Black Hole Ringdown Seen in Photon Polarization Swings

Probing Gravitational Perturbations through EM Polarimetry

Based on arXiv: **2605.11499**

Yehui Hou (侯业辉)



李政道研究所
TSUNG-DAO LEE INSTITUTE

Shanghai Jiao Tong University

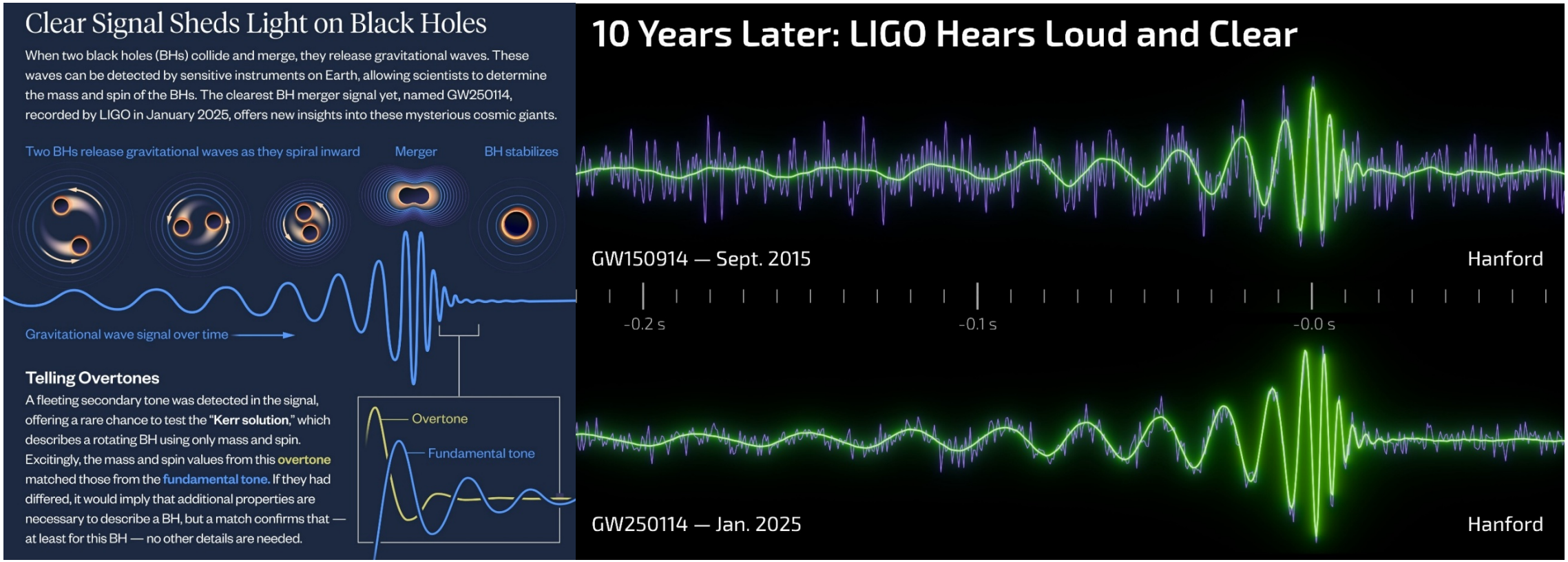
With Jiewei Huang (PKU), Zhen Zhong (Rome U), Minyong Guo (BNU), Bin Chen (NBU)

The 6th BRICS-AGAC Symposium 2026, Hangzhou, China

The paper

Background

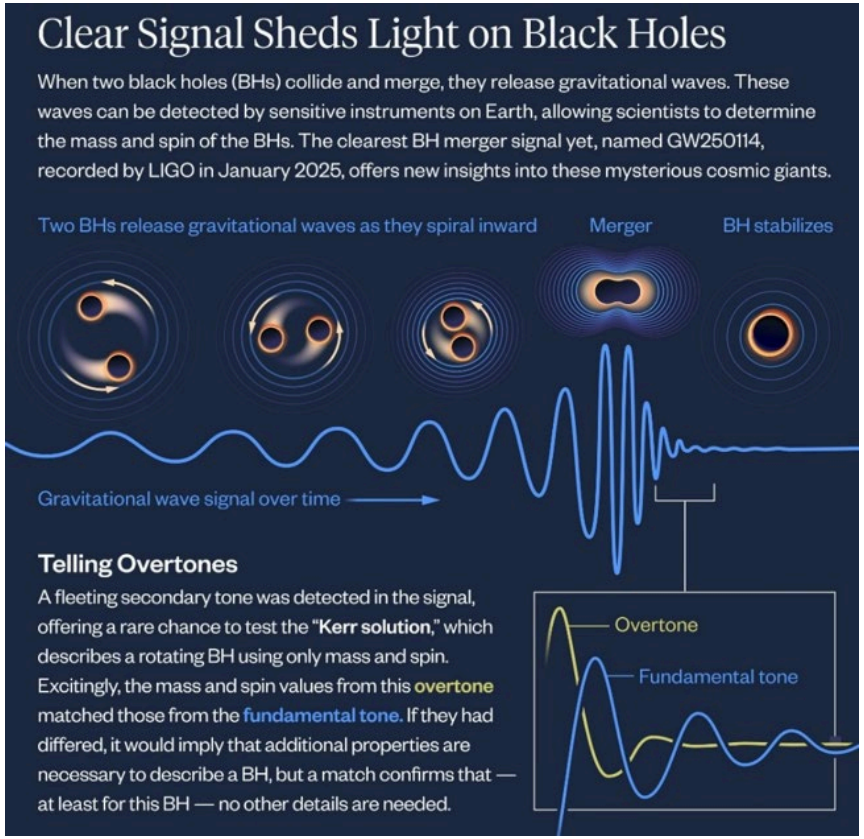
Observations of compact object mergers are becoming increasingly informative

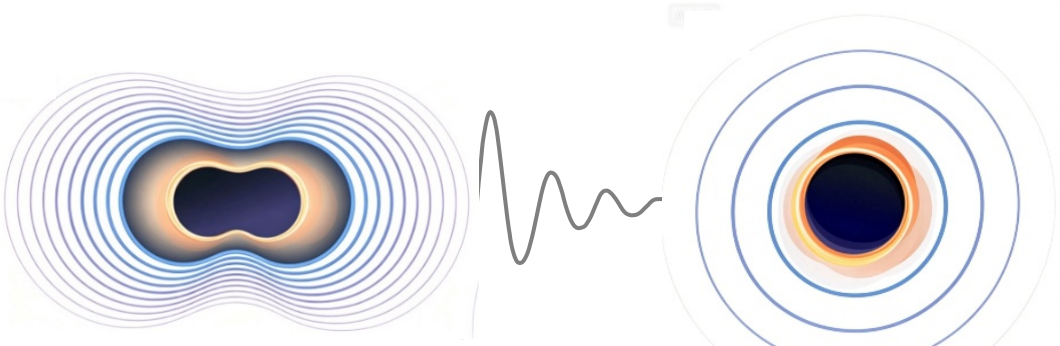


Lucy Reading-Ikkanda/Simons Foundation; LIGO/J. Tissino (GSSI)/R. Hurt (Caltech-IPAC)

Background

Observations of compact object mergers are becoming increasingly informative



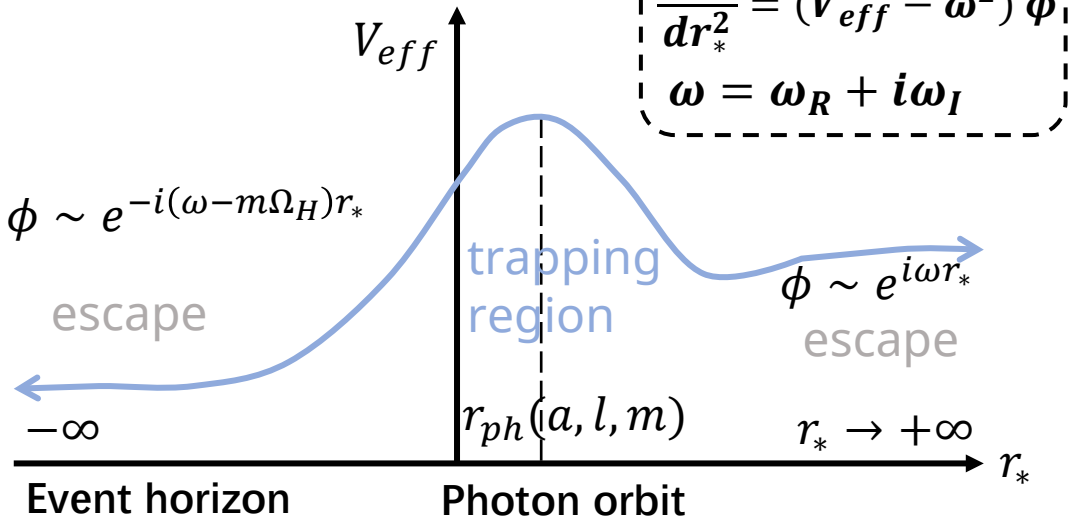


quasinormal modes. QNMs

An oscillatory, decaying mode

$$\frac{d^2\phi}{dr_*^2} = (V_{eff} - \omega^2)\,\phi$$

$$\omega = \omega_R + i\omega_I$$

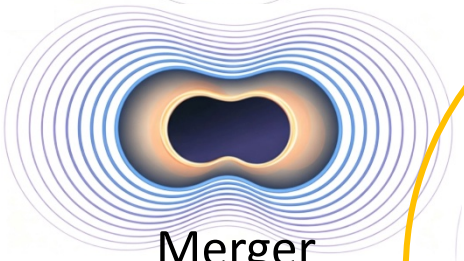


Background

Can black-hole ringdown leave an observable electromagnetic signature?



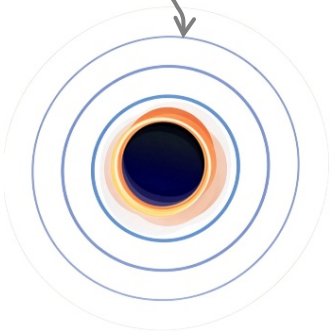
Inspiraling

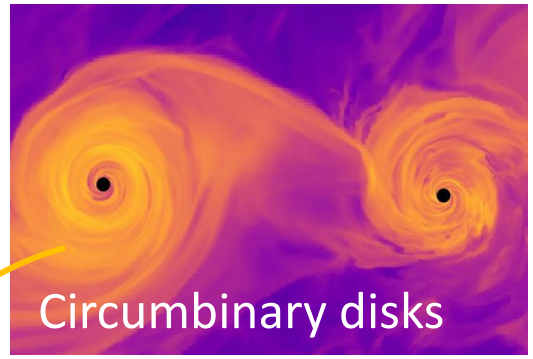


Merger

Background source

Ringdown





Accreting plasma, magnetic field

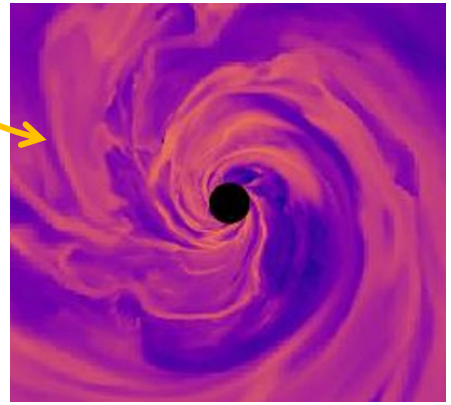
Potential multimessenger sources

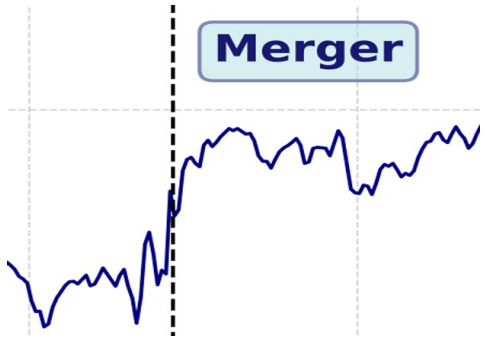
Continuous EM emission

① Can photons encode QNM signatures?

② Is there an exact correspondence?

③ Is the effect observable?

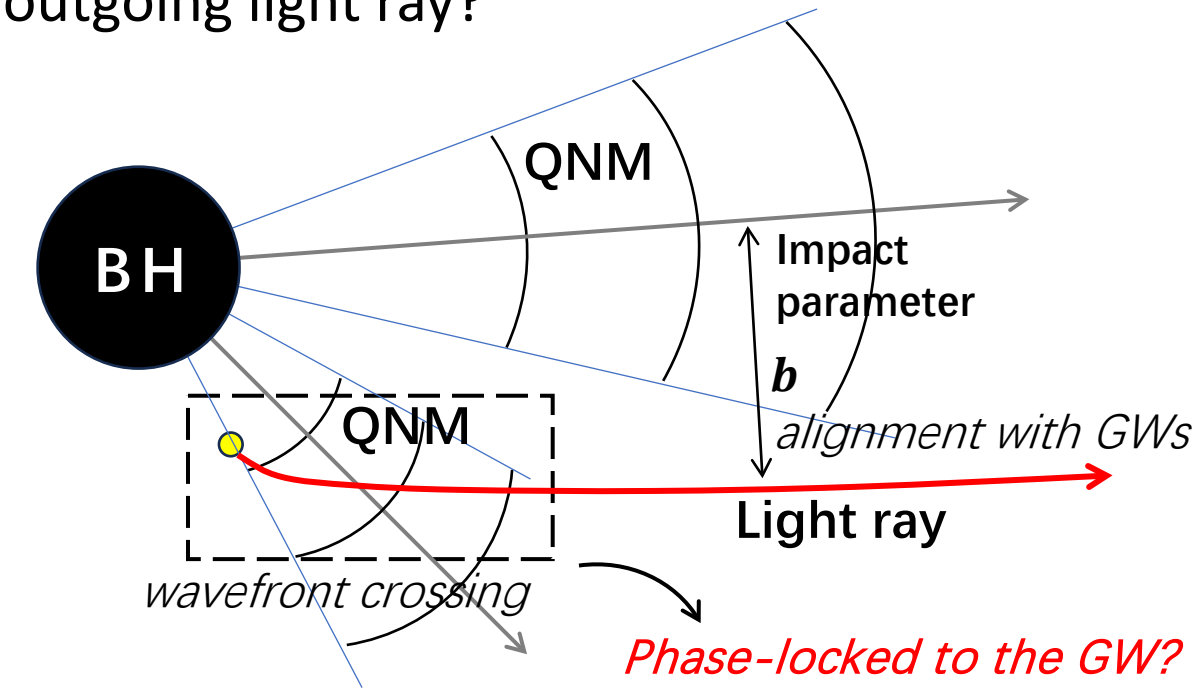




L. Ennoggi et al., PRL. 136 (2026) 11, 111401.

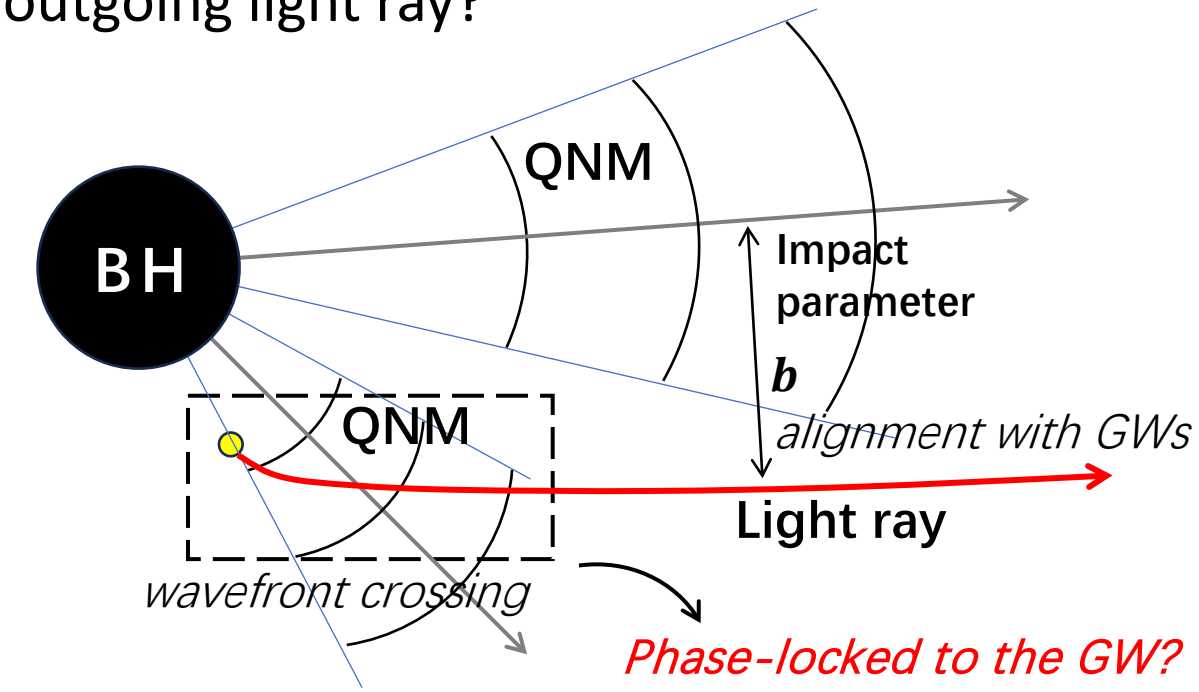
Strong-field perturbations

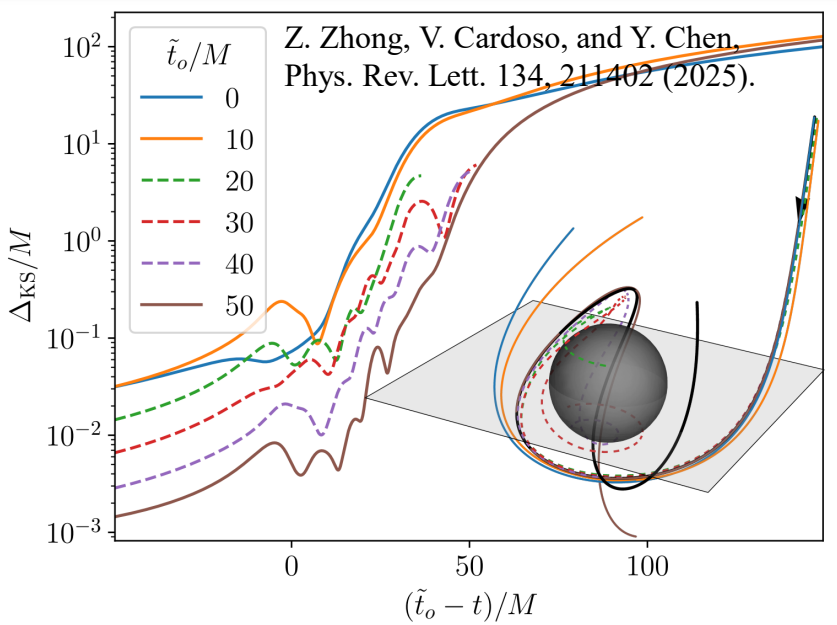
- Light can probe perturbations in the strong-field region.
- Light rays cross GW wavefronts over only a short segment of their trajectories.
- Does the GW phase become “frozen into” the outgoing light ray?

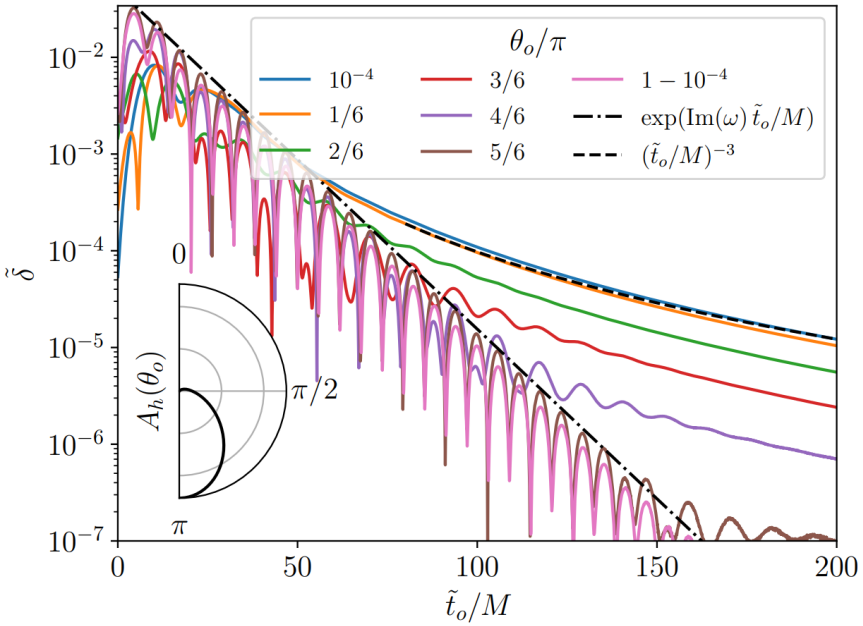


Strong-field perturbations

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Gravitational Faraday rotation

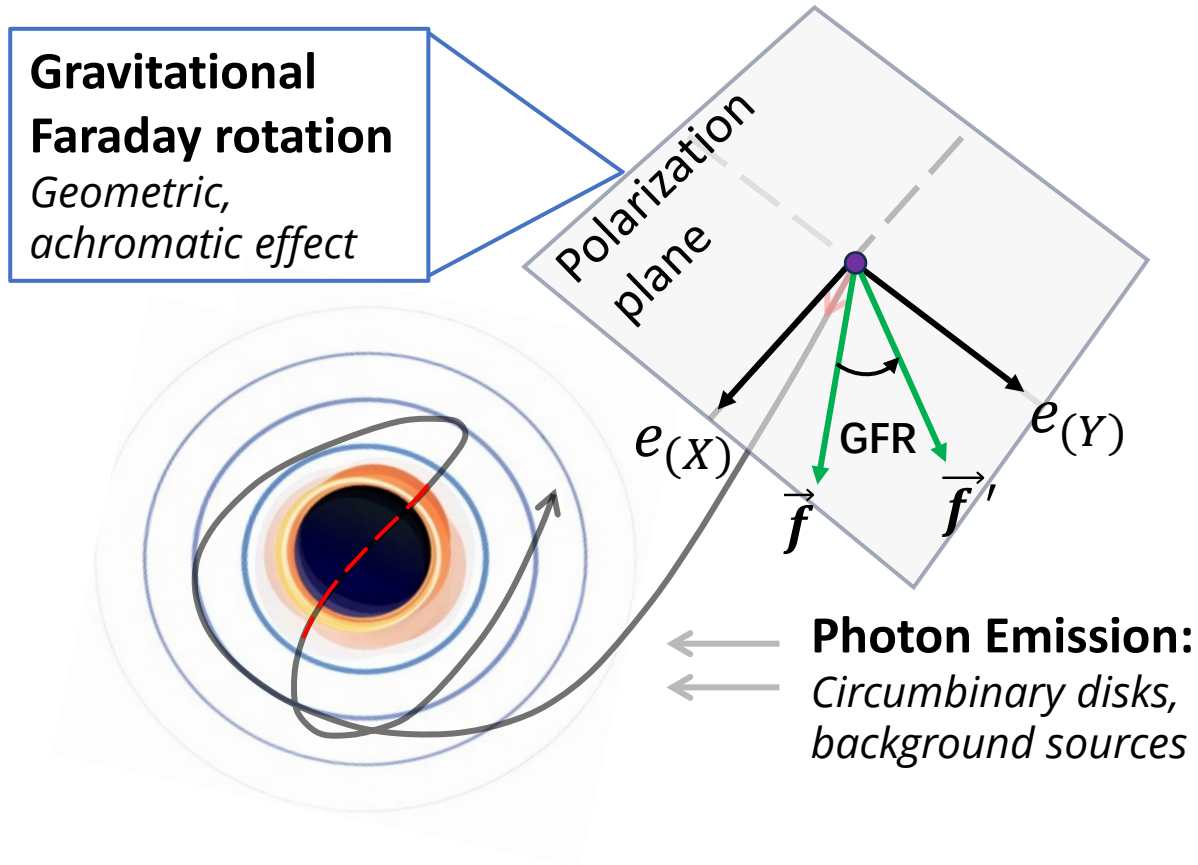
- **Astrometry vs. polarimetry**

$$\delta\vartheta \propto \frac{M}{r_o}$$ scale-free (Morphologically)

**When the angular scale M/r_o cannot be spatially resolved, polarimetry may still probe strong-field gravity.*

- **Gravitational Faraday rotation (GFR)**
  - Induced by a nonspherical gravitational field { BH spin; GWs }
  - A geometric and achromatic effect

Gravitational Faraday rotation
Geometric, achromatic effect

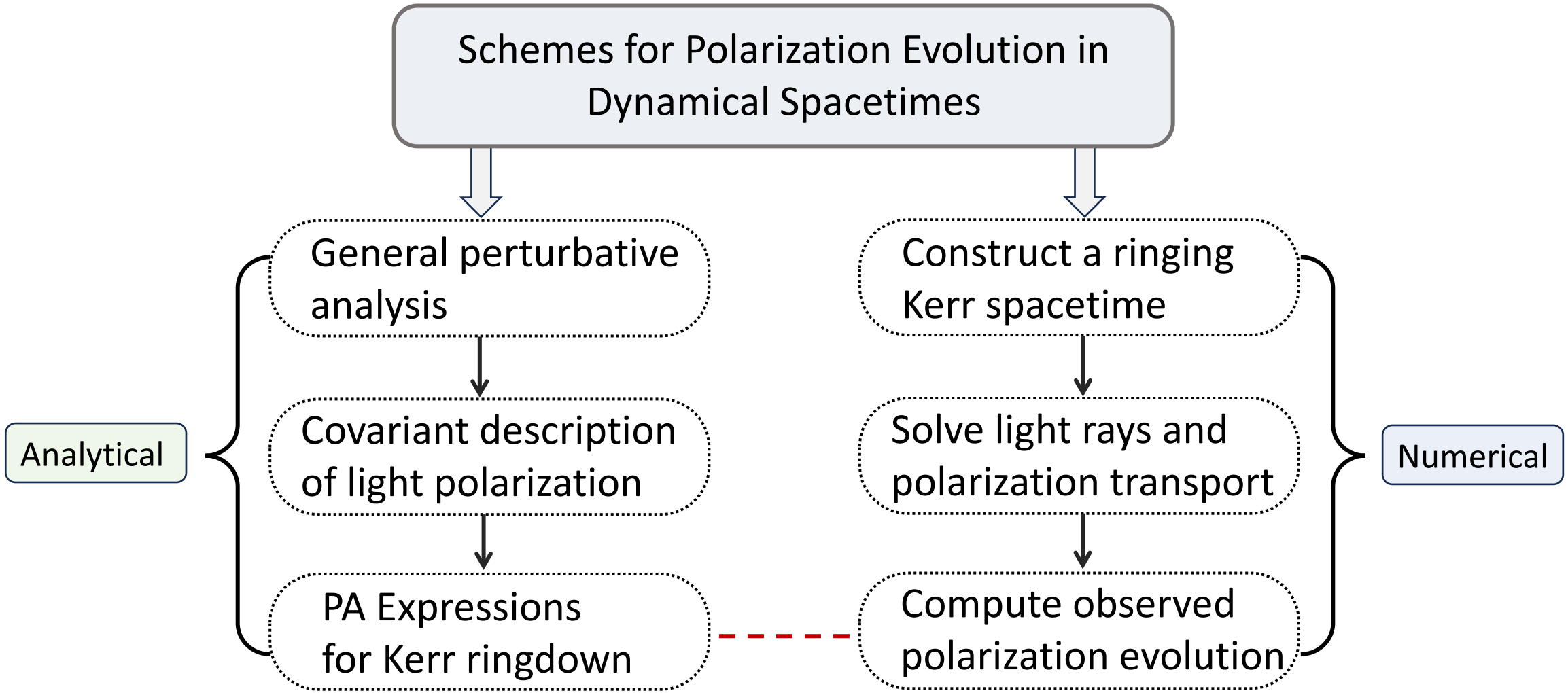


Photon Emission:
Circumbinary disks, background sources

Can polarization-angle swings encode the ringdown waveform?

Ringdown → damped harmonic polarization patterns?

Overall Scheme

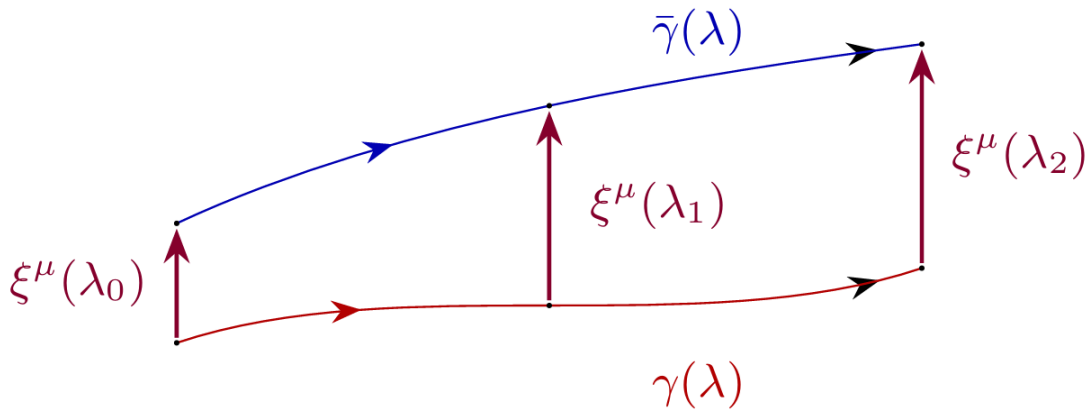


Perturbative framework

- **Perturbative expansion**

$$\bar{g}_{\mu\nu} = g_{\mu\nu} + \epsilon\, h_{\mu\nu}$$

$$\bar{x}^{\mu}(\lambda) = x^{\mu}(\lambda) + \epsilon\xi^{\mu}(\lambda) + \mathcal{O}\left(\epsilon^{2}\right)$$



- **Background geodesic**

$$\frac{\mathrm{d}}{\mathrm{d}\lambda}k^{\mu} = -\Gamma^{\mu}{}_{\nu\rho}k^{\nu}k^{\rho} \qquad k^{\mu} = \mathrm{d}x^{\mu}/\mathrm{d}\lambda$$

- **Deviation equation**

$$H^{\mu}{}_{\nu\rho} = \frac{1}{2}g^{\mu\sigma}\left(\nabla_{\nu}h_{\sigma\rho} + \nabla_{\rho}h_{\nu\sigma} - \nabla_{\sigma}h_{\nu\rho}\right)$$

$$k^{\alpha}\nabla_{\alpha}(k^{\beta}\nabla_{\beta}\xi^{\mu}) = \boxed{R^{\mu}{}_{\nu\alpha\beta}}k^{\nu}k^{\alpha}\xi^{\beta} - \boxed{H^{\mu}{}_{\nu\rho}}k^{\nu}k^{\rho}$$

Curvature term GW source term

Polarization transport

- **Photon polarization** $S^{\mu\nu} = \frac{1}{2}\left(\mathcal{I}\, e_B^{\mu\nu} + \mathcal{Q}\, e_+^{\mu\nu} + \mathcal{U}\, e_\times^{\mu\nu} + i\mathcal{V}\, e_A^{\mu\nu}\right)$

$$\mathcal{S} = \{\mathcal{I}, \mathcal{Q}, \mathcal{U}, \mathcal{V}\}$$

$$e_+^{\mu\nu} = e^\mu_{(X)} e^\nu_{(X)} - e^\mu_{(Y)} e^\nu_{(Y)} \qquad e_A^{\mu\nu} = e^\mu_{(X)} e^\nu_{(Y)} - e^\mu_{(Y)} e^\nu_{(X)}$$
$$e_\times^{\mu\nu} = e^\mu_{(X)} e^\nu_{(Y)} + e^\mu_{(Y)} e^\nu_{(X)} \qquad e_B^{\mu\nu} = e^\mu_{(X)} e^\nu_{(X)} + e^\mu_{(Y)} e^\nu_{(Y)}$$

Parallel transport: $k^\nu \nabla_\nu\, e^\mu_{(a)} = 0\,, \quad \frac{\mathrm{d}}{\mathrm{d}\lambda}\mathcal{S} = 0$

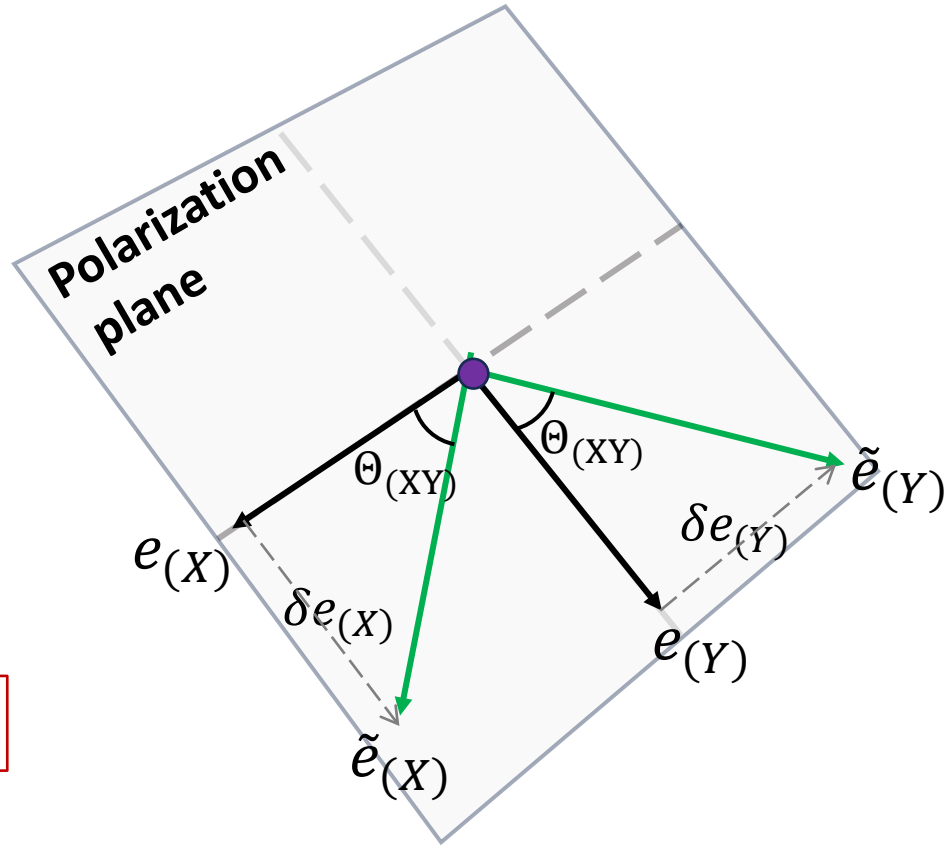
- **Perturbative polarization rotation (PPR)**

$$\Theta_{(a)(b)} = g_{\mu\nu}\delta e^\mu_{(a)} e^\nu_{(b)}$$

$$\Theta_{\mu\nu} = \Theta_{(a)(b)} e^{(a)}_\mu e^{(b)}_\nu = \eta_{(a)(b)}\delta e^{(a)}_\mu e^{(b)}_\nu$$

$$\boxed{k^\alpha \nabla_\alpha \Theta_{\mu\nu} = R_{\mu\nu\alpha\beta} k^\alpha \xi^\beta + k^\rho \nabla_{[\mu} h_{\nu]\rho}}$$

The PPR is uniquely given by: $\boxed{\vartheta = \Theta_{\mu\nu}\, e^\mu_{(X)} e^\nu_{(Y)}}$



Accumulated polarization angle

Geodesic deviation vector

$$k^\alpha \nabla_\alpha \Theta_{\mu\nu} = R_{\mu\nu\alpha\beta} k^\alpha \xi^\beta + k^\rho \nabla_{[\mu} h_{\nu]\rho}$$

Curvature term — QNM-induced term

- **PPR accumulation**

$$\vartheta(x_s^\mu, x_o^\mu) \simeq \int_{x^\mu(\lambda)} \Omega\,(x^\mu)\,\mathrm{d}\lambda\,, \qquad \Omega\,(x^\mu) \equiv e^\mu_{(Y)} e^\nu_{(X)}\, k^\rho \nabla_{[\mu} h_{\nu]\rho}$$

- **Kerr ringdown phase** $\Omega\,(x^\mu) = \Re[\tilde{\Omega}\,(r,\theta)\, e^{i(m\phi - \omega t)}]$

Explicit form of the QNM-induced signal

$$\vartheta\left(\tilde{t}_o\right) = |\mathcal{A}| \cos\left(\omega_R\, \tilde{t}_o + \Phi\right) e^{-\omega_I \tilde{t}_o}$$

*for light rays that are perturbed mainly along their outgoing segment

Numerical verification: Kerr ringdown

- **Weyl scalars** $\psi_s = \dfrac{{}_sZ}{\sqrt{2\pi}} R_s(r)\, S_s^{lm}(\theta)\, e^{-i\omega t + im\phi}$

  Solve Teukolsky equation with spin weight $s = \pm 2$ to get $R_s(r)$

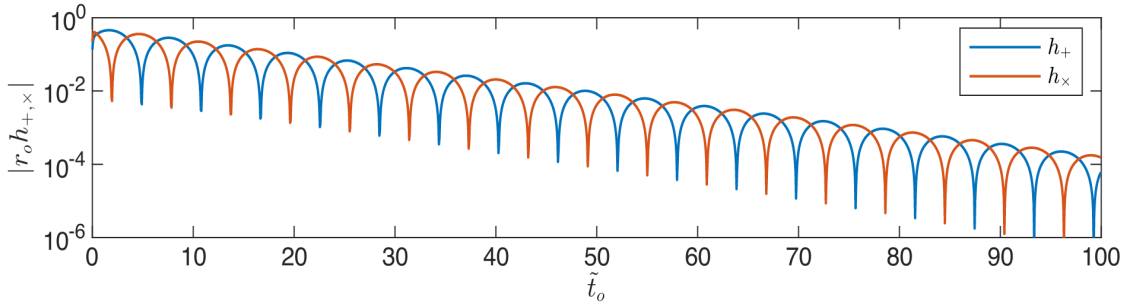
- **Metric reconstruction** $\psi_{\pm 2} \longrightarrow h_{\mu\nu}(x^\mu)$

  Chrzanowski–Cohen–Kegeles (CCK) scheme

- **Fundamental mode** We set $E_{\rm tot} \simeq 0.6\%\, M$

with a = 0.7M, $\{n, l, m\} = \{0,2,2\}$

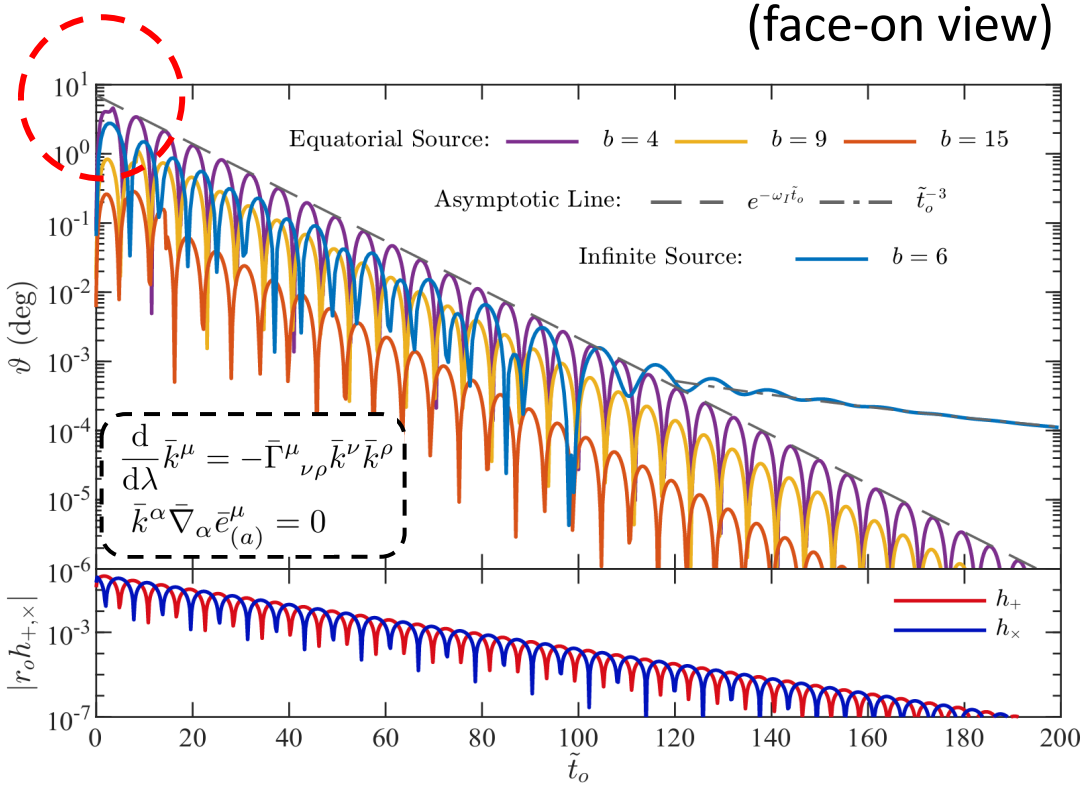
The frequency is $M\omega = 0.5326 - 0.08079\, i$



Numerical verification: time-domain result

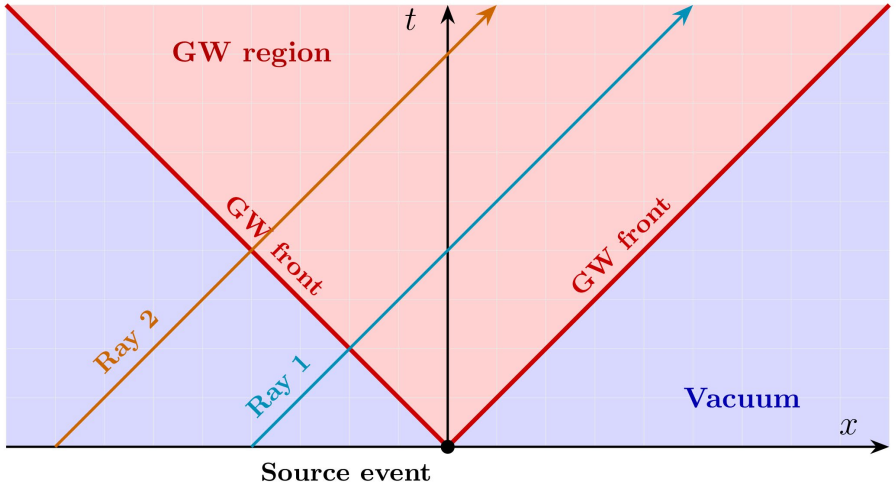
- **PA swing as a function of observer time**

(face-on view)



Equator-to-infinity geodesics → disk emission

Infinity-to-infinity geodesics → distant emission



$$\vartheta\left(\tilde{t}_o\right) = |\mathcal{A}|\cos\left(\omega_R\,\tilde{t}_o + \Phi\right)e^{-\omega_I\tilde{t}_o}$$

for light rays that are perturbed mainly along their outgoing segment

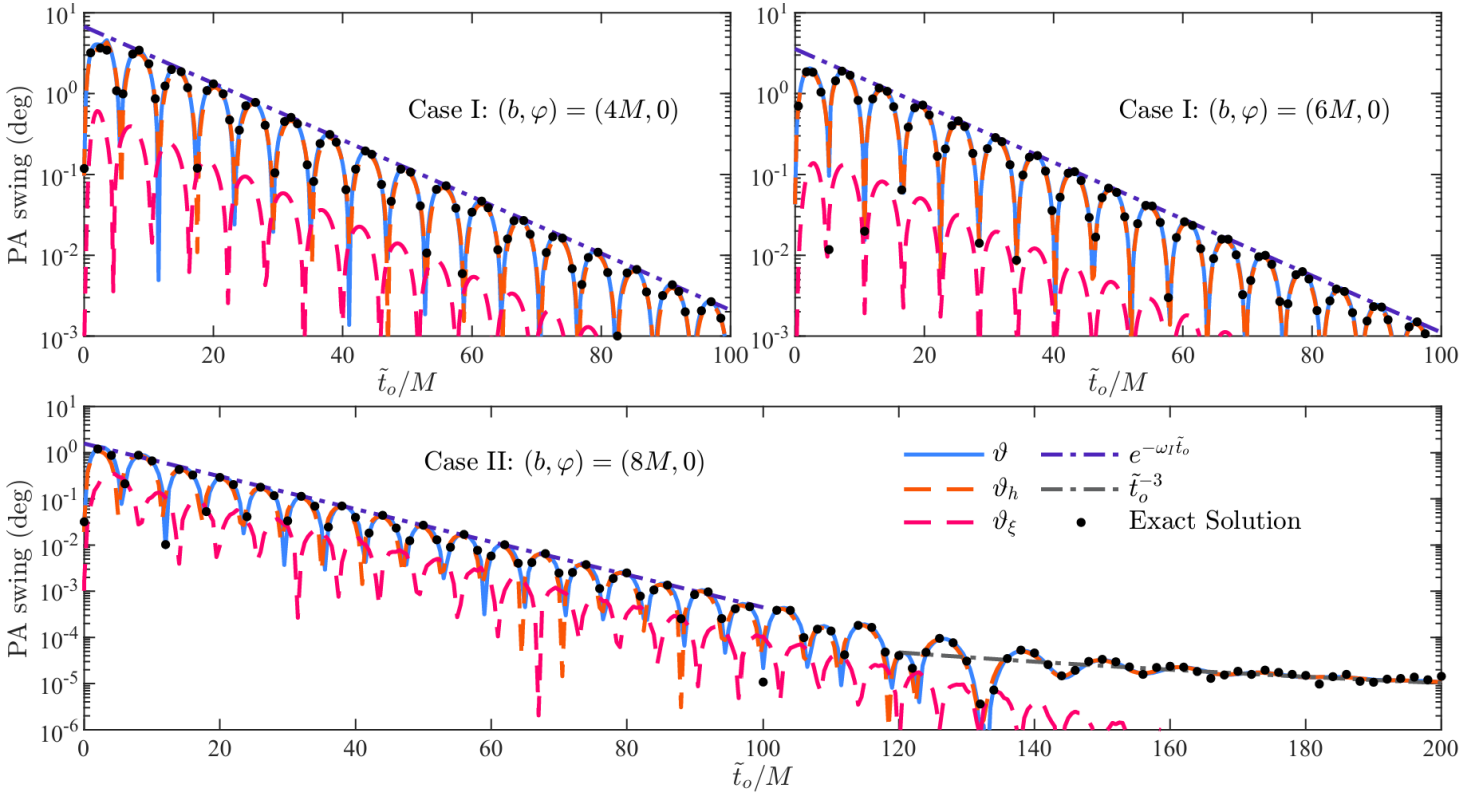
① Early times: the swing traces the QNM

② A peak amplitude of up to 10 degrees

③ Late times: a power-law tail $\simeq \tilde{t}_o{}^{-3}$ for a source at infinity

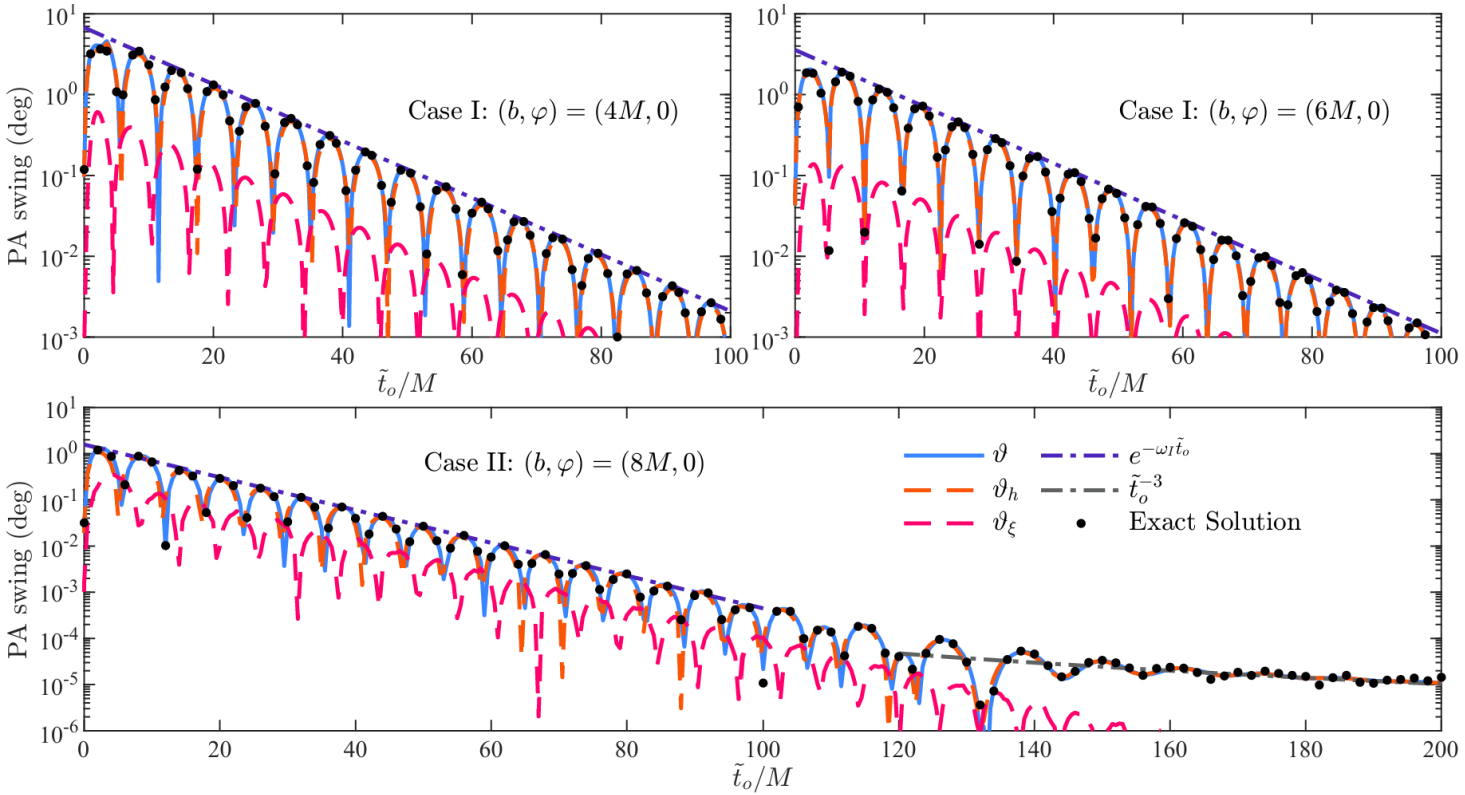
Numerical verification: time-domain result

- **Comparison between numerical results and perturbative predictions**

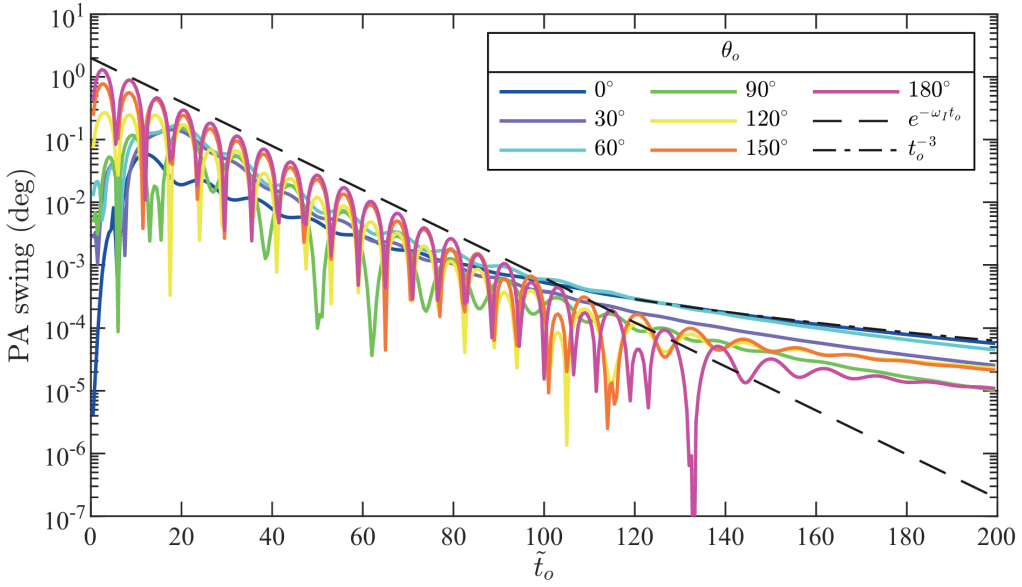


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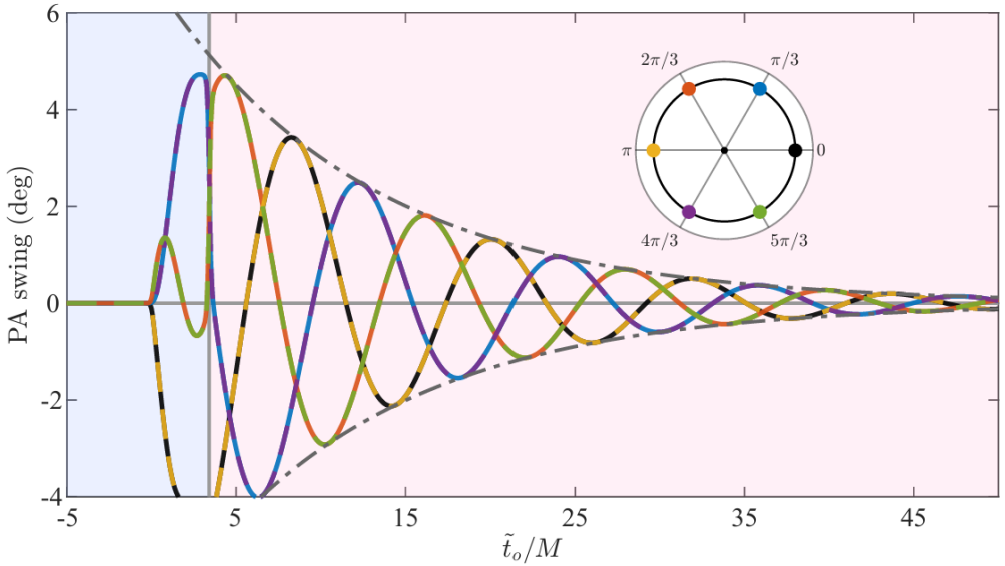
- **Swings under various viewing angles**



Numerical verification: phase and amplitude

$$\vartheta\left(\tilde{t}_o\right) = |\mathcal{A}| \cos\left(\omega_R \tilde{t}_o + \Phi\right) e^{-\omega_I \tilde{t}_o}$$

- **PA swings at different azimuthal angles**



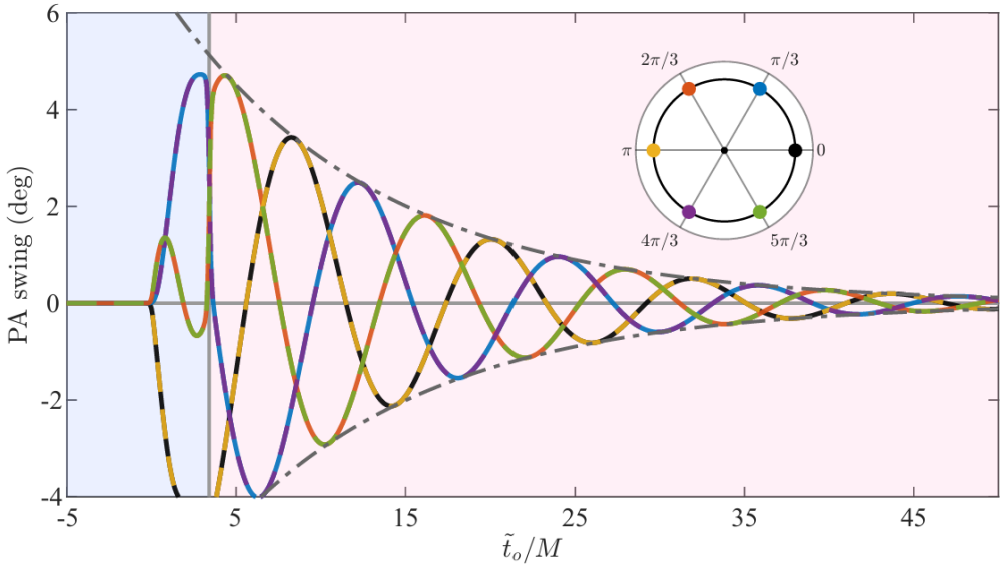
Correspondence between the PPR's phase and QNM's angular mode (face-on):

$$\delta\Phi = m \cdot \delta\varphi$$

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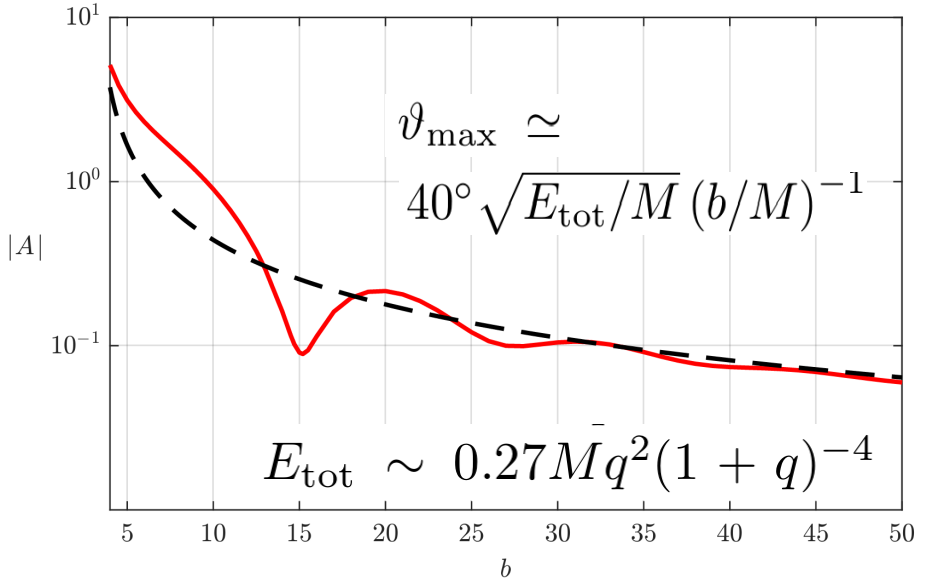
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Correspondence between the PPR's phase and QNM's angular mode (face-on):

$$\delta\Phi = m \cdot \delta\varphi$$

- **Amplitude vs. screen-plane radius**



Detectability condition:

$$\frac{1}{(1+q)\left(1+q^{-1}\right)} \gtrsim 0.048 \frac{b}{M} \sigma_{\rm PA}$$

Image-plane correlations

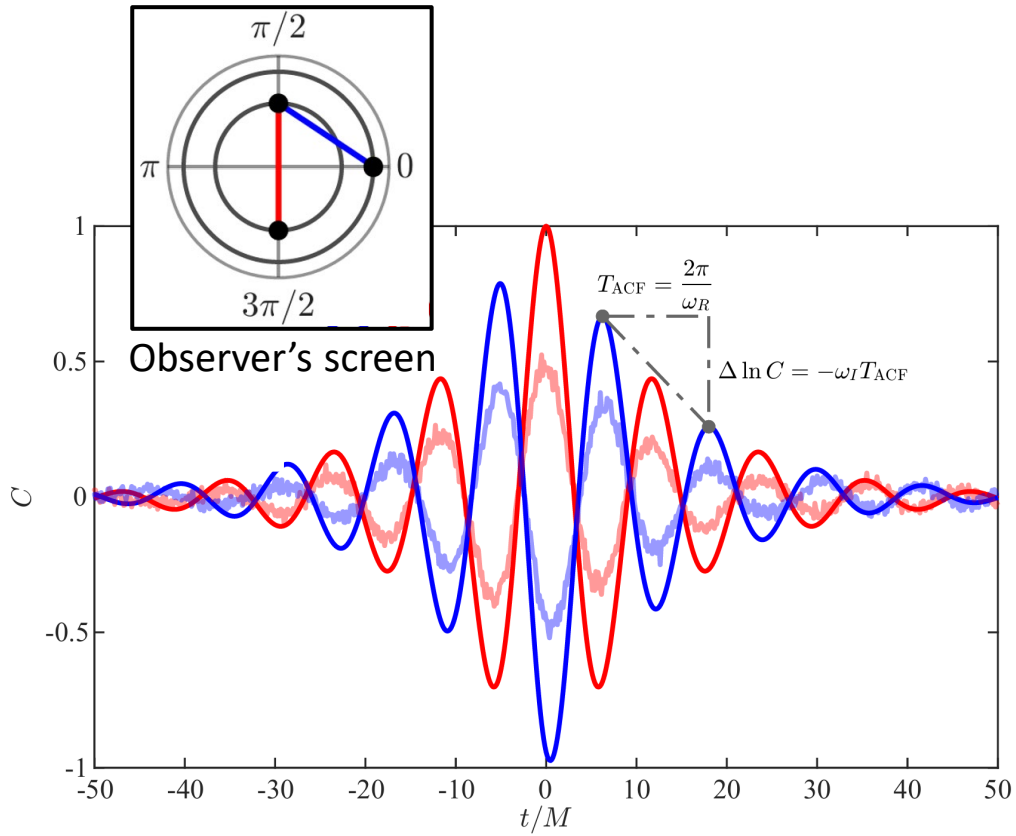
- **Two-point correlation**

$$C(\vec{x},\vec{y},t) = \frac{1}{c_0}\int_{-\infty}^{\infty} \vartheta_o(\vec{x},t')\,\vartheta_o(\vec{y},t'+t)\,\mathrm{d}t'$$

When viewed face-on (with $\vec{x} = (x, 0)$):

$$C = \frac{|\mathcal{A}_x||\mathcal{A}_y|}{4\,\omega_I c_0}\cos\left(\omega_R t + m\varphi_y - \phi'\right) e^{-\omega_I t}$$

$$\phi' = \arctan\left[2\omega_R\omega_I(\omega_R^2 + 2\omega_I^2)^{-1}\right]$$



$$T_{\rm ACF} = 2\pi/\omega_R \approx 11.8M \qquad \Delta \ln C = -\omega_I T_{\rm ACF} \approx -0.95$$

Image-plane correlations

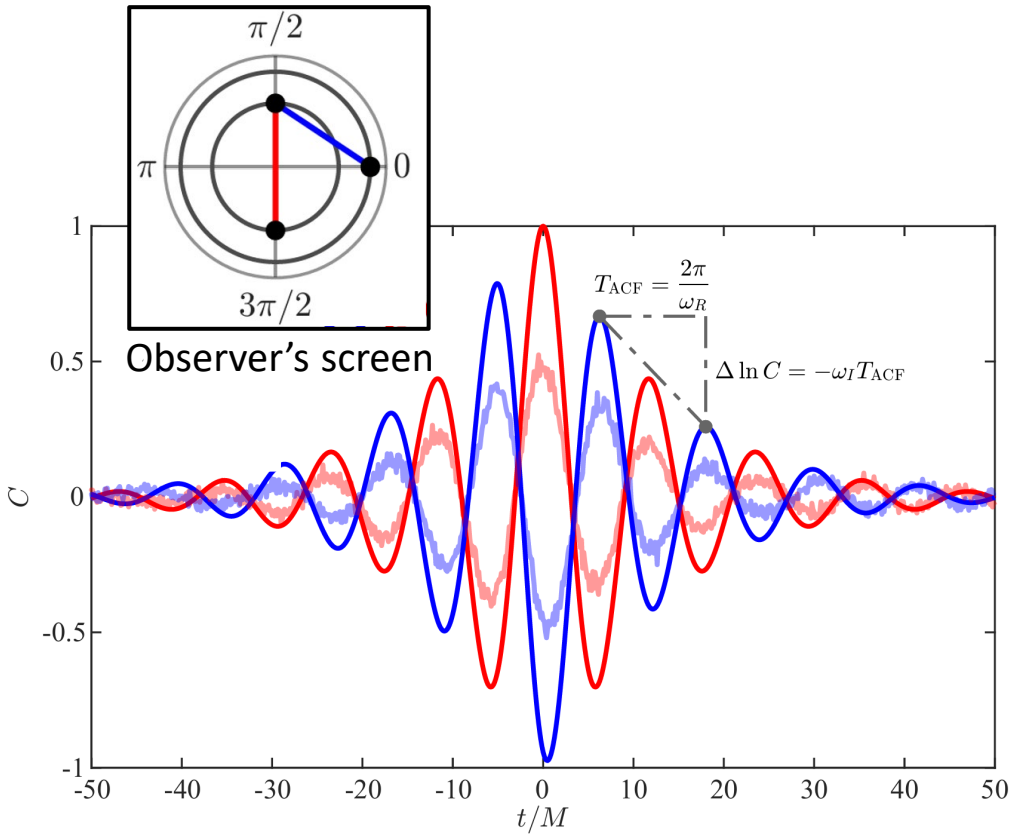
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- **Astrophysical contamination and MHD variability**

$$\mathrm{T}_{MHD} \sim T_{ISCO} \sim \frac{GM}{c^3}$$

Source (plasma) effect : chromatic

QNM-induced effect : achromatic

Multifrequency observations ?

Summary

Key takeaways:

△ QNM-induced GFR produces PA swings.

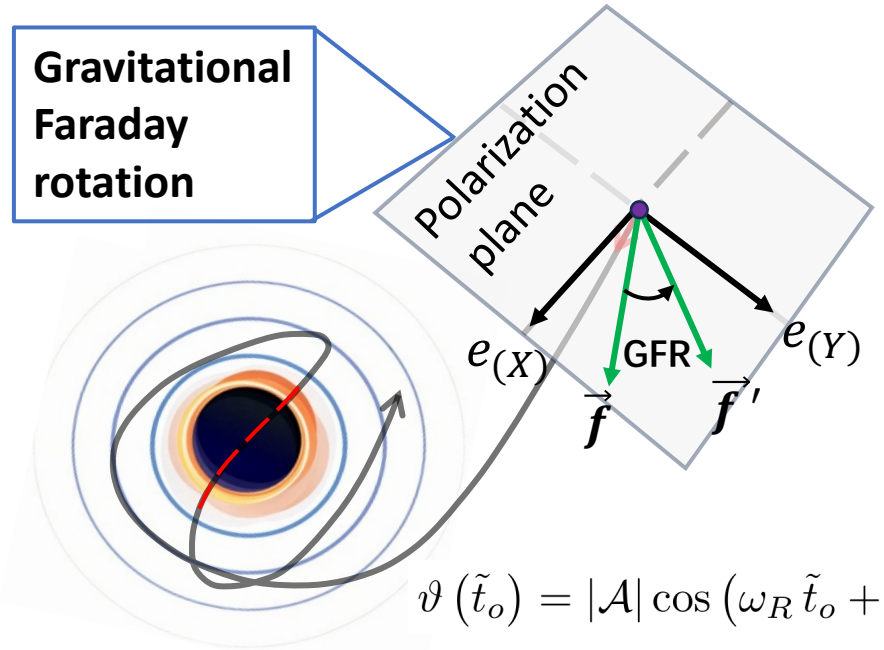
△ In the outgoing-dominated regime, the PA swing exactly traces the QNM pattern.

△ The peak amplitude can reach $\sim 10°$

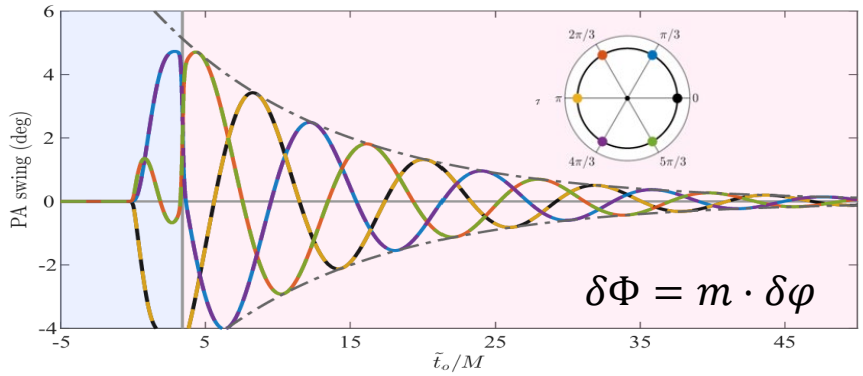
Future directions:

△ Extending the frozen-in mechanism to general GW systems

△ Inferring spacetime geometries from PA swings



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Thank you! Questions and comments are welcome.

Contact me: yehuihou@sjtu.edu.cn

The paper