

Black Hole Ringdown Seen in Photon Polarization Swings

Probing Gravitational Perturbations through EM Polarimetry

Based on arXiv:2605.11499

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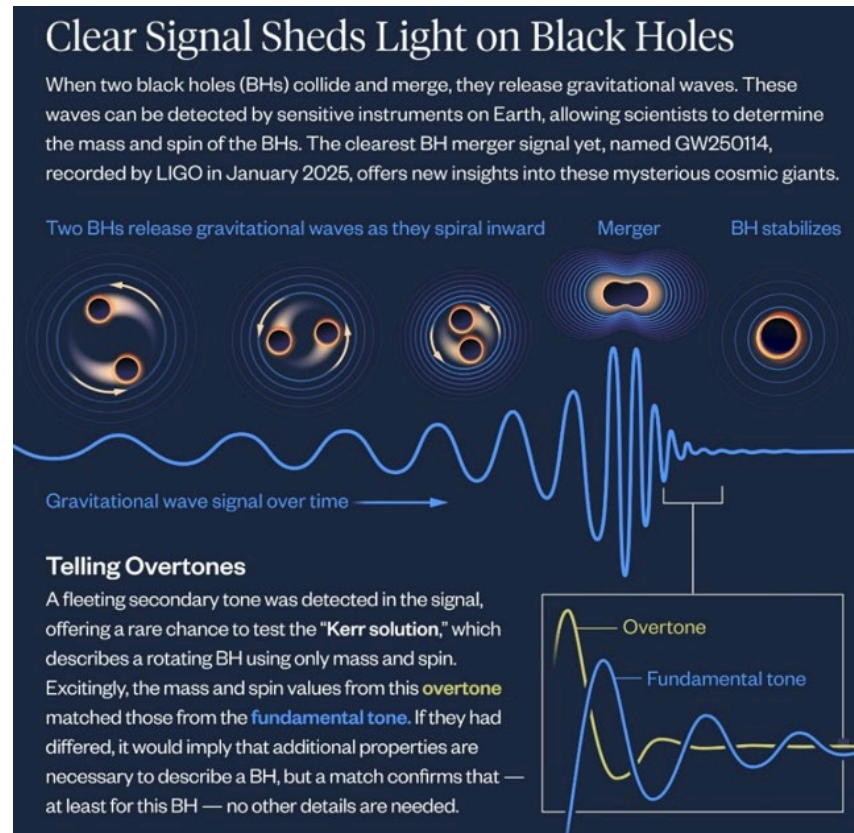
2nd New Horizons for Psi Workshop, ICTP-AP, Beijing, China



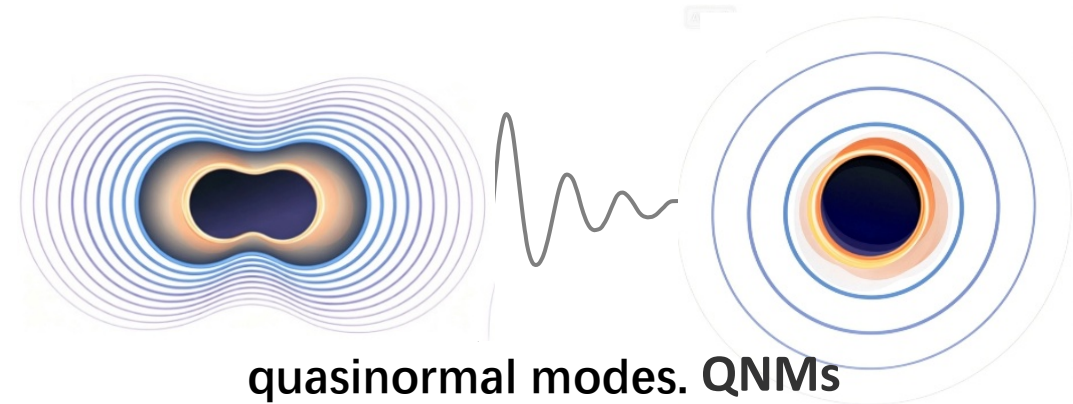
The paper

Background

Observations of compact object mergers are becoming increasingly informative

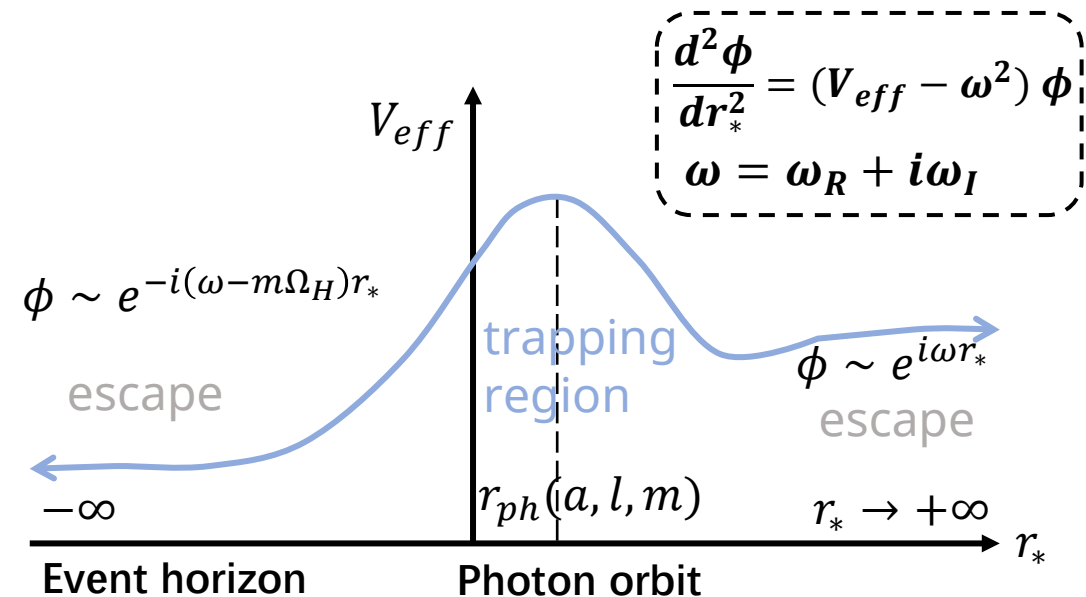


Lucy Reading-Ikkanda/Simons Foundation; LIGO/J. Tisso (GSSI)/R. Hurt (Caltech-IPAC)



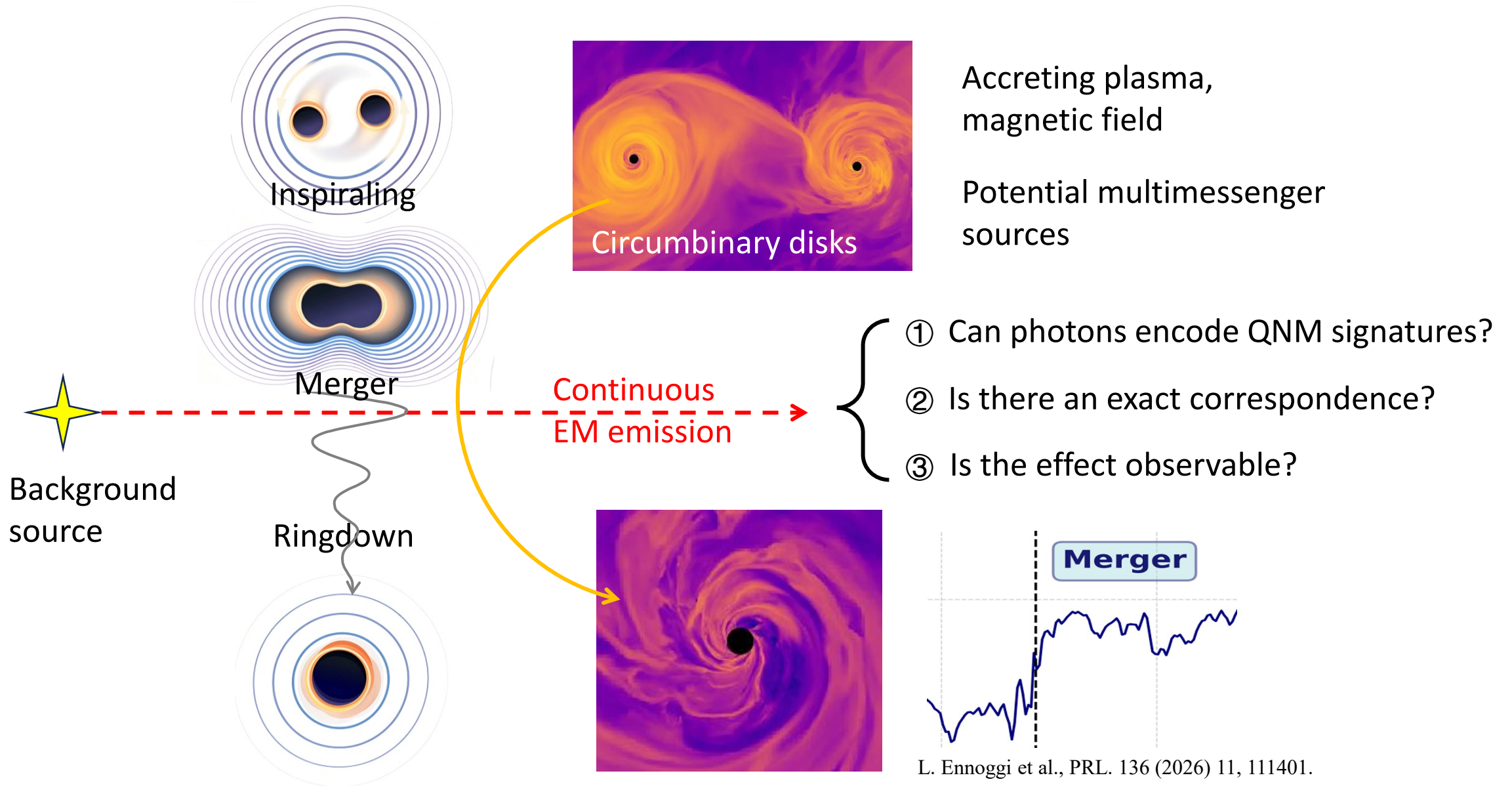
quasinormal modes. QNMs

An oscillatory, decaying mode



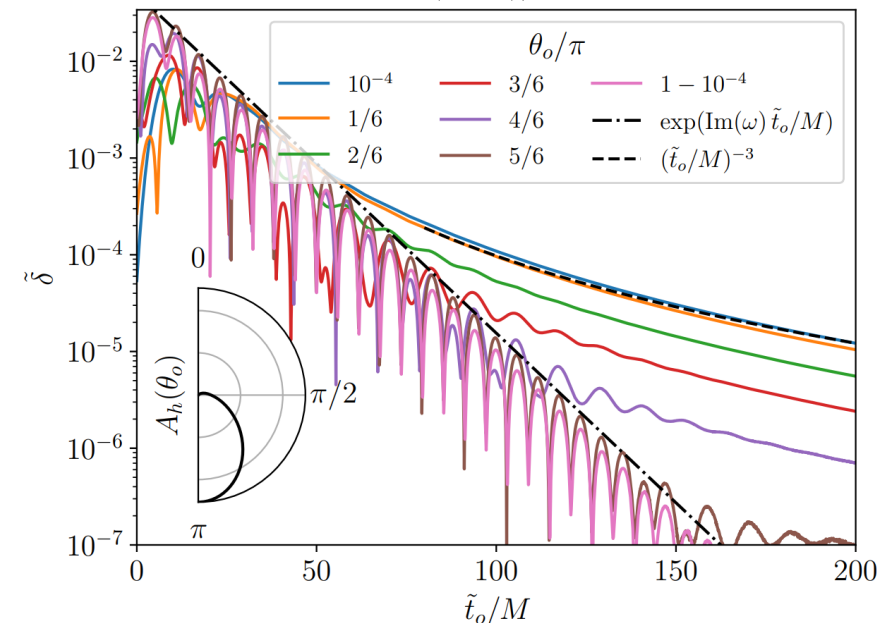
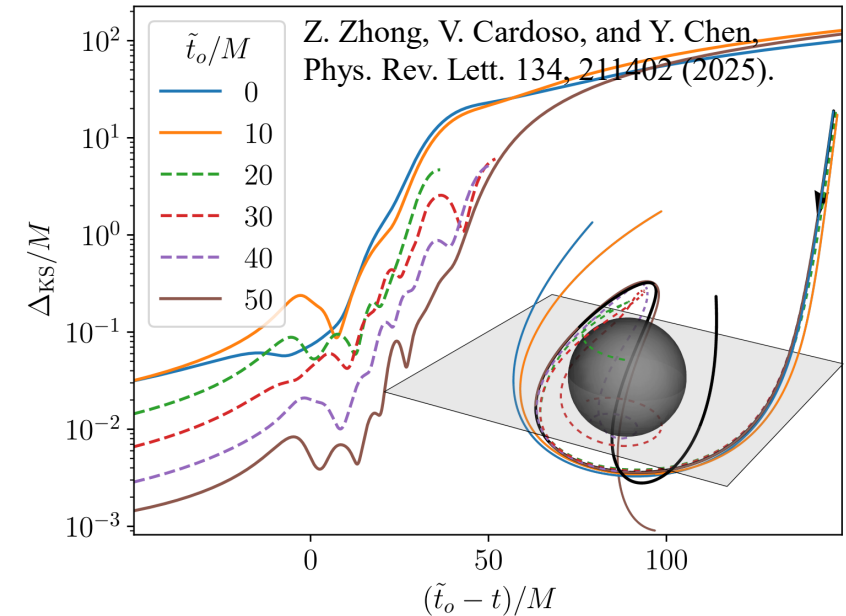
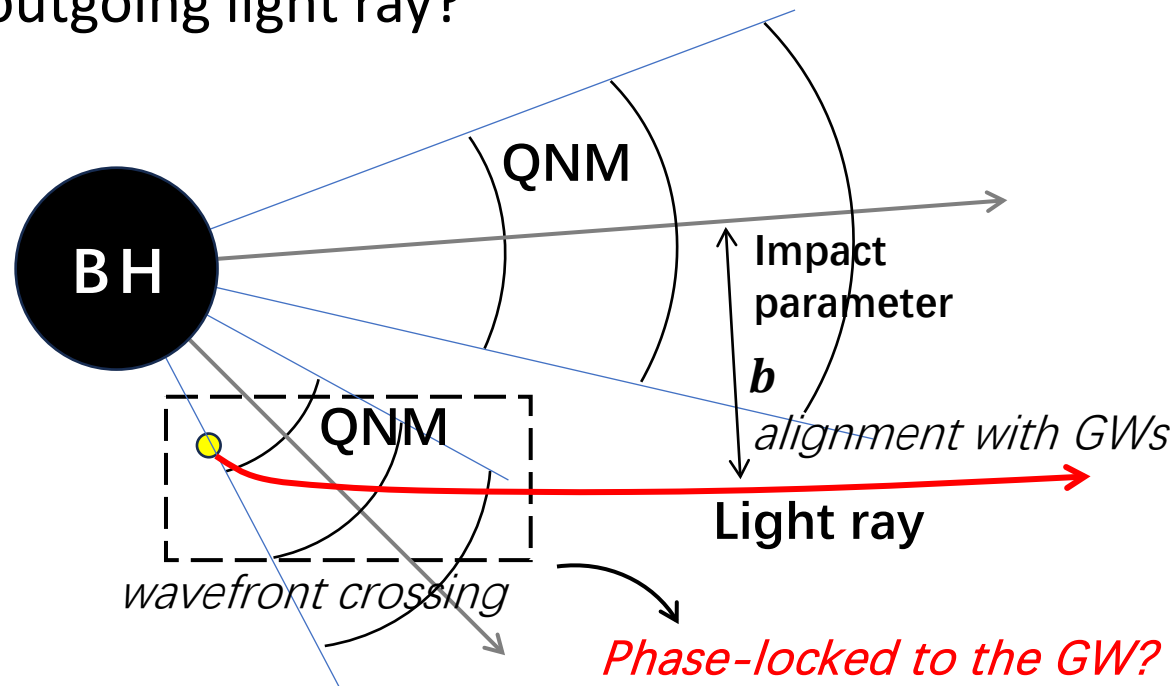
Background

Can black-hole ringdown leave an observable electromagnetic signature?



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?



Polarimetry and GFR

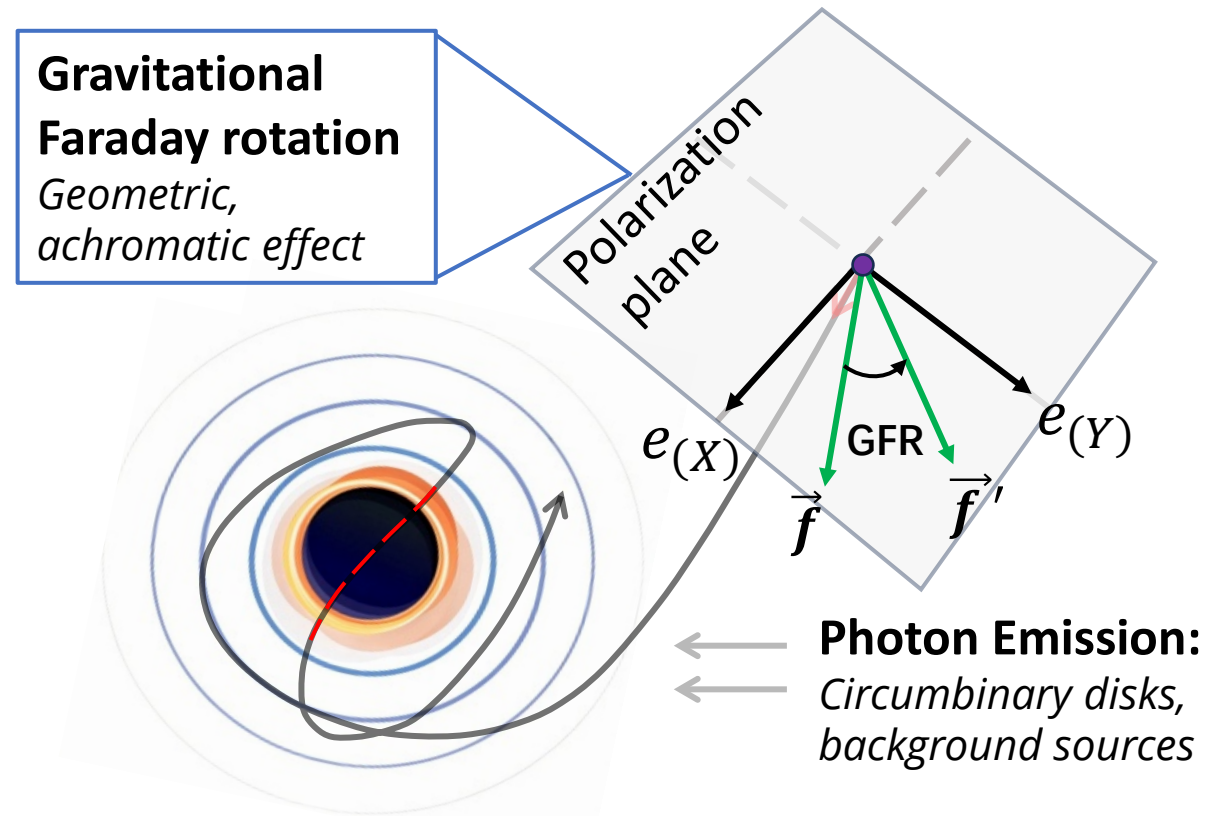
- **Astrometry vs. polarimetry**

$$\delta\vartheta \propto \frac{M}{r_o} \quad \text{scale-free}$$

** 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 $\left\{ \begin{array}{l} \text{BH spin} \\ \text{GWs} \end{array} \right.$
- A geometric and achromatic effect



Can polarization-angle swings encode the ringdown waveform?

Ringdown $\rightarrow$ damped harmonic polarization patterns?

Polarization transport

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

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

$$e_+^{\mu\nu} = e_{(X)}^\mu e_{(X)}^\nu - e_{(Y)}^\mu e_{(Y)}^\nu \quad e_A^{\mu\nu} = e_{(X)}^\mu e_{(Y)}^\nu - e_{(Y)}^\mu e_{(X)}^\nu$$

$$e_\times^{\mu\nu} = e_{(X)}^\mu e_{(Y)}^\nu + e_{(Y)}^\mu e_{(X)}^\nu \quad e_B^{\mu\nu} = e_{(X)}^\mu e_{(X)}^\nu + e_{(Y)}^\mu e_{(Y)}^\nu$$

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

- Perturbative polarization rotation (PPR)**

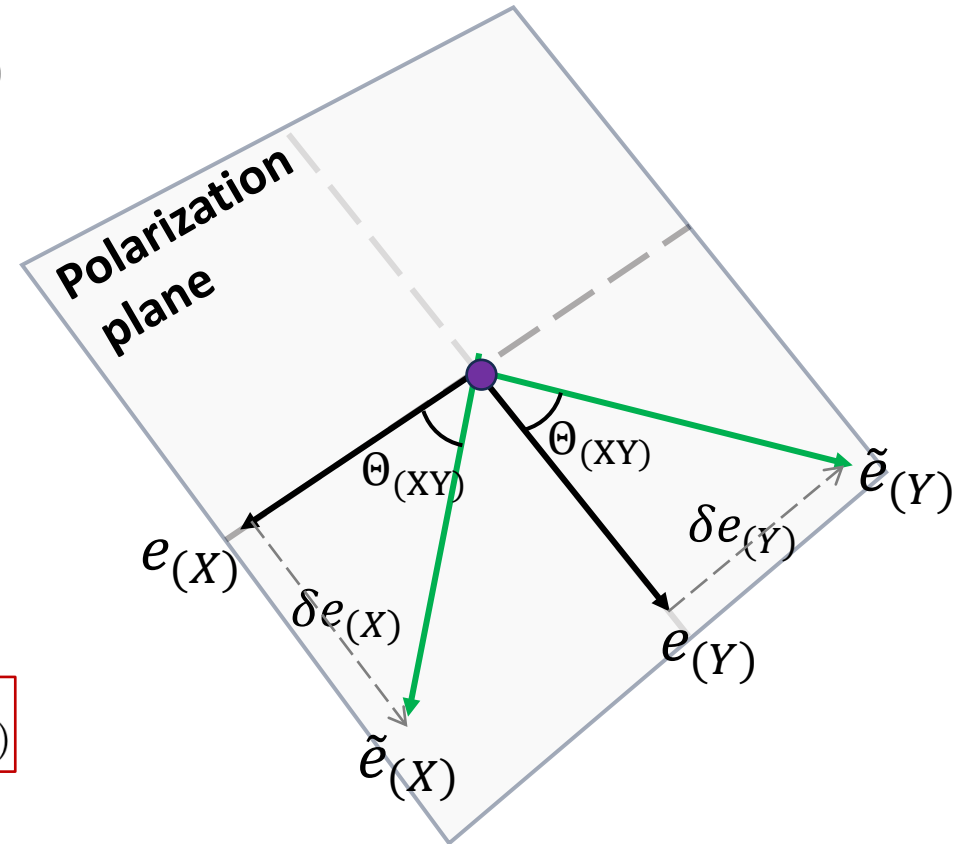
$$\Theta_{(a)(b)} = g_{\mu\nu} \delta e_{(a)}^\mu e_{(b)}^\nu$$

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

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

The PPR is uniquely given by:

$$\vartheta = \Theta_{\mu\nu} e_{(X)}^\mu e_{(Y)}^\nu$$



Accumulated polarization angle

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

Geodesic deviation vector

Curvature term QNM-induced term

- PPR accumulation

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

- Kerr ringdown phase

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

Explicit form of the QNM-induced signal

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

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

Numerical verification: Kerr ringdown

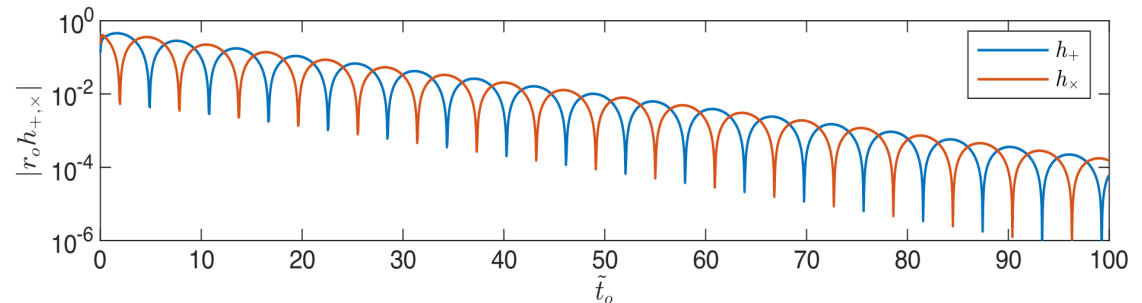
- **Weyl scalars** $\psi_s = \frac{s^Z}{\sqrt{2\pi}} R_s(r) S_s^{lm}(\theta) e^{-i\omega t + im\phi}$ Solve Teukolsky equation with spin weight $s = \pm 2$ to get $R_s(r)$

- **Metric reconstruction** $\psi_{\pm 2} \xrightarrow[\text{I}]{\quad} h_{\mu\nu}(x^\mu)$
Chrzanowski–Cohen–Kegeles (CCK) scheme

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

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

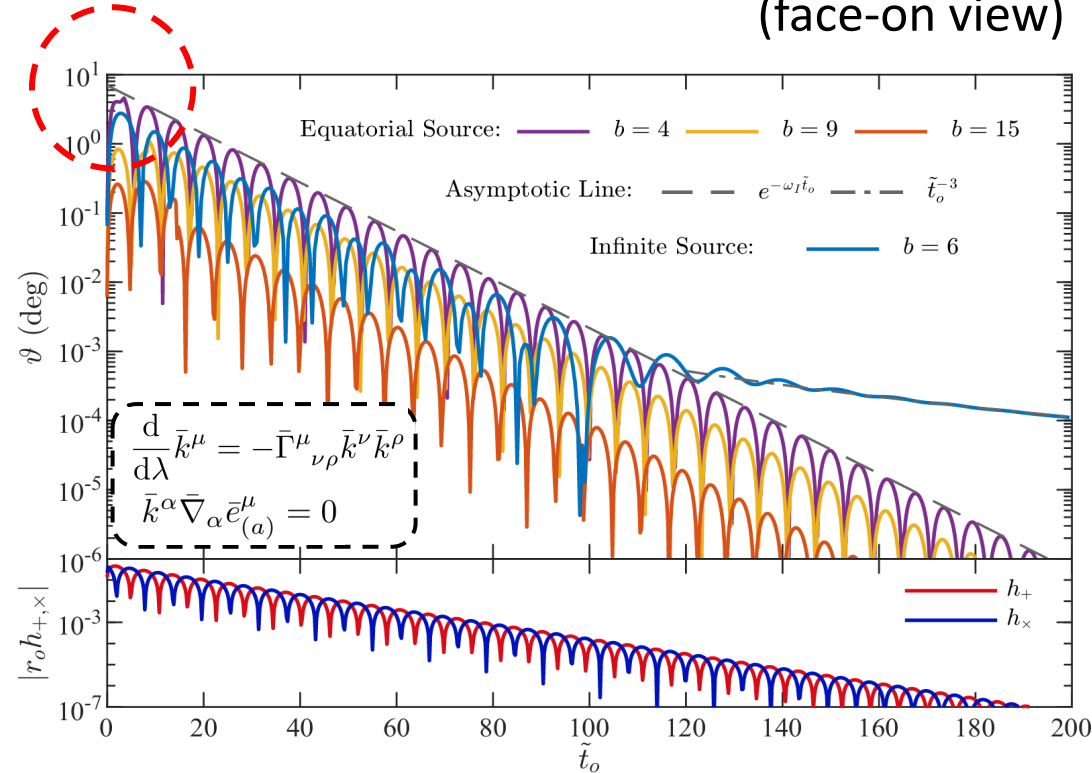
The frequency is $M\omega = 0.5326 - 0.08079i$



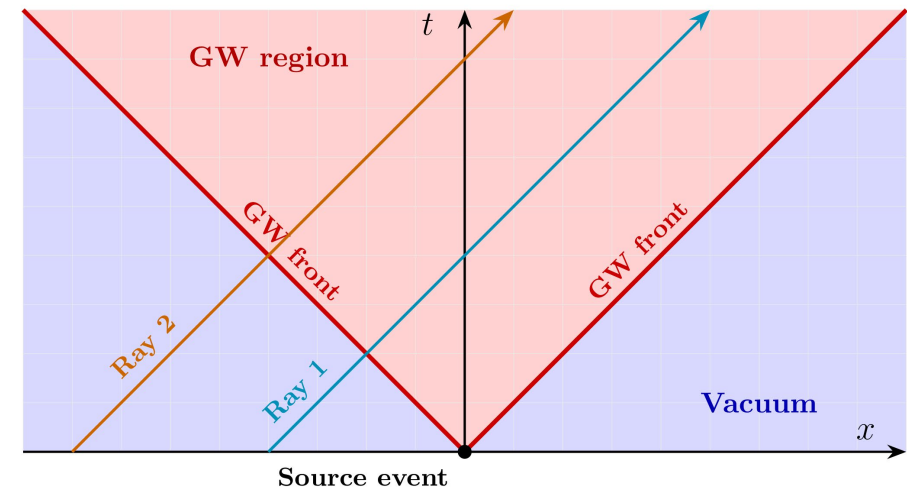
Numerical verifications: time-domain result

• PA swing as a function of observer time

(face-on view)



{ Equator-to-infinity geodesics $\rightarrow$ disk emission
 Infinity-to-infinity geodesics $\rightarrow$ distant emission



- 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

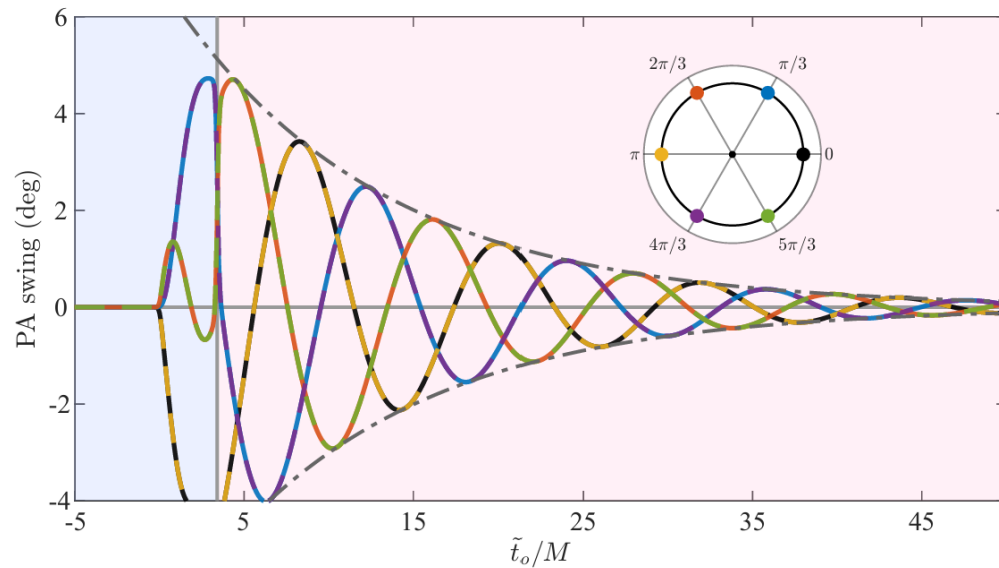
$$\vartheta(\tilde{t}_o) = |\mathcal{A}| \cos(\omega_R \tilde{t}_o + \Phi) e^{-\omega_I \tilde{t}_o}$$

for light rays that are perturbed mainly along their outgoing segment

Numerical verifications: phase and amplitude

$$\vartheta(\tilde{t}_o) = \underbrace{|\mathcal{A}|}_{\text{Amplitude}} \cos(\omega_R \tilde{t}_o + \underbrace{\Phi}_{\text{Phase}}) e^{-\omega_I \tilde{t}_o}$$

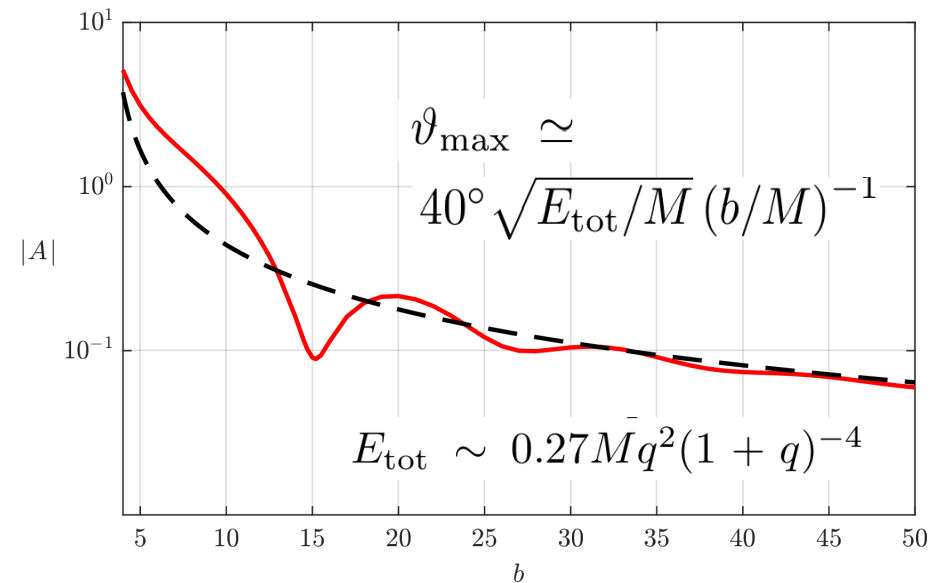
• PA swings at different azimuthal angles



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

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

• Amplitude vs. screen-plane radius



Detectability condition:

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

Image-plane correlations

- Two-point correlation

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

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

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

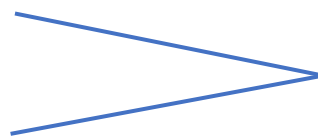
$$\phi' = \arctan[2\omega_R\omega_I(\omega_R^2 + 2\omega_I^2)^{-1}]$$

- Astrophysical contamination and MHD variability

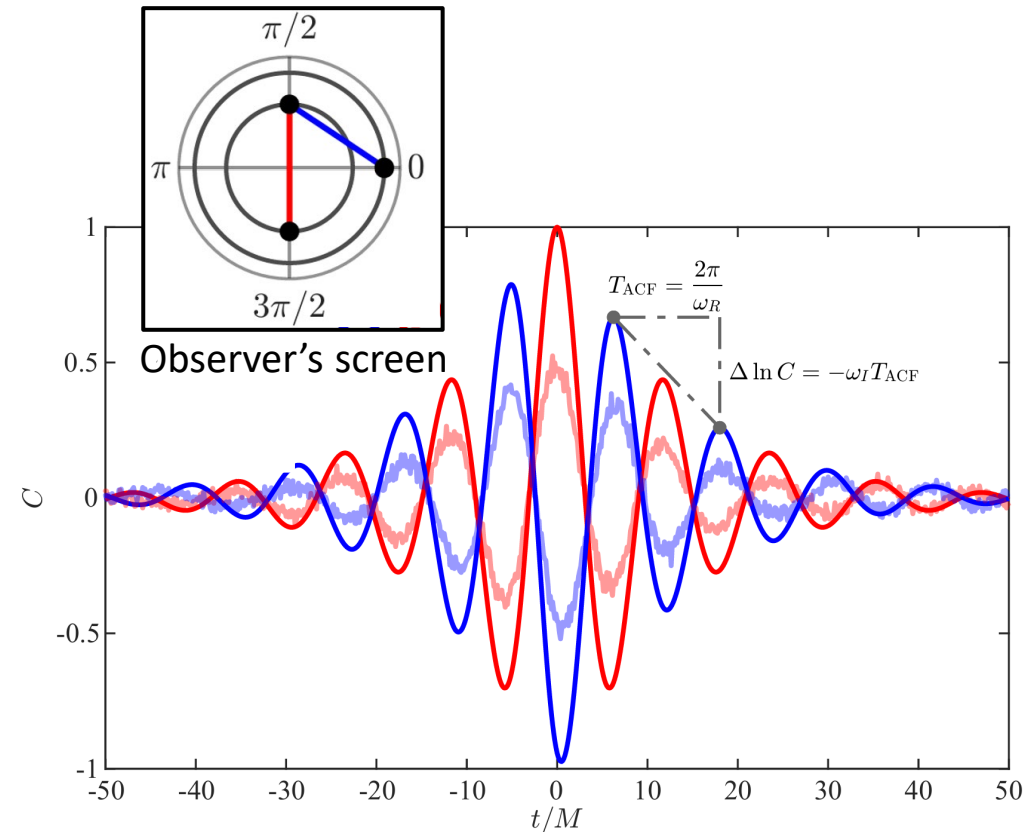
$$T_{MHD} \sim T_{ISCO} \sim \frac{GM}{c^3}$$

Source (plasma) effect : chromatic

QNM-induced effect : achromatic



Multifrequency observations



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

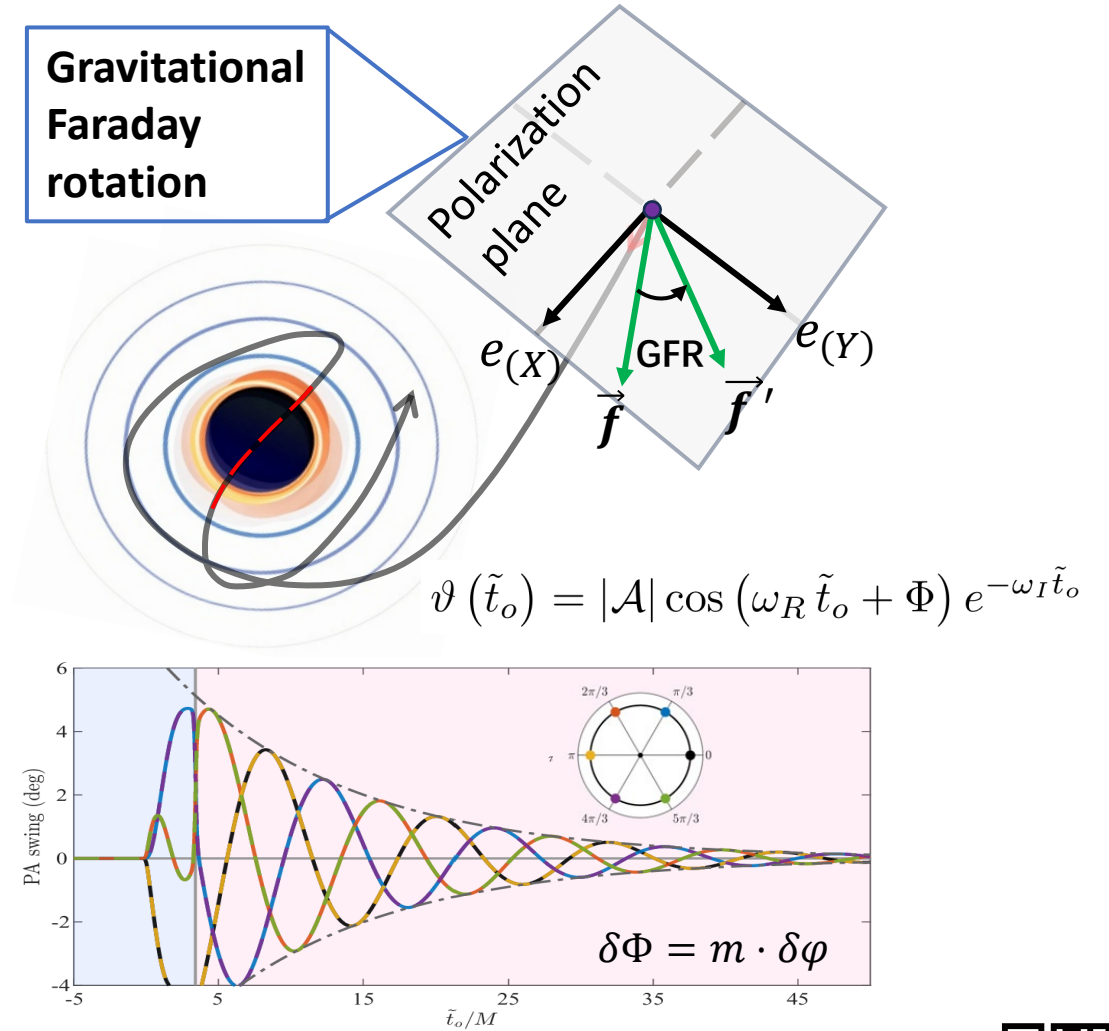
Summary

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 $\sim 10^\circ$

Future directions:

- △ Extending the frozen-in mechanism to general GW systems
- △ Inferring spacetime geometries from PA swings



Thank you! Questions and comments are welcome.

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The paper