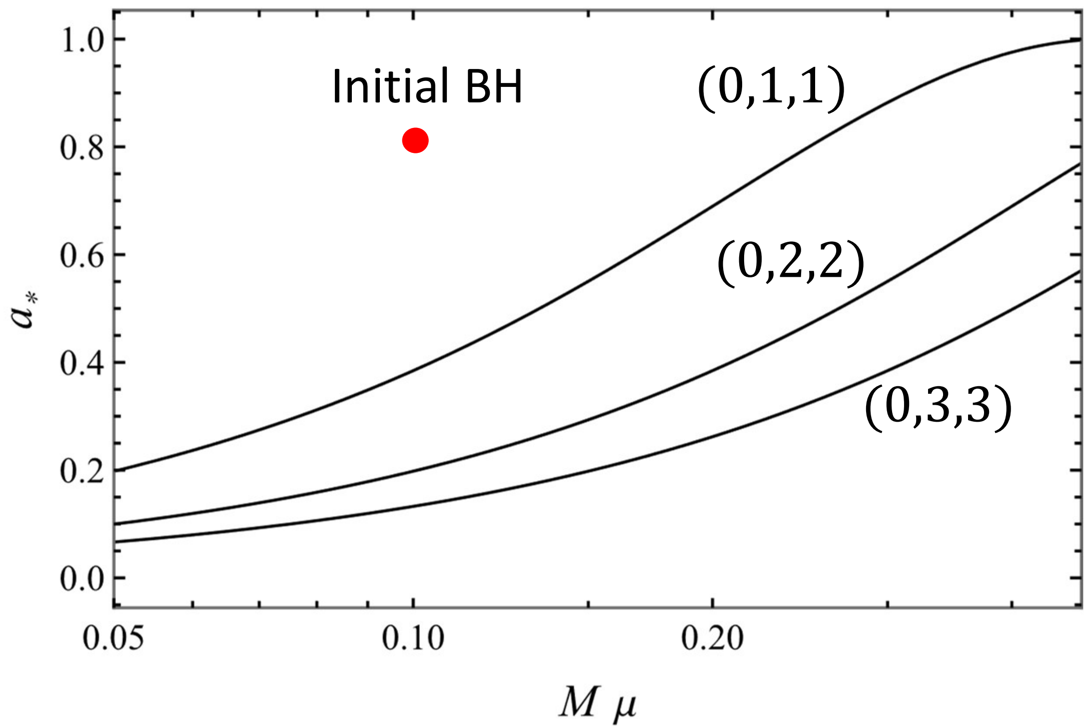




Evolution on the Regge Plot

- A Kerr BH is characterized by its angular momentum J and mass M
- Regge plot: a plot of BH spin $a_* \equiv J/M^2$ vs. BH mass



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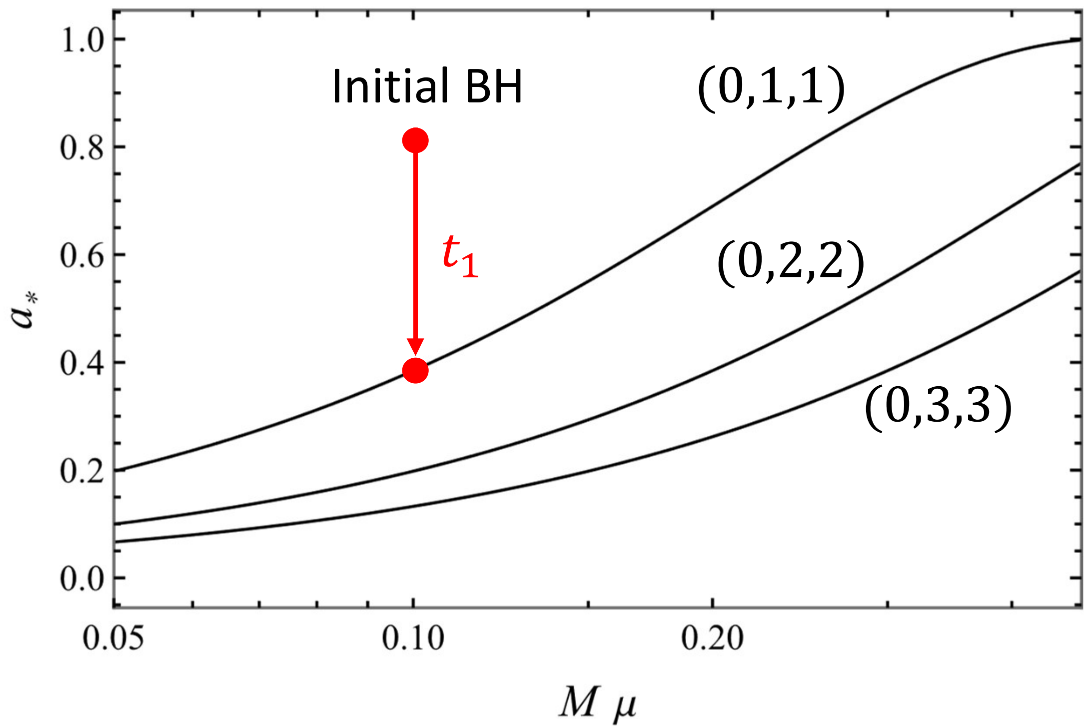
- With superradiance, the BH steps down on each Regge trajectory

Regge trajectory is determined by superradiance condition



$$a_*^{(nlm)} \approx \frac{4m\ M\mu}{m^2 + 4(M\mu)^2}$$

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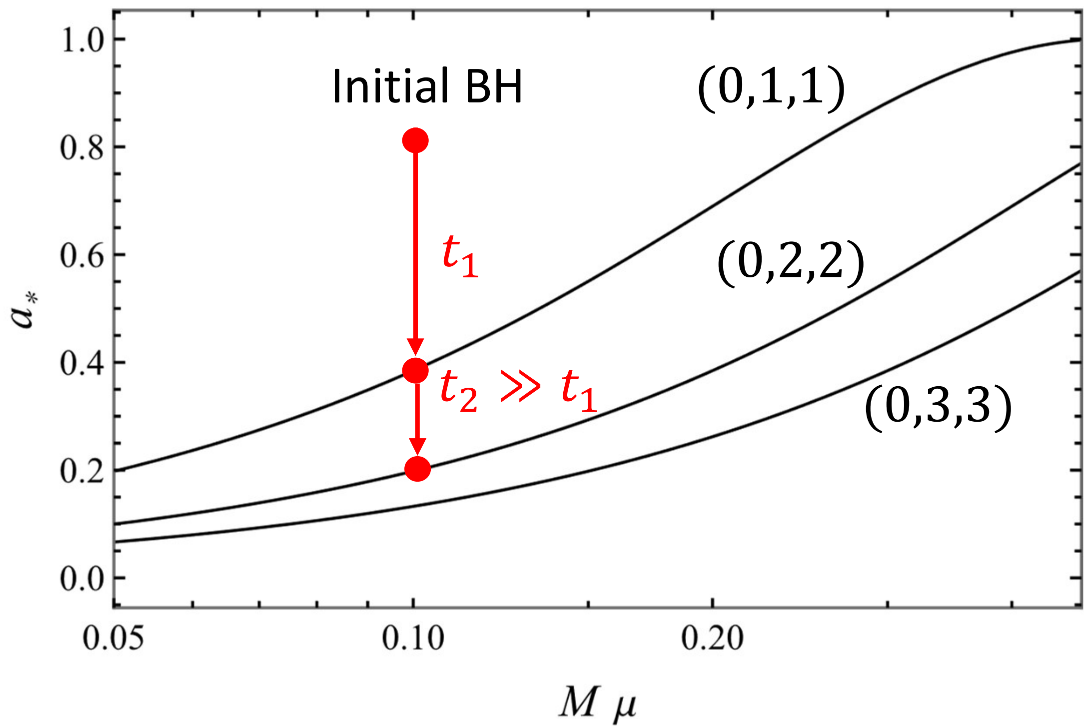

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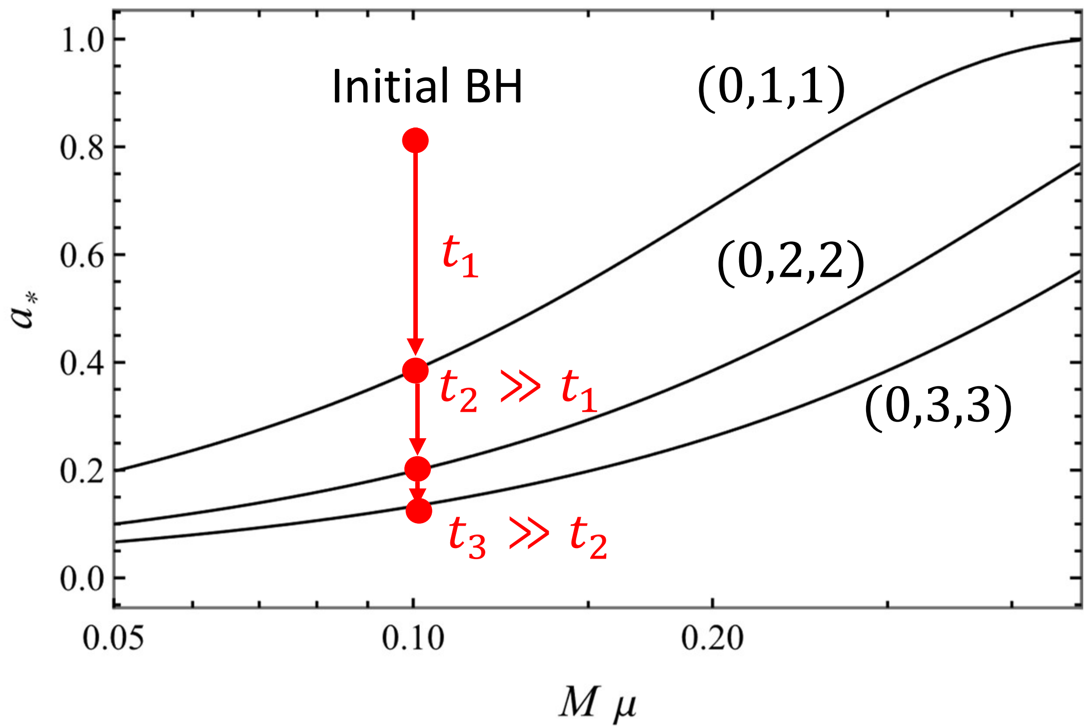

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Important quantities can be estimated wth simple analytic expressions.

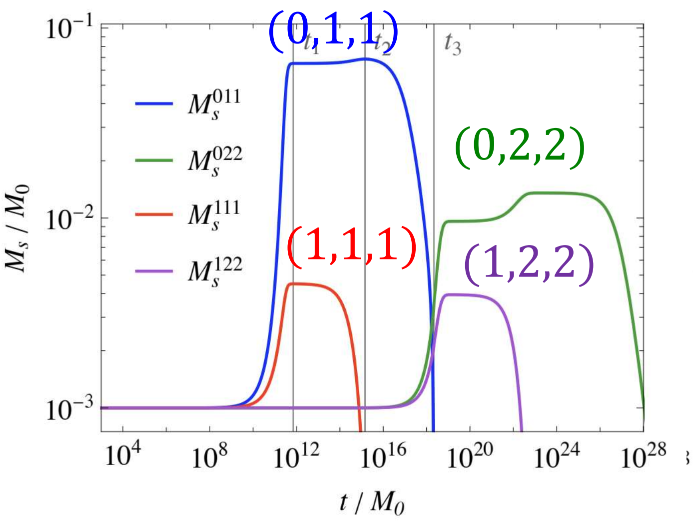
Guo, Bao, and **HZ,** PRD (2023)

- High-spin BHs are very rare with superradiance

Condensate Evolution

- At the beginning of each l stage, the modes with the same l **grow exponentially**
- The modes lose energy via GW emission ⟹ GW signal!

Condensate mass



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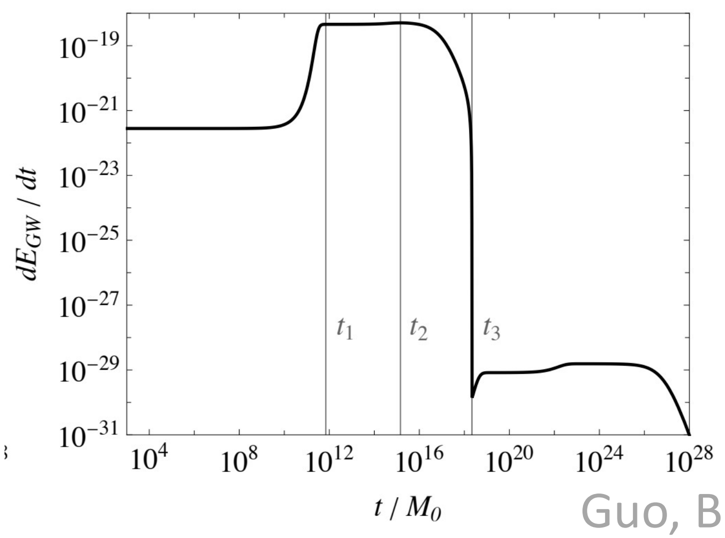

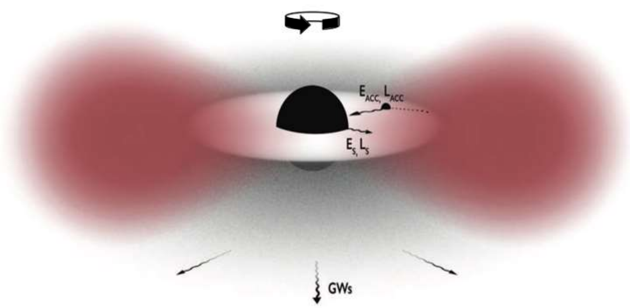

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Condensate Evolution

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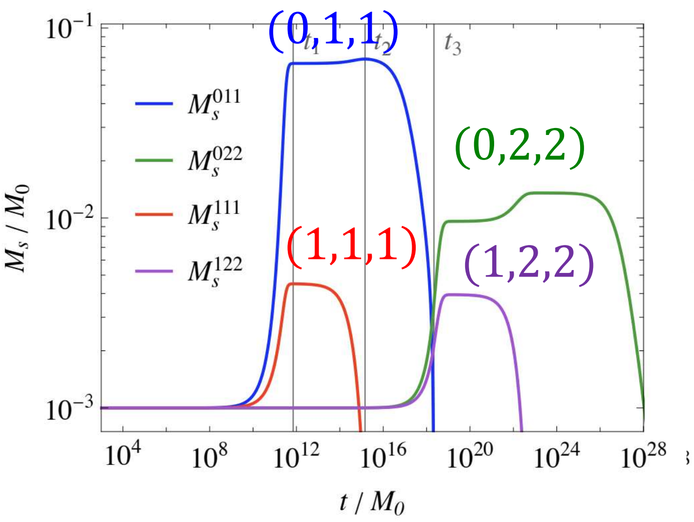
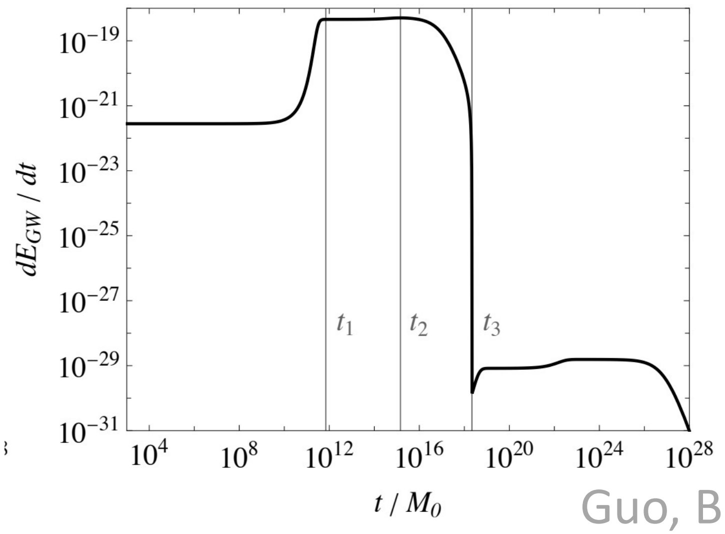
- The modes lose energy via GW emission ⟹ GW signal!
- The coexistence of $(0, l, l)$ and $(1, l, l)$ modes produces an unique GW beat signal

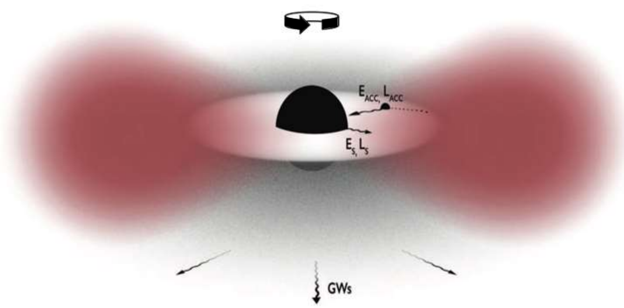
$$\cos[(\omega + \Delta\omega)t] + \cos[(\omega - \Delta\omega)t] = 2\cos(\Delta\omega\, t)\cos(\omega t)$$

Condensate mass



GW flux





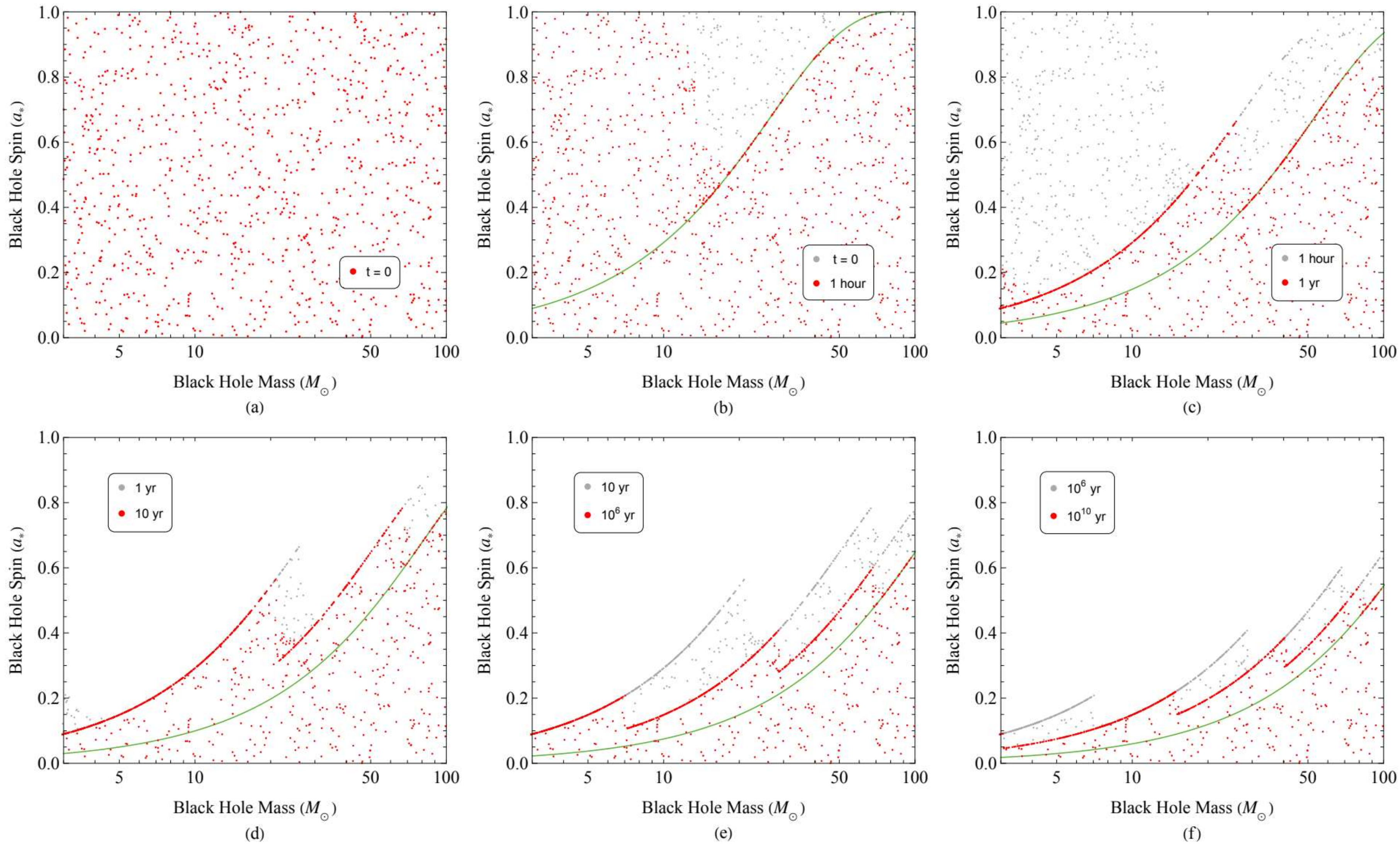
Guo, Bao, and **HZ,** PRD (2023)

Outline

- ✧ Introduction
- ✧ The fast-growing cloud
- ✧ Evolution of BH-cloud system
- ✧ **Observables**
- ✧ Summary

High-spin BHs are Rare

Guo, Bao and **HZ,** PRD 2023

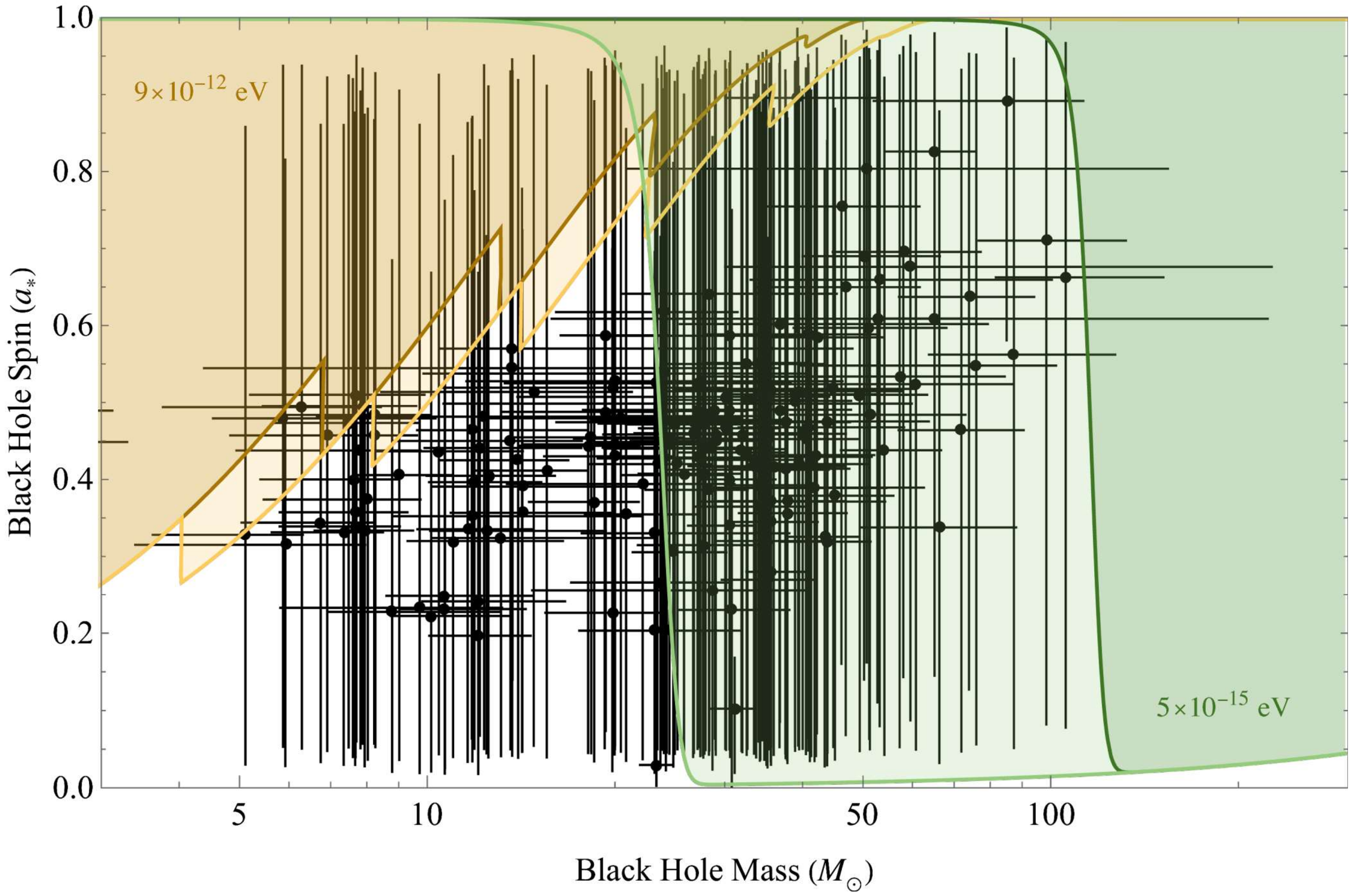


- Angular mom. transfers from BH to the cloud.
- BHs prefer to reside on Regge trajectories.

BH Spin Measurement

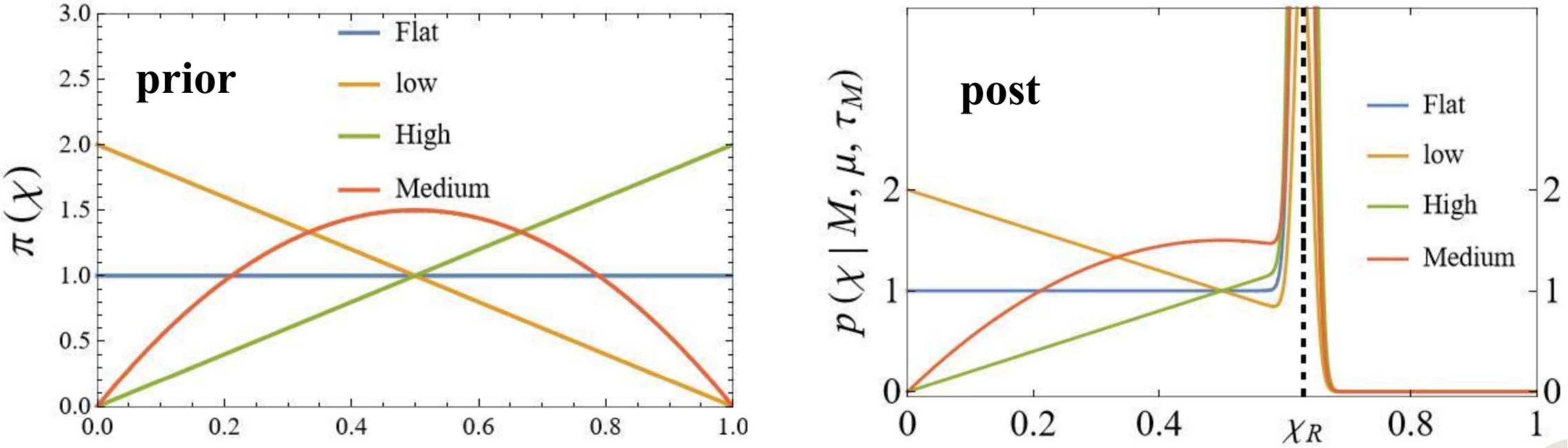
- LVK can measure the individual BH spin, with huge error.
- The error can be reduced to ~30% in the future

LIGO, Virgo, PRX 2016



Survive with the Current Data

- Consider 3 scenarios: **high**, **flat**, **low** to estimate the effect of the initial BH spin.



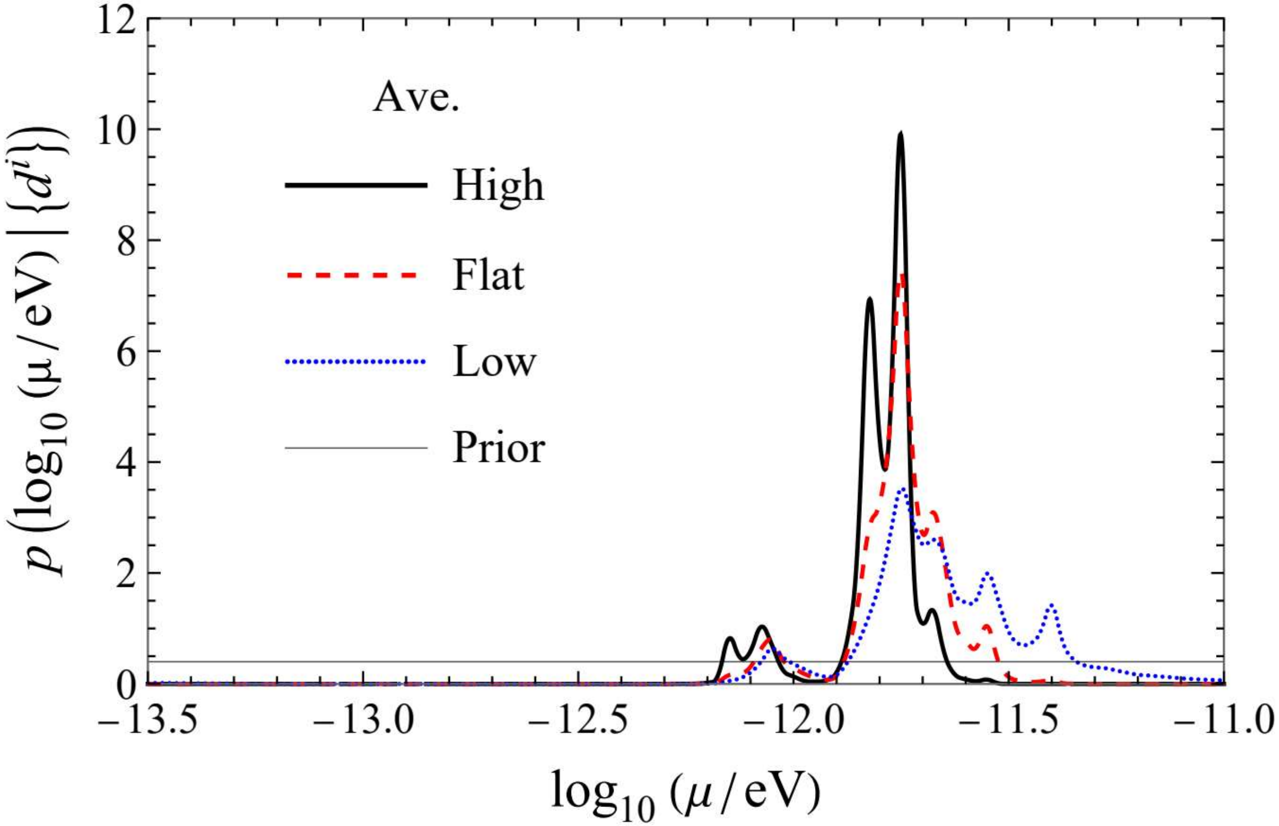
BH spin a BH spin a

- Assume the Lifetime of BHs distributes log-uniformly between 10^6 to 10^{10} years

Cheng, Bao and **HZ,** PRD 2023

Constrain Scalar Mass

- **Include all BBHs in three phases of GTWC data** reported by LVK collaboration, only excluding the events with neutron.
- **scalar mass prior** is log-uniform between $10^{-13.5}$ to 10^{-11} eV.

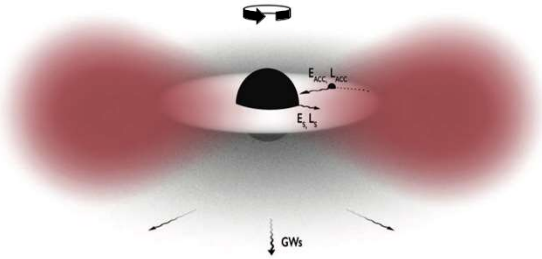


Cheng, Bao and **HZ,** PRD 2023

- Two slightly favored ranges are identified, but evidence is weak.

GW Emission from Real Fields

- Previous calculation only consider the $(n = 0, l = 1, m = 1)$ mode



Monochromatic, constant energy flux,
Cannot distinguish from neutron stars

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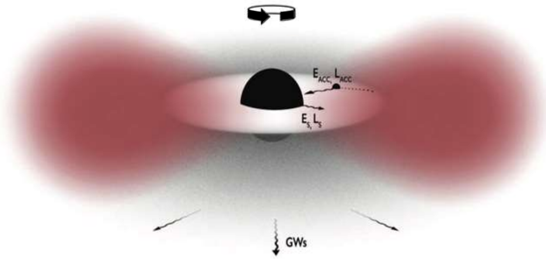

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- Different modes have slightly different angular speeds

$$\phi(t,\vec{r}) = \sum_{l,m} \int d\omega \left[e^{i(m\varphi - \omega t)} R_{lm}(r) S_{lm}(\theta) + \text{c.c.} \right]$$

$$\omega_R^{nlm} \approx \mu \left[1 - \frac{\alpha^2}{2(n+l+1)^2} \right] + O(\alpha^4)$$

e.g. $\cos[(\omega + \Delta\omega)t] + \cos[(\omega - \Delta\omega)t] = 2\cos(\Delta\omega\, t)\cos(\omega t)$

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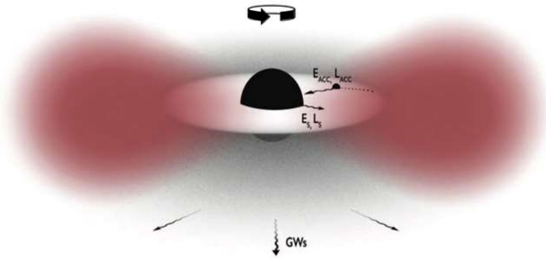

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e.g.

$$\cos[(\omega + \Delta\omega)t] + \cos[(\omega - \Delta\omega)t] = 2 \boxed{\cos(\Delta\omega\, t)} \cos(\omega t)$$

Modulation of amp. and energy flux. **Beat!**

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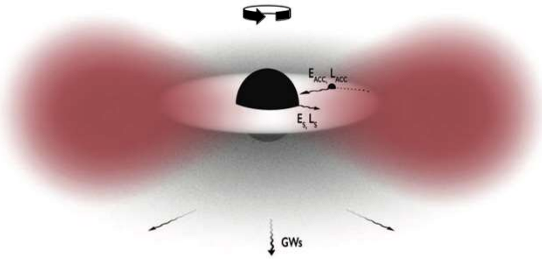

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e.g $\quad \cos[(\omega + \Delta\omega)t] + \cos[(\omega - \Delta\omega)t] = 2\cos(\Delta\omega\, t)\cos(\omega t)$

- Strength of the beat signal.

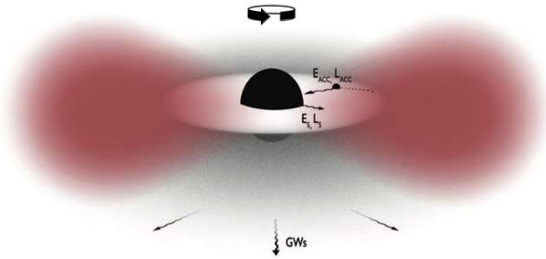
Two $(0,1,1)$ axions $\Rightarrow$ graviton: Amp.$\propto N_{011}$, freq. $= 2\omega^{011}$

$(0,1,1) + (1,1,1)$ $\Rightarrow$ graviton: Amp.$\propto \sqrt{N_{011} N_{111}}$, freq. $= \omega^{011} + \omega^{111}$

Energy flux $\propto Amp^2$, so beat Amp. $\propto \sqrt{\frac{N_{111}}{N_{011}}}$, with freq. $\omega^{111} - \omega^{011}$

GW Emission from Real Fields

- Previous calculation only conside

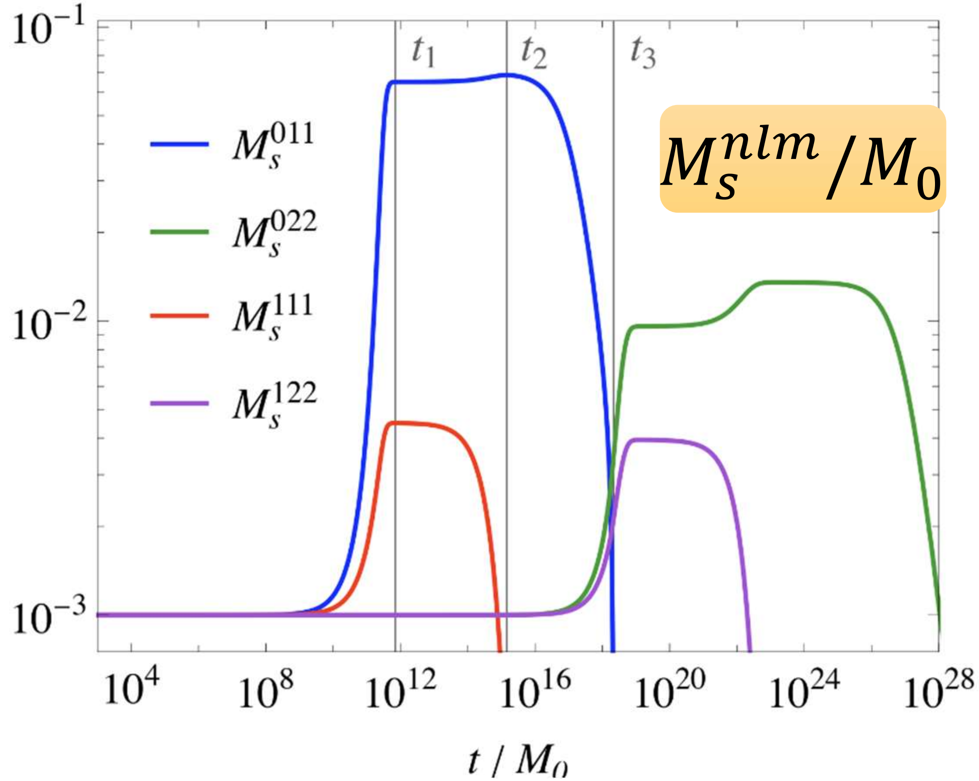


Mo
Can

- Different modes have slightly dif

$$\phi(t,\vec{r}) = \sum_{l,m} \int d\omega \left[e^{i(m\varphi-\omega t)} R_{lm}(r) S_{lm}\right.$$

e.g $\cos[(\omega+\Delta\omega)t] + \cos[($



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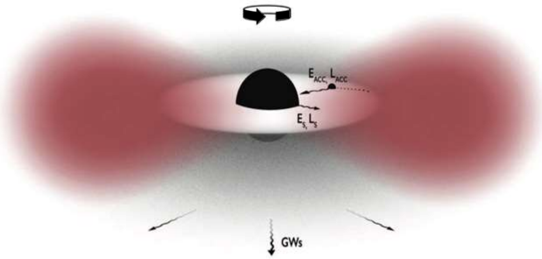

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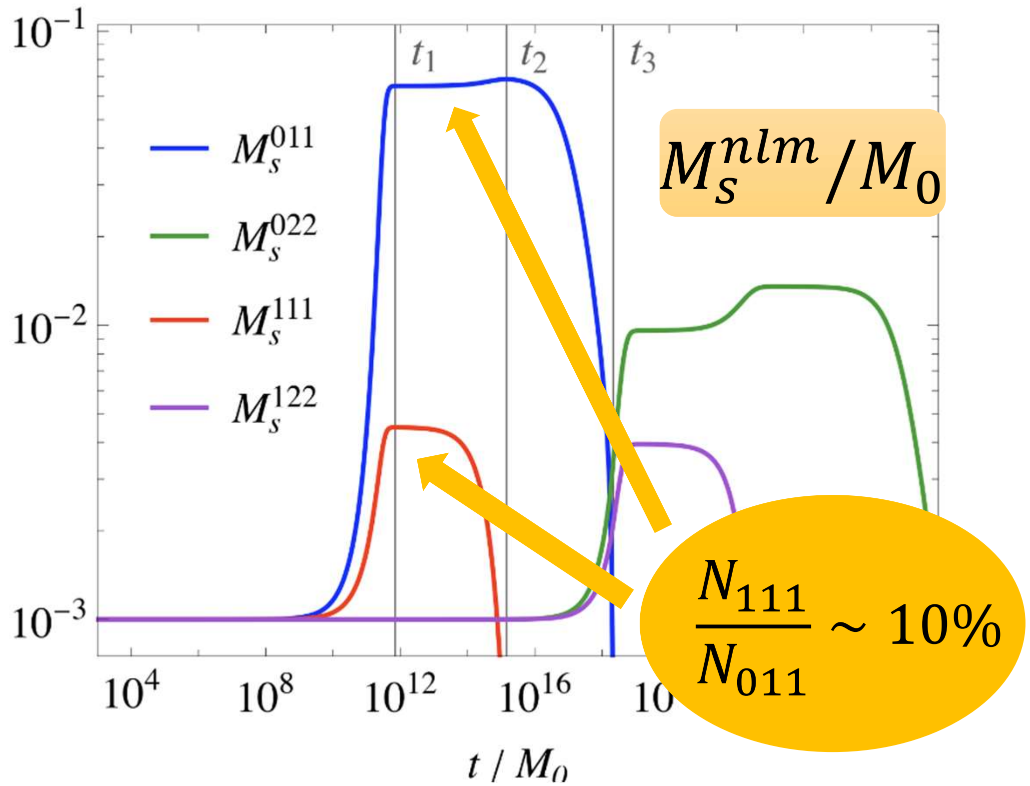

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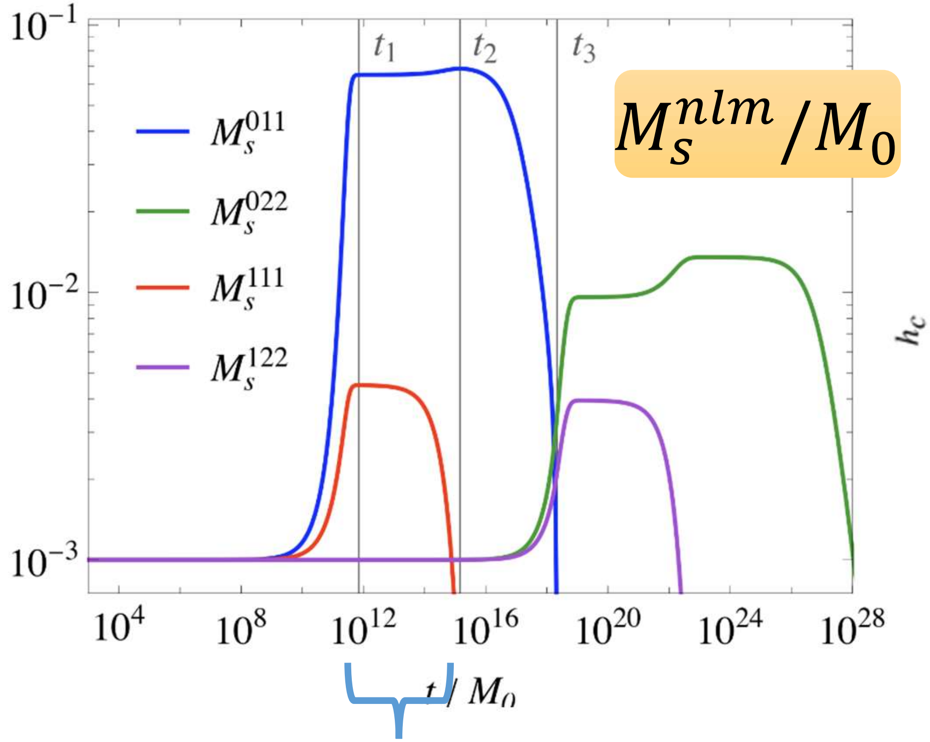
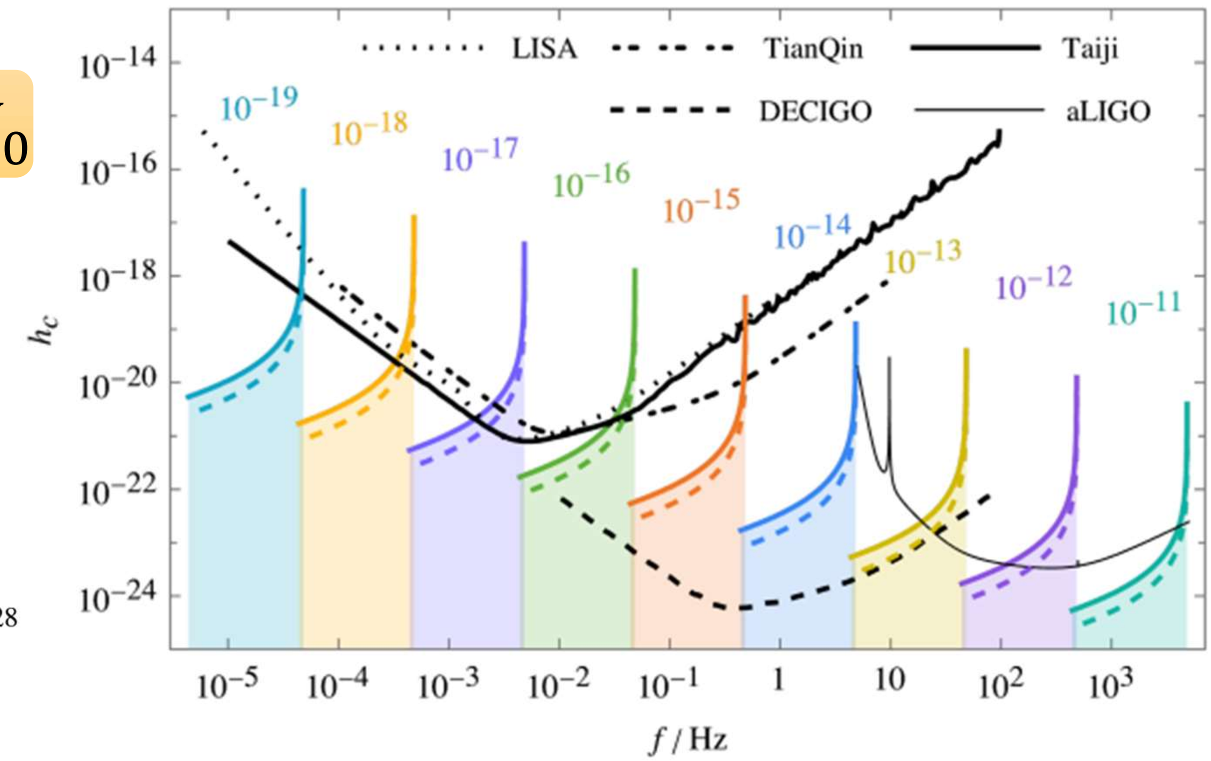
GW Beat: Observation





The BH spin here is determined by $M\mu$

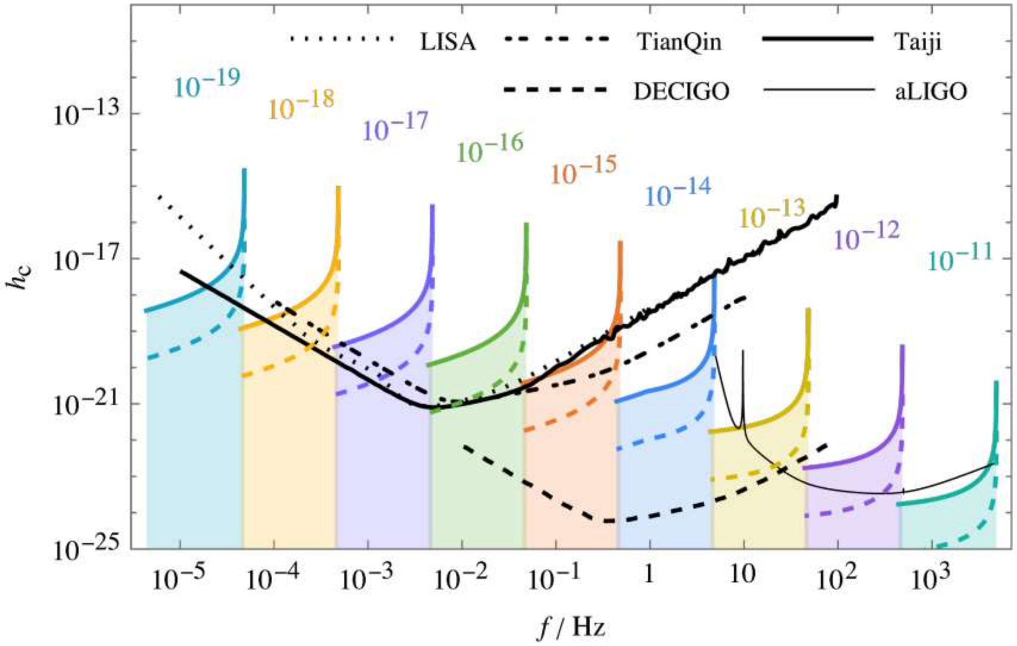
Guo, Bao and **HZ,** PRD (2023)

- Parameters: $M\mu = 0.17$ (so $a_C = 0.6$), $M_s/M = 0.1,\ N_{111}/N_{011} = 0.1$
- The red shift ranges from 0.001 to 10
- The current and future GW telescope can cover a large range of scalar mass.

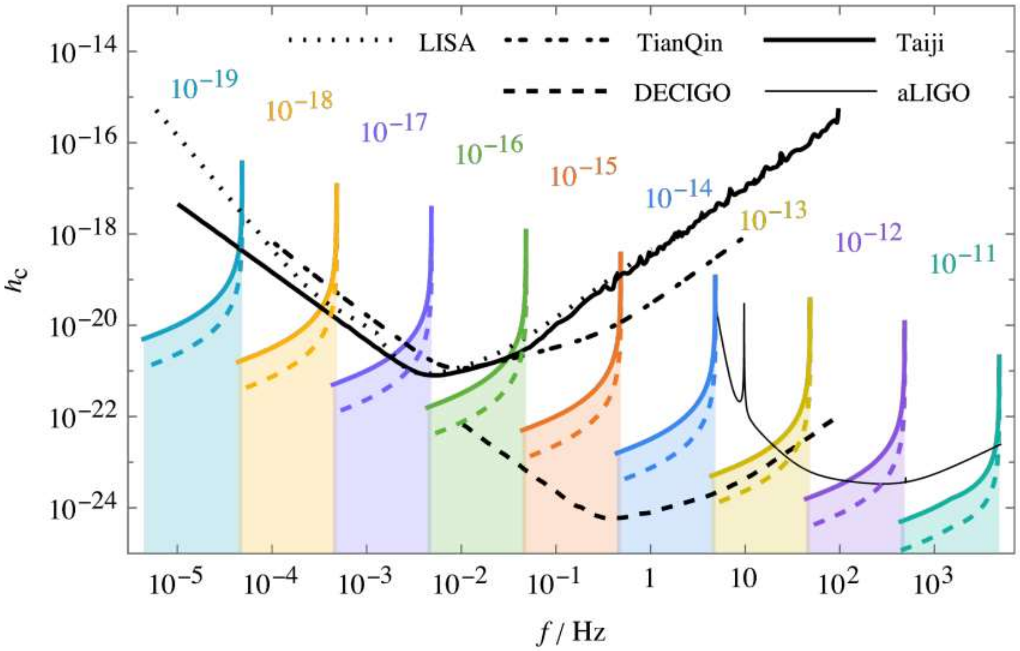
Fields with Other Spins

- Real vector

J=m=1 stage



J=m=2 stage



Guo, Jia, Bao, **HZ,** Zhang, Accepted by PRD

- Real tensor field: unknown

- Complex field does not radiate GW. Then BHs reside on the first Regge trajectory for very long time.

Other Gravitational Observables

- Since real vector and tensor fields grow very fast, one could search the GW right after BH merger events.

  Arvanitaki, Baryakhtar, Dimopoulos, Dubovsky, and Lasenby, PRD 2017

  . Baryakhtar, Lasenby, and Teo, PRD 2017

- With perturbation (e.g. self-interaction or a companion star), the transitions between different modes radiate GW.

  Scalar: Yoshino and Kodama, Class Quant. Grav. 2015

  Vector: Siemonsen and East, PRD 2020

- Stochastic GW background

  Brito, Ghosh, Barausse, Berti, Cardoso, Dvorkin, Klein, and Pani, PRL 2017

- GW burst in bosenova

  Yoshino and Kodama, Prog. Theor. Phys. 2012
  Arvanitaki, Baryakhtar, and Huang, PRD 2015

- Floating orbit of companion stars

  Kavic, Liebling, Lippert, and Simonetti, JCAP 2020

Optical Observables

- BH shadow from lensing

  Cunha, Herdeiro, Radu, and Runarsson, PRL 2015

  Cunha, Herdeiro, Radu, and Runarsson, Int. J. Mod. Phys. 2016

  Vincent, Gourgoulhon, Herdeiro, and Radu, PRD 2016

- If assuming coupling between the boson field and photon
  - ➢ birefringence causes time-dependent polarization

    Plascencia and Urbano, JCAP 2018

    Chen, Shu, Xue, Yuan, and Zhao, PRL 2020

  - ➢ BH laser: oscillating charged field generates photon field

    Ikeda, Brito, and Cardoso, PRL 2019

    Boskovic, Brito, Cardoso, Ikeda, and Witek, PRD 2019

Summary

- If boson de Brogile wave length ~ BH horizon size, the boson field could grow exponentially around Kerr BHs.

- With the same parameters, the tensor field has the largest superradiance rate, while the scalar has the smallest rate.

- The superradiance can be detected without assuming the coupling between the boson field and the SM.

  ⇨ Model-independent search of new boson field.

- The superradiance can also test the strong field region of GR.

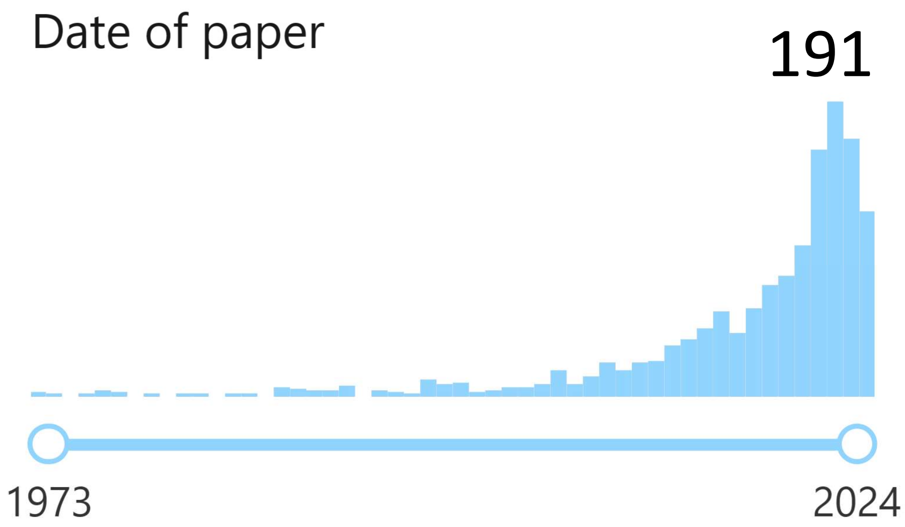
  Jia, Guo, Liang, Mai, Zhang, arXiv:2309.05108

- Very rich phenomenology if assuming coupling between the boson field and the SM.

Sorry if I have Missed Your Work…

- New ideas emerge quickly.

Number of papers with "superradiance" in the title



Good reviews and lecture notes:

- Brito, Cardoso and Pani, Lect.Notes Phys. 906 (2015)
- Brack, Cardoso, Nissanke, Sotiriou, and Askar, Class.Quant.Grav. 36 (2019) 14, 143001
- Cardoso and Pani, Living Rev. Rel. 22 (2019) 1

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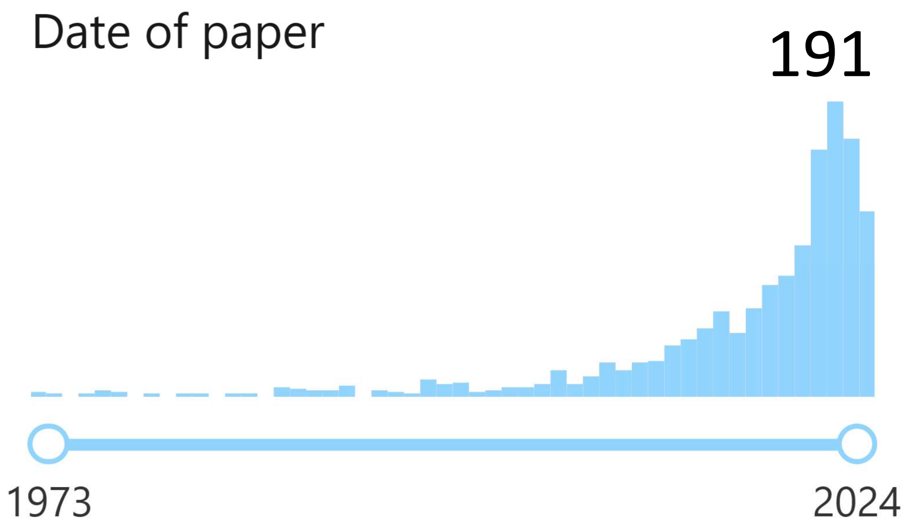

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Thank you!