Eikonal quasinormal modes of rotating black holes beyond GR: A window into extremality

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Based on

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Upcoming work w/ M. David and Guido Van der Velde

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Universitat de Barcelona

Institute for Basic Science - Daejeon

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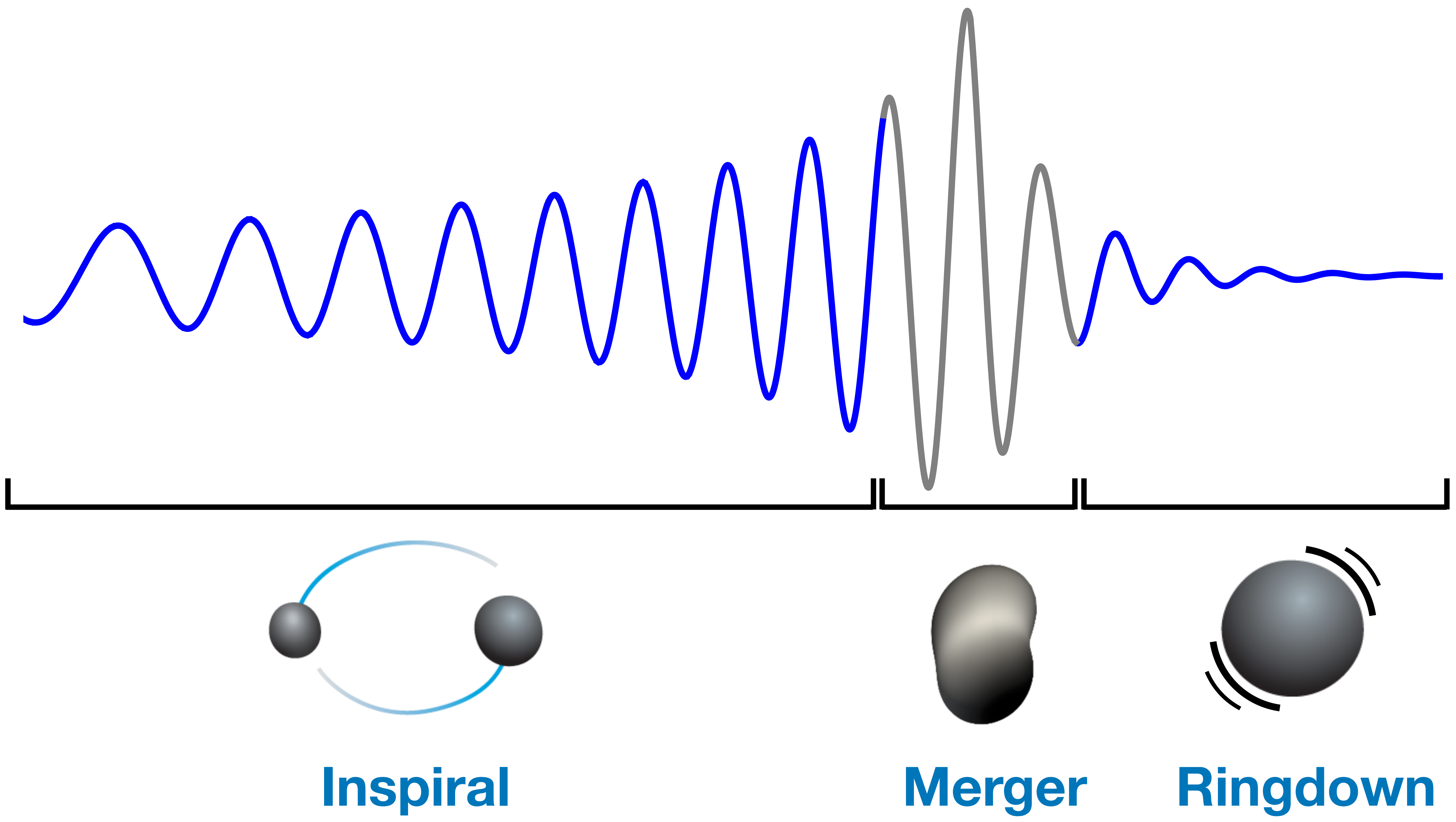
Introduction

Testing GR with black hole binaries



Einstein field equations

$$R_{\mu\nu} = 0\,?$$

Introduction

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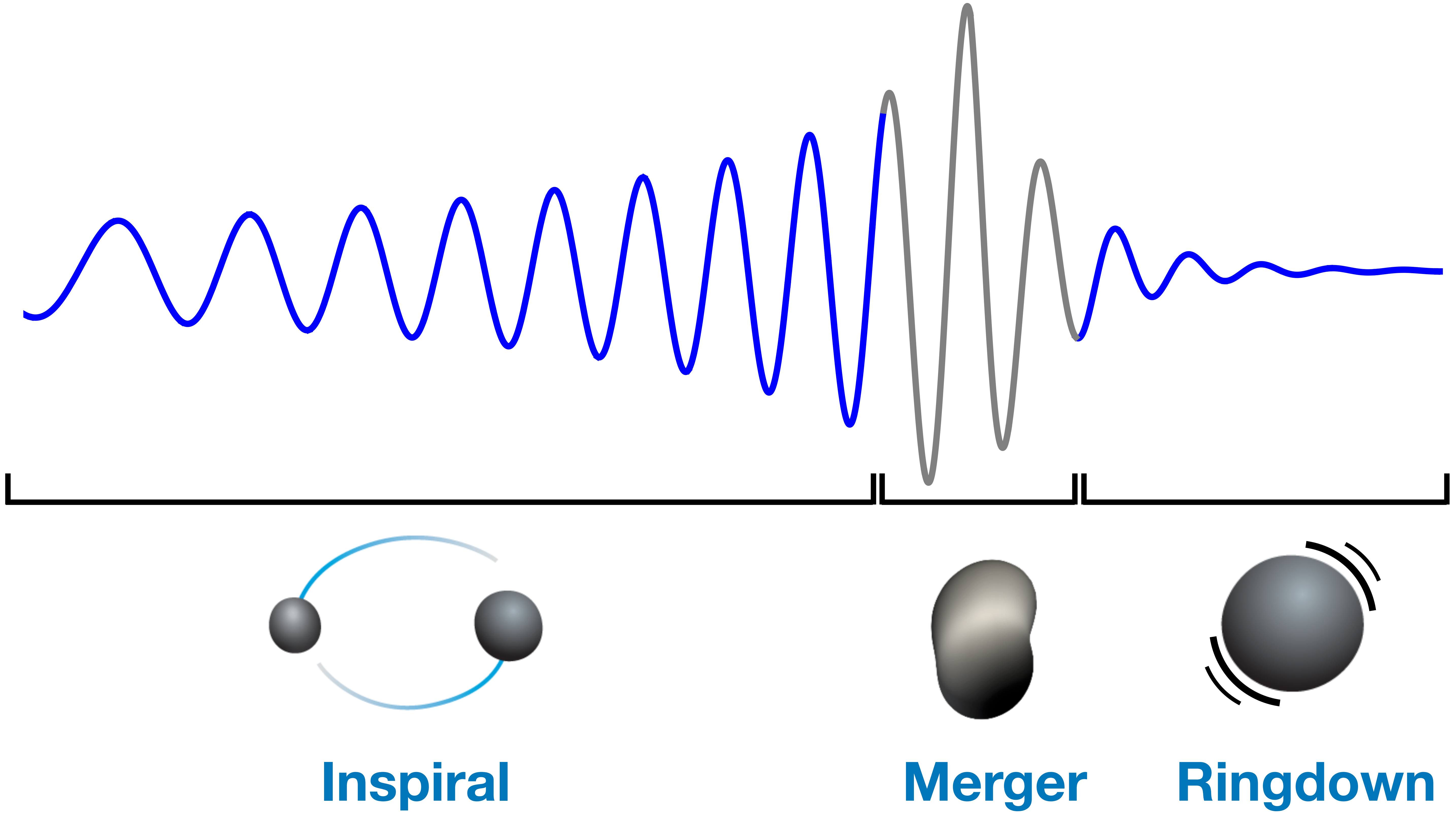


Einstein field equations

$$R_{\mu\nu} = 0\ ?$$

Gravity at a **new scale**

New physics?

Introduction

GR as an Effective Field Theory

Agnostic and **universal** approach to include new physics

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{|g|}\,\left[R + \ell^4\mathcal{R}^3 + \ell^6\mathcal{R}^4 + \ldots\right]$$

Einstein

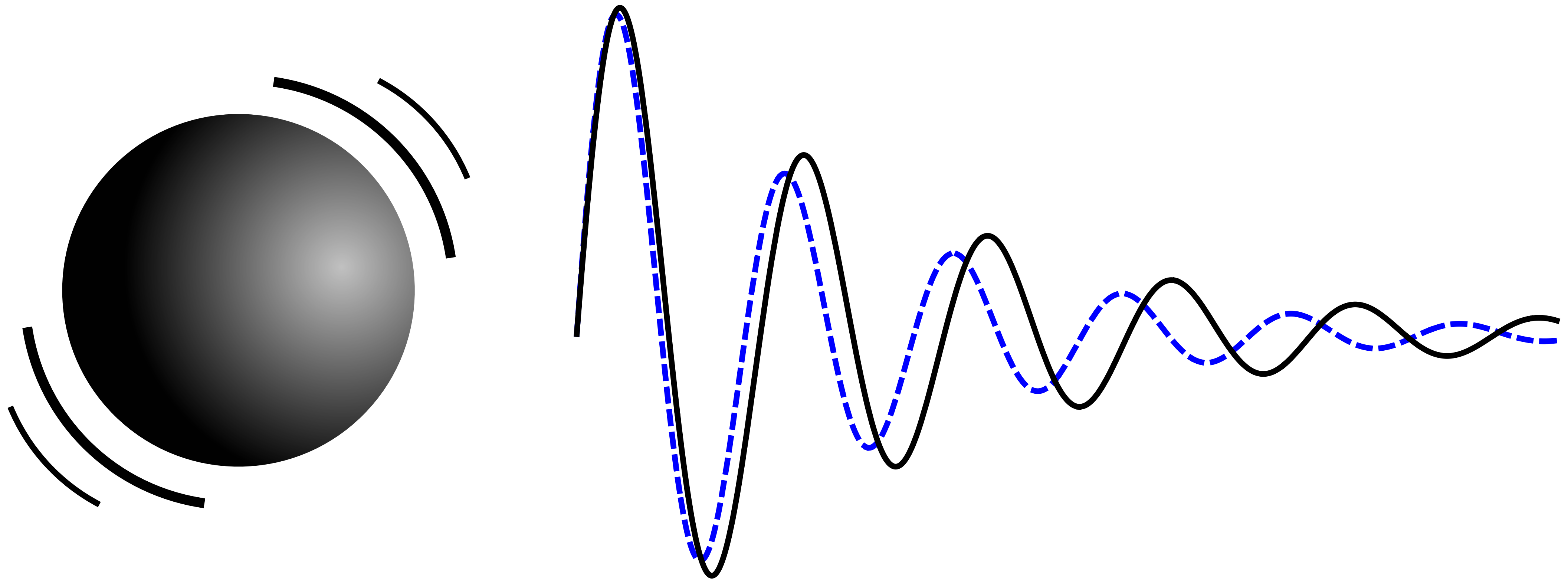
Beyond Einstein

ℓ: scale of new physics

- **Extreme gravity = new window** to observe beyond-GR effects
- **Potential for discovery**

Introduction

Ringdown as a test of new physics



$$\Psi = \sum_{l,m,n} A_{lmn} e^{-i\omega_{lmn} t}$$

QNM frequencies → underlying gravitational theory

Introduction

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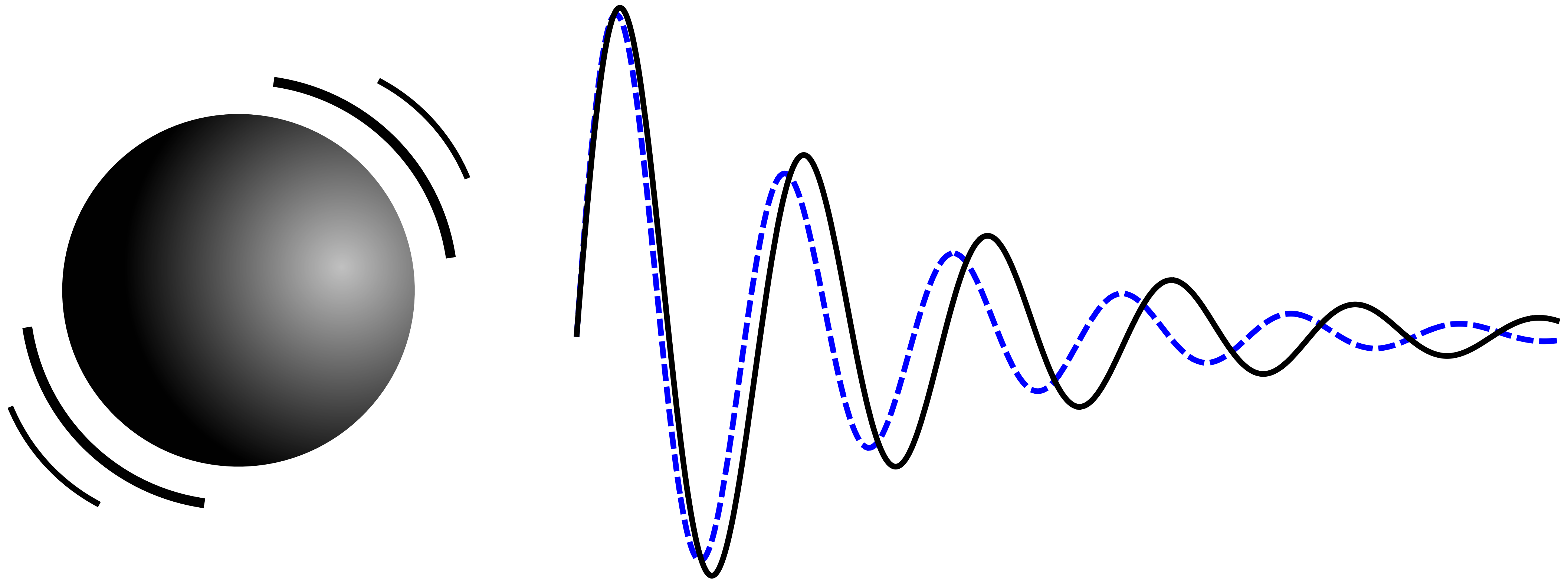

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QNM frequencies ➡ **underlying gravitational theory**

Challenge: QNMs of rotating black holes in theories beyond GR

$$\omega_{lmn} = \omega_{lmn}^{\rm Kerr} + \delta\omega_{lmn}$$

Alternative approach: parametrized framework [see Sebastian's talk!]

Introduction

BH perturbation theory

GR: perturbations of Kerr BHs described by the **Teukolsky equation**

$$\mathcal{O}(\delta\Psi_4) = 0$$

- Kerr is Petrov D
- Hidden symmetries (Killing tensor)

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Beyond GR: many problems

- Background not known analytically
- No Petrov D $\longrightarrow$ No Teukolsky equation
- No separability

QNMs beyond GR

Modified Teukolsky equation

[Li, Wagle, Chen, Yunes '22]
[Hussain, Zimmerman '22]
[PAC, Fransen, Hertog, Maenaut '23]

$$\mathcal{O}^{(0)}(\delta\Psi_4) + \mathcal{O}^{(1)}(\delta\Psi_n, \delta e^a, \delta\gamma_{abc}) = 0$$

QNMs beyond GR

Modified Teukolsky equation

[PAC, Fransen, Hertog, Maenaut ’23]
[PAC, Capuano, Franchini, Maenaut, Völkel ’24]

Result for the EFT:

$$\Delta^{1-s}\frac{d}{dr}\left[\Delta^{1+s}\frac{dR}{dr}\right] + \left(V + \delta V^{\pm}\right) R = 0$$

$$\delta V^{\pm} = \frac{A_{-2}}{r^2} + A_0 + A_1 r + A_2 r^2 \,, \qquad A_k = \sum_{n=0}^{n_{\max}} A_{k,n}\chi^n$$

← Spin expansion

QNMs beyond GR

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- Correction is different for each polarization $\delta V^{\pm}$
- QNM frequencies from **generalized Leaver** or **eigenvalue perturbation**

QNMs beyond GR

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Alternative: spectral decomposition of the modified Einstein equations

[Chung, Yunes '24; Blázquez-Salcedo+ '24]

QNMs beyond GR

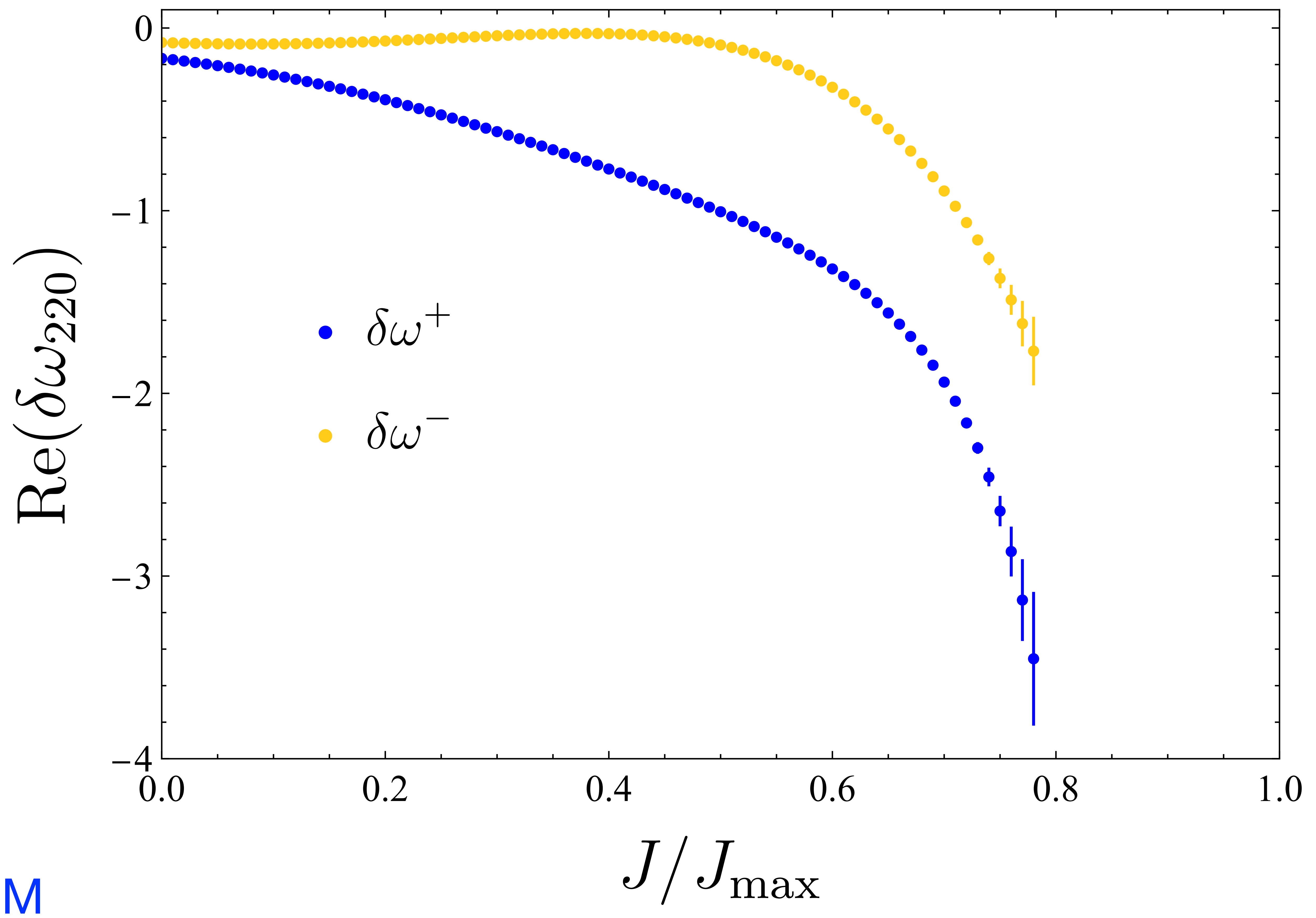
Example: quartic correction

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{|g|}\left[R + \epsilon\left(R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}\right)^2\right]$$

$$\epsilon \sim \ell^6$$

$$\omega^{\pm} = \omega^{\text{Kerr}} + \frac{\epsilon}{M^7}\delta\omega^{\pm}$$

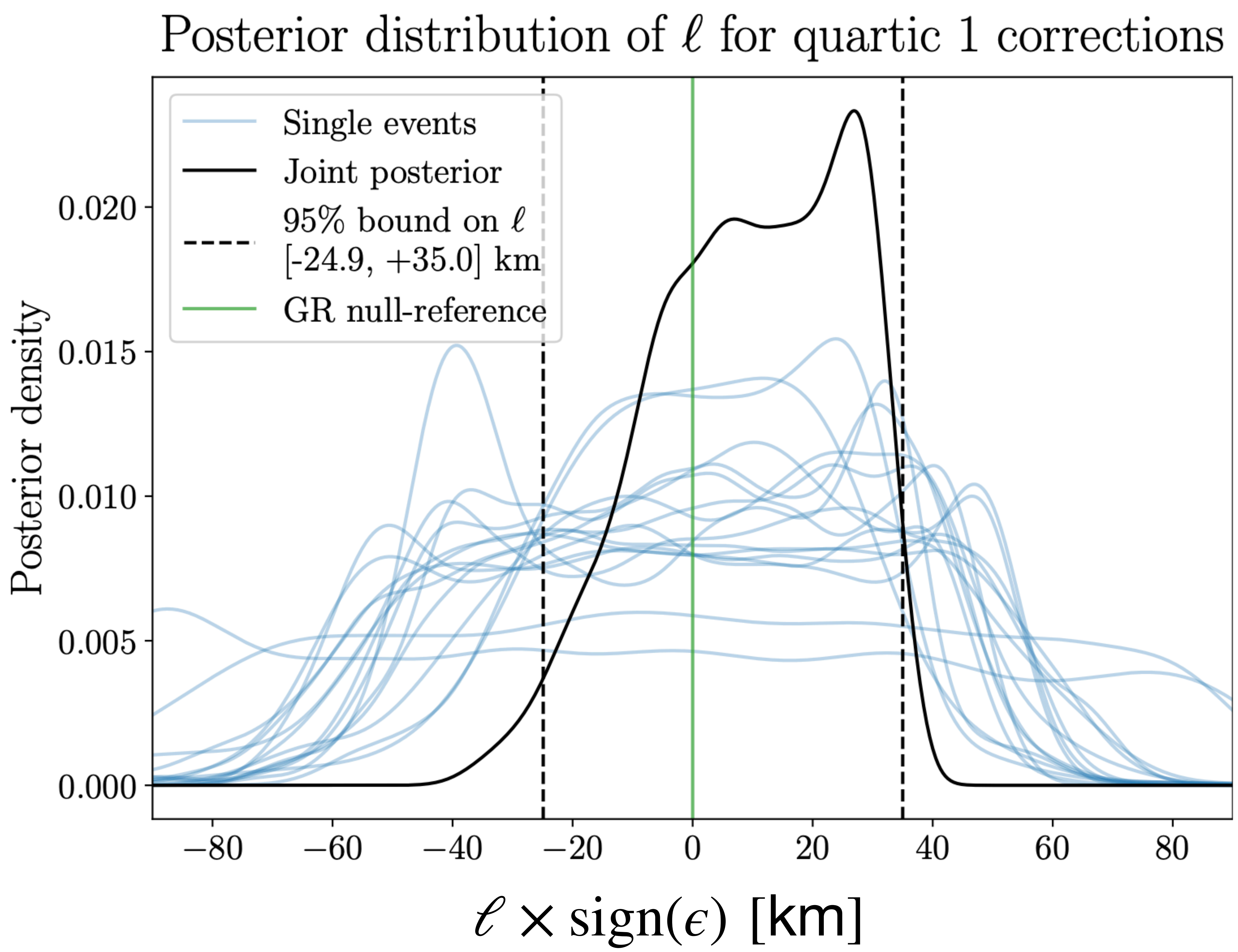
Results at order $\mathcal{O}(\chi^{18})$



Complete results in github.com/pacmn91/BeyondKerrQNM

QNMs beyond GR

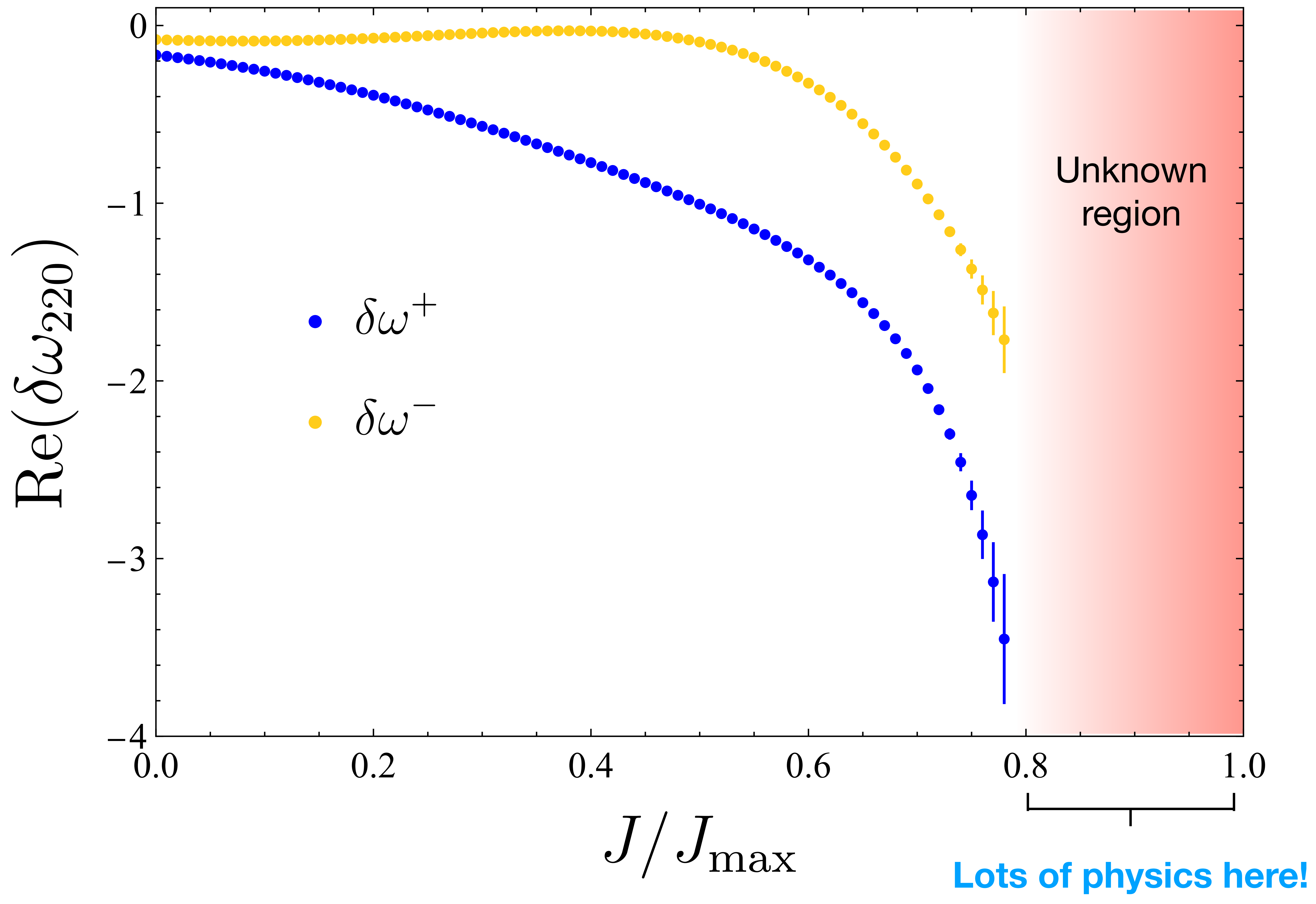
LVK constraints on quartic corrections



[Maenaut+’24]

QNMs beyond GR

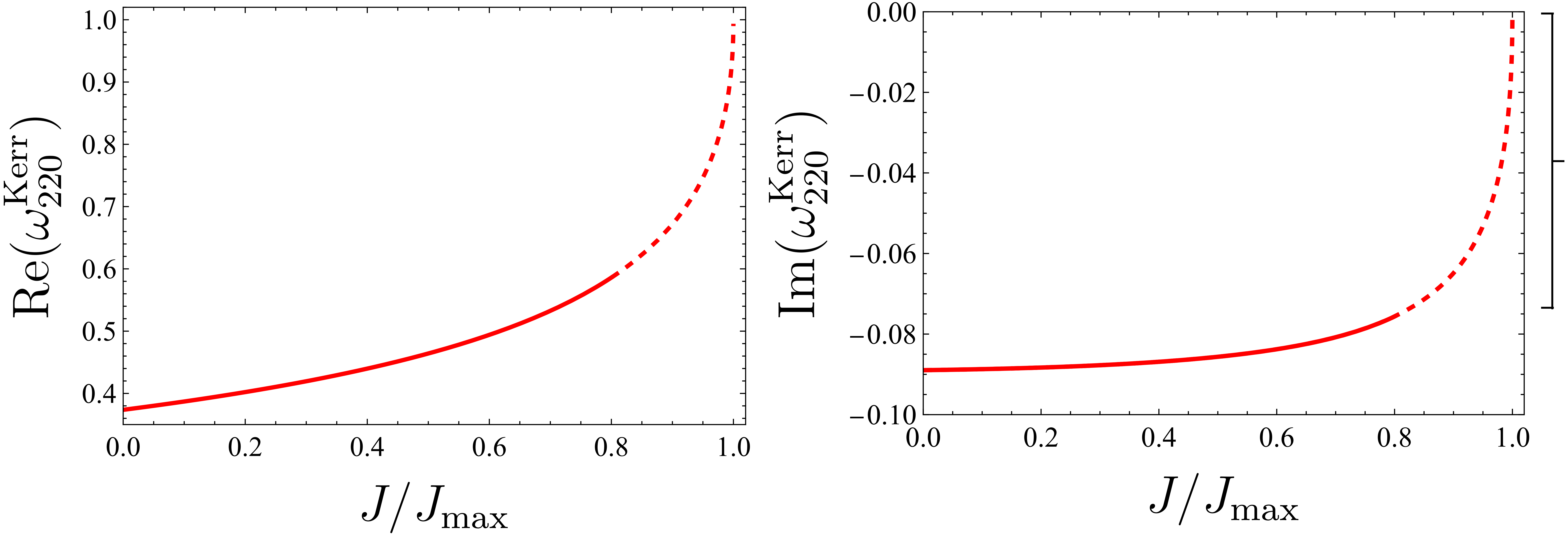
Highly rotating black holes?



QNMs beyond GR

Highly rotating black holes?

For Kerr, most of the variation happens in the large rotation region



At 80% rotation, we are missing all this

QNMs beyond GR

High-rotation regime is still out of reach

- Spectral methods have not been able to probe it either
- Relevant for BH spectroscopy with 3G detectors
- We should investigate it!

Plan of the talk

1. Special subset of theories

2. New way of obtaining QNMs (in the eikonal limit)

3. Results for QNMs with arbitrary rotation

Part 1: Isospectral EFTs

EFT extension of GR

$$S_{\text{EFT}} = \frac{1}{16\pi}\int d^4x\sqrt{|g|}\left[R + \ell^4\left(\lambda_{\text{ev}}R_3 + \lambda_{\text{odd}}\tilde{R}_3\right) + \ell^6\left(\epsilon_1 R_2^2 + \epsilon_2 \tilde{R}_2^2 + \epsilon_3 R_2 \tilde{R}_2\right) + \ldots\right]$$

Two cubic invariants: $R_3 = R_{\mu\nu}{}^{\rho\sigma}R_{\rho\sigma}{}^{\delta\gamma}R_{\delta\gamma}{}^{\mu\nu}, \quad \tilde{R}_3 = R_{\mu\nu}{}^{\rho\sigma}R_{\rho\sigma}{}^{\delta\gamma}\tilde{R}_{\delta\gamma}{}^{\mu\nu}$

Three quartic invariants: formed from $R_2 = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}, \quad \tilde{R}_2 = R_{\mu\nu\rho\sigma}\tilde{R}^{\mu\nu\rho\sigma}$

Dual Riemann tensor $\tilde{R}_{\mu\nu\rho\sigma} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}R^{\alpha\beta}{}_{\rho\sigma}$

$(\lambda_{\text{ev}}, \epsilon_1, \epsilon_2)$ even parity $\qquad (\lambda_{\text{odd}}, \epsilon_3)$ odd parity

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- Low l: $\delta V_l^{+} \neq \delta V_l^{-}$ ➡ No isospectrality for low l modes

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- We look at **“eikonal” modes** $l \to \infty$

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- We look at **"eikonal" modes** $l \to \infty$

Cubic theories:

$$\delta V_l^{(6)\pm} = \pm\sqrt{\lambda_{\rm ev}^2+\lambda_{\rm odd}^2}\,\frac{360 l^2 M(7M-3r)\Delta}{r^6}+\lambda_{\rm ev} l^2 \delta V_0$$

➡ No isospectral cubic theory

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Quartic theories:

$$\delta V_l^{(8)\pm} = -\frac{576 l^4 M^2 \Delta}{r^8}\left(\epsilon_1+\epsilon_2 \pm \sqrt{(\epsilon_1-\epsilon_2)^2+\epsilon_3^2}\right)$$

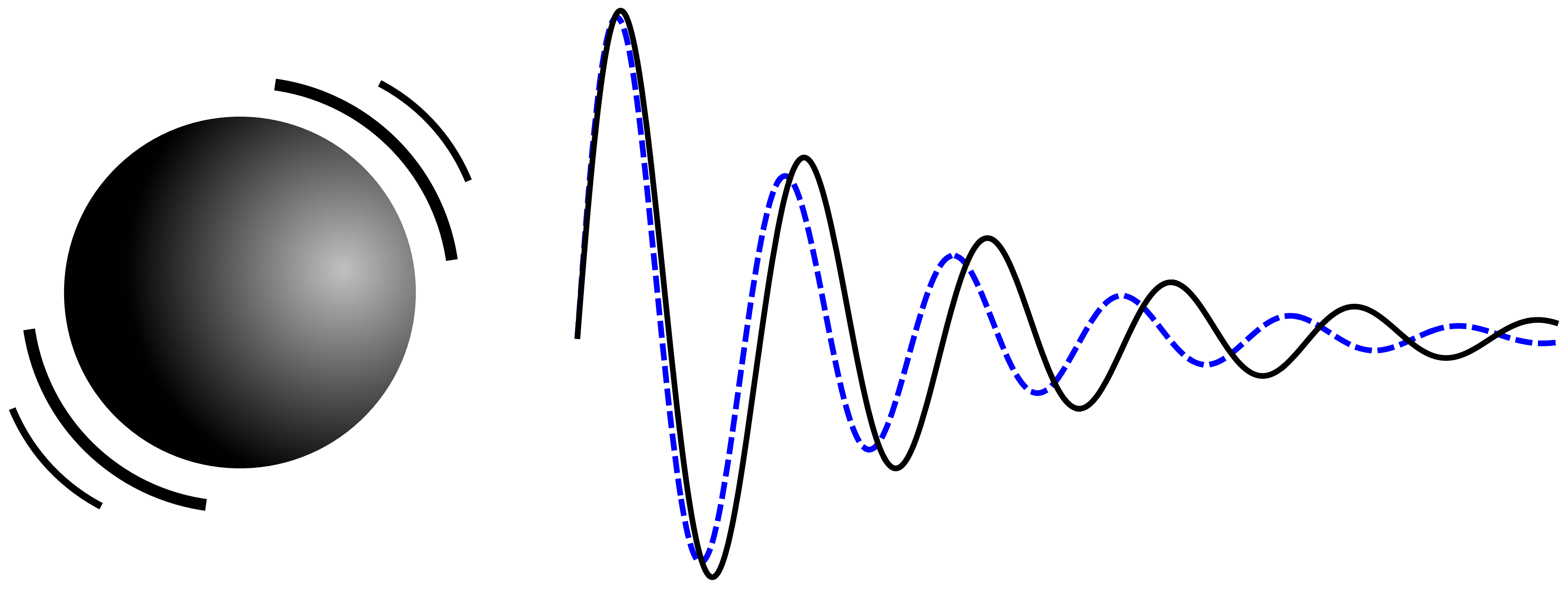
➡ **Isospectral theory!** $\epsilon_1=\epsilon_2\,,\ \epsilon_3=0$

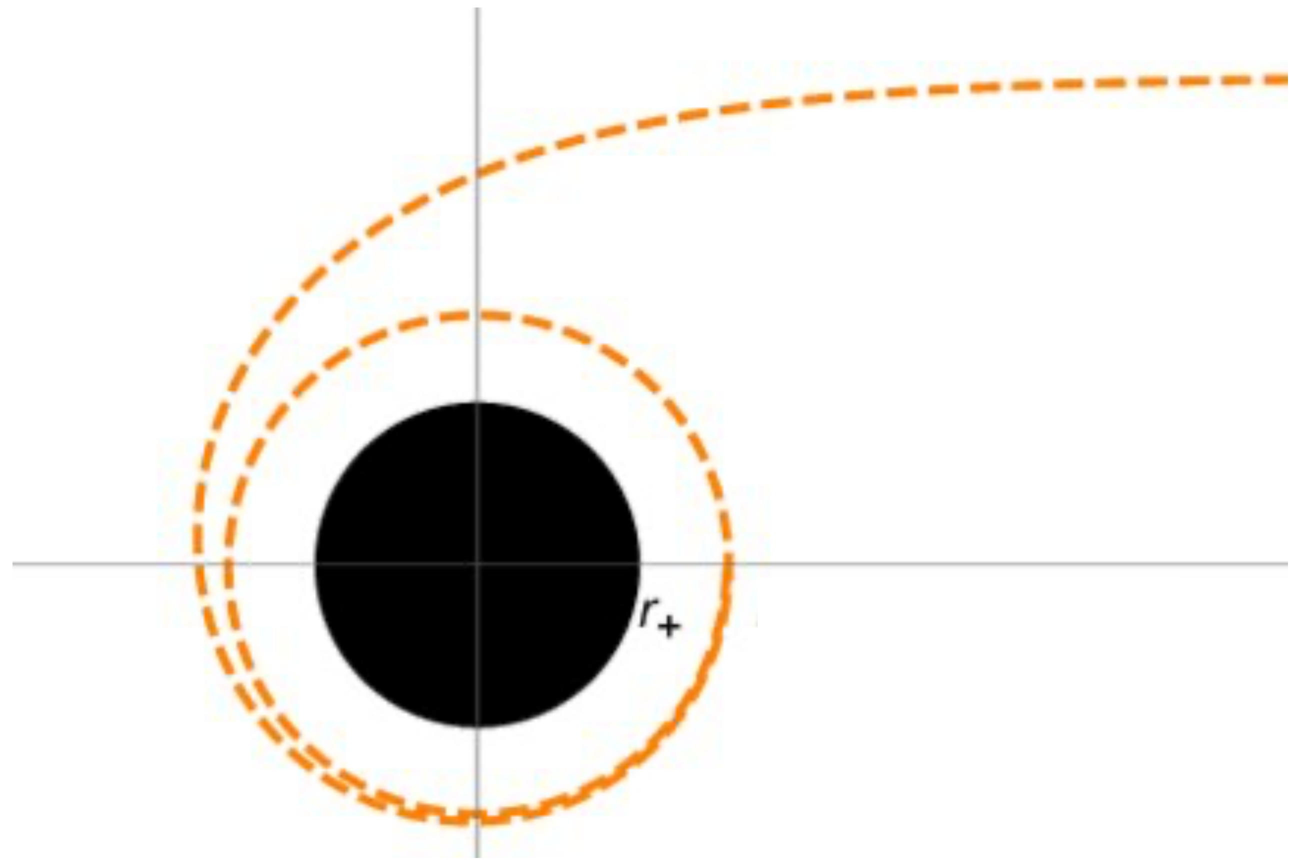
Eikonal QNMs and photon sphere

In GR eikonal QNMs are related to **unstable photon sphere geodesics**

[Cardoso+ '08] [Yang+ '12]

Real frequency	⟷	Orbital frequency
Damping time	⟷	Lyapunov exponent





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Real frequency ⟷ Orbital frequency

Damping time ⟷ Lyapunov exponent

Beyond GR: Generalized correspondence

QNMs ⟷ Unstable **GW *orbits***

(not geodesic!)

Something special about the theory $R_2^2 + \tilde{R}_2^2$??

Dispersion relation of GWs

Geometric optics limit $k_\mu \to \infty$

GR: $$G^L_{\mu\nu} \sim -\frac{1}{2}\nabla^2 h_{\mu\nu} = 0 \quad \Rightarrow \quad k^2 = 0$$

Dispersion relation of GWs

Geometric optics limit $k_\mu \to \infty$

Quartic theories:

$$k^2 = 64\epsilon_1 (S_{\mu\nu} e^{\mu\nu})^2 + 64\epsilon_2 (\tilde{S}_{\mu\nu} e^{\mu\nu})^2 + 64\epsilon_3 (\tilde{S}_{\mu\nu} e^{\mu\nu})(S_{\alpha\beta} e^{\alpha\beta})$$

$S_{\mu\nu} = k^\rho k^\sigma R_{\mu\rho\sigma\nu}\,, \quad \tilde{S}_{\mu\nu} = k^\rho k^\sigma \tilde{R}_{\mu\rho\sigma\nu}\,, \quad e_{\mu\nu}$ = polarization tensor

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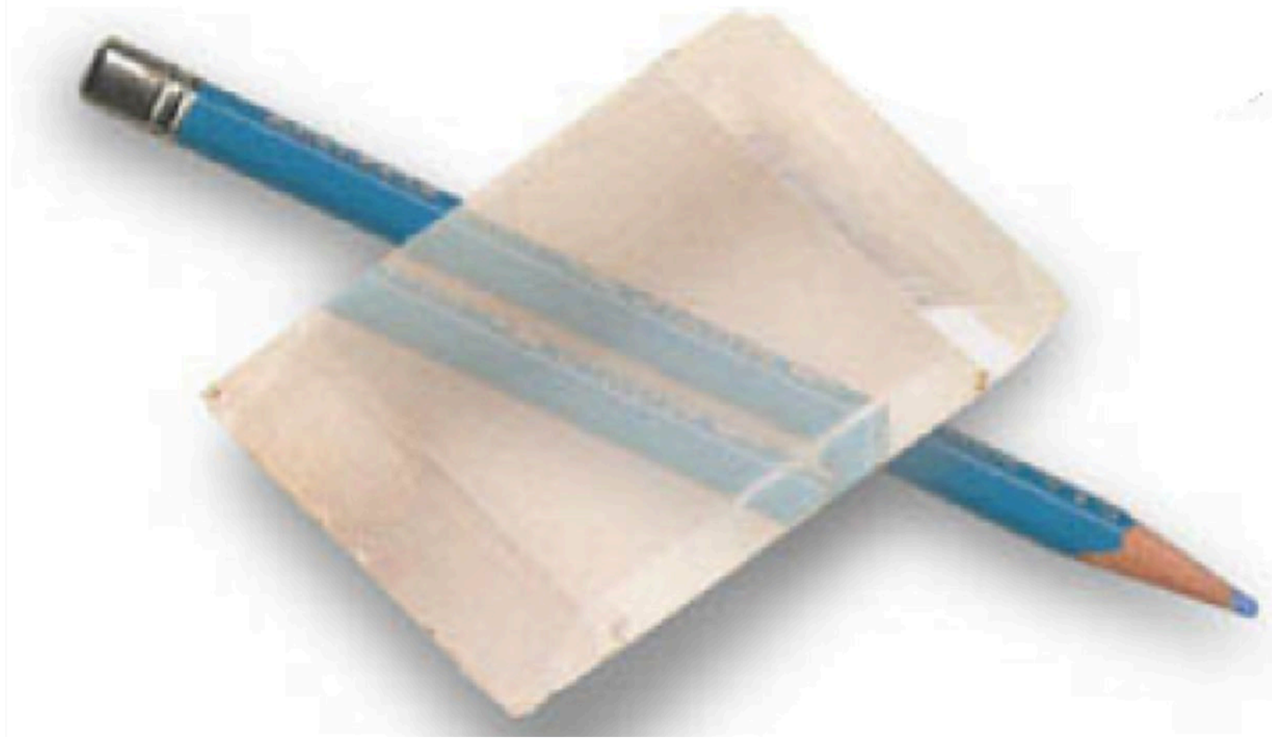
- GWs not null, $k^2 \neq 0$
- Dispersion relation depends on polarization → birefringence



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- GWs not null, $k^2 \neq 0$
- Dispersion relation depends on polarization ➡ **birefringence**
- For the theory $\epsilon_1 = \epsilon_2\,, \epsilon_3 = 0$ we find

$$k^2 = 64\epsilon_1 S_{\mu\nu}S^{\mu\nu}$$

Non-birefringent theory!!

Summary

$$S_{\rm iso} = \frac{1}{16\pi G}\int d^4x\sqrt{|g|}\left[R + \epsilon\left(R_2^2 + \tilde{R}_2^2\right)\right]$$

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1. Non-birefringent dispersion relation
2. Isospectral eikonal QNMs

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} ***Isospectral EFTs***

Generalizable to higher orders

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} ***Isospectral EFTs***

Generalizable to higher orders

Isospectrality related to String Theory

$$S_{\text{iso}} = S_{II}^{\text{string theory}}, \qquad \epsilon = \frac{\zeta(3)}{256}\alpha'^3$$

Supersymmetry? Duality? Born-Infeld-like gravity?

Part 2: BH perturbations in the isospectral EFT

Master equation for perturbations

Dispersion relation for GWs

$$k^2 = 64\epsilon R^{\lambda\ \ \eta}_{\ \ \alpha\ \ \beta} R^{\rho\alpha\sigma\beta} k_\lambda k_\eta k_\rho k_\sigma$$

Intuitive idea: **effective scalar equation** that yields the same dispersion relation

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$$\left(\nabla^2 + 64\epsilon R^{\lambda}{}_{\alpha}{}^{\eta}{}_{\beta} R^{\rho\alpha\sigma\beta} \nabla_\lambda \nabla_\eta \nabla_\rho \nabla_\sigma \right) \Phi = 0$$

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More rigorously: $\mathscr{D}^2 h^{\mathrm{TT}}_{\mu\nu} = 0$ (diagonal operator=isospectrality)

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Remark: it is enough to consider the **Kerr background** (w/o corrections)

Solving the equation

Step 1: decompose the field in spheroidal harmonics

$$\Phi = e^{-i\omega t + im\varphi} \left[S_{lm}(x; a\omega) R_{lm}(r) + \epsilon \sum_{l' \neq l} S_{l'm}(x; a\omega) R_{lm}(r) \right]$$

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Step 2: project the equation on S_{lm}

$$\int_{-1}^{1} dx S_{lm}(x;a\omega)(r^2 + a^2x^2)D^2\Phi = 0$$

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$$\frac{d}{dr}\left[\Delta \frac{dR_{lm}}{dr}\right] + (V + \delta V)\, R_{lm} = 0$$

$$\delta V = 1152\epsilon M^2 \big(\underbrace{A_{lm} - 2ma\omega + (a\omega)^2}_{\sigma_{lm}}\big)^2 \int_{-1}^{1} dx \frac{S_{lm}(x;a\omega)^2}{2\pi(r^2 + a^2x^2)^4}$$

Solving the equation

Step 3: simplify the potential

$$\delta V = 1152\epsilon M^2\sigma_{lm}^2\int_{-1}^{1}dx\frac{S_{lm}(x;a\omega)^2}{2\pi(r^2+a^2x^2)^4}$$

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$$\delta V = \frac{576\epsilon M^2\sigma_{lm}^2}{K(-k)} \int_0^{\pi} \frac{d\theta}{(r^2 + a^2x_0^2 \sin^2\theta)^4 \sqrt{1 + k\sin^2\theta}}$$

$$k = \frac{u^2x_0^2(1 - x_0^2)}{\mu^2 - u^2(1 - x_0^2)}, \quad \mu^2 - (1 - x_0^2)\left(\frac{A_{lm}}{l^2} + u^2x_0^2\right) = 0, \quad \mu = \frac{m}{l}, \quad u = \frac{a\omega}{l}$$

Solving the equation

QNMs through the WKB formula

$$\frac{d^2R}{dr_*^2} + UR = 0$$

$$\frac{d}{dr_*} = \frac{\Delta}{r^2 + a^2}\frac{d}{dr}\,, \qquad U = \frac{\Delta}{(r^2 + a^2)^2}(V + \delta V)$$

Solving the equation

QNMs through the WKB formula

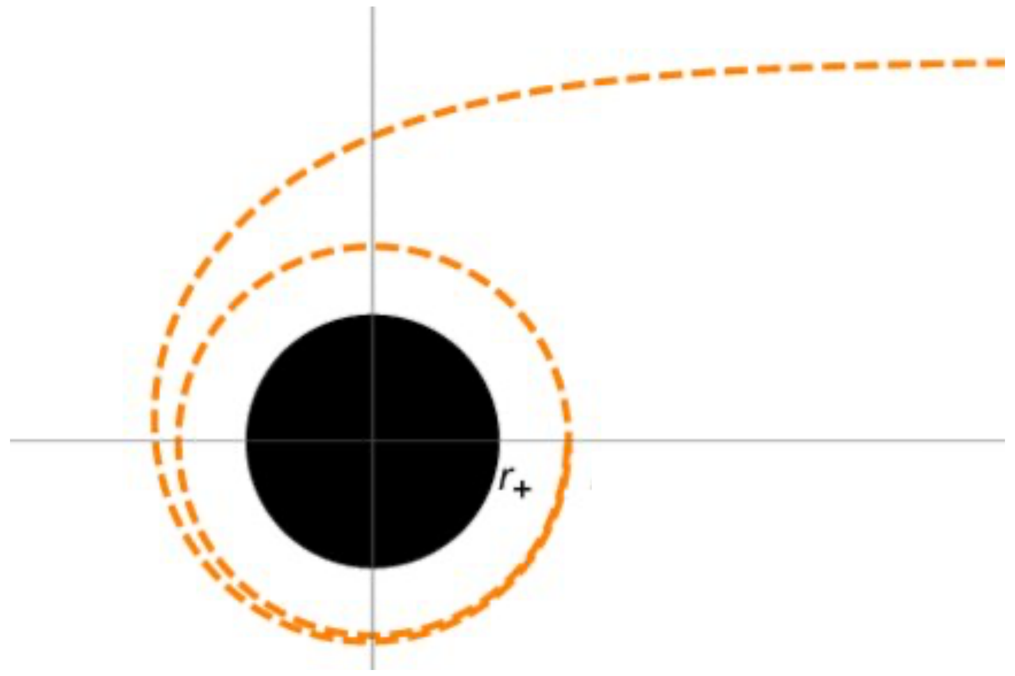
$$\boxed{\frac{d^2R}{dr_*^2} + UR = 0} \qquad \frac{d}{dr_*} = \frac{\Delta}{r^2+a^2}\frac{d}{dr}\,, \qquad U = \frac{\Delta}{(r^2+a^2)^2}(V+\delta V)$$

Real part of the frequency: $U(r_0) = \left.\frac{dU}{dr}\right|_{r_0,\omega_R} = 0$

Imaginary part of the frequency: $\omega_I = -\left(n+\frac{1}{2}\right)\left.\frac{\sqrt{2\partial^2_{r_*}U}}{\partial_\omega U}\right|_{r_0,\omega_R}$

Alternative way: geometric optics

Modified geodesic trajectories



$$k^2 = 64\epsilon R^{\lambda\ \ \eta}_{\ \ \alpha\ \ \beta} R^{\rho\alpha\sigma\beta} k_\lambda k_\eta k_\rho k_\sigma \quad \longrightarrow \quad \frac{dx^\mu}{d\lambda} = k^\mu$$

Application for equatorial orbits (corresponding to l=m QNMs**)**

- Orbital frequency = real part of QNM frequency!
- Lyapunov exponent: connection with imaginary part is subtle

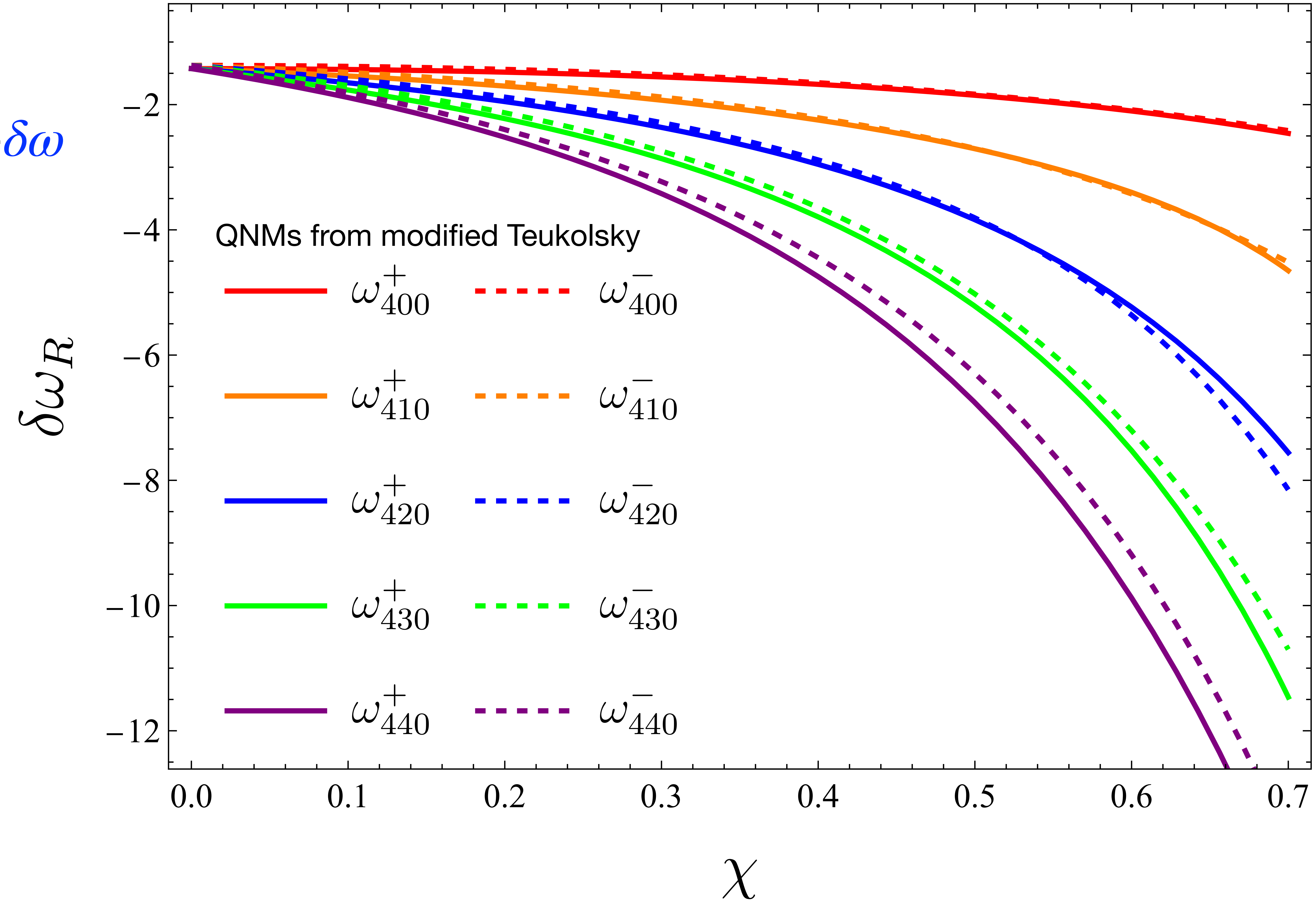
Different notions of Lyapunov exponents — only one relates to ω_I

Part 3: Results for QNMs

Comparison with modified Teukolsky

Real part

$$\omega = \omega^{\text{Kerr}} + \frac{\epsilon}{M^7}\delta\omega$$



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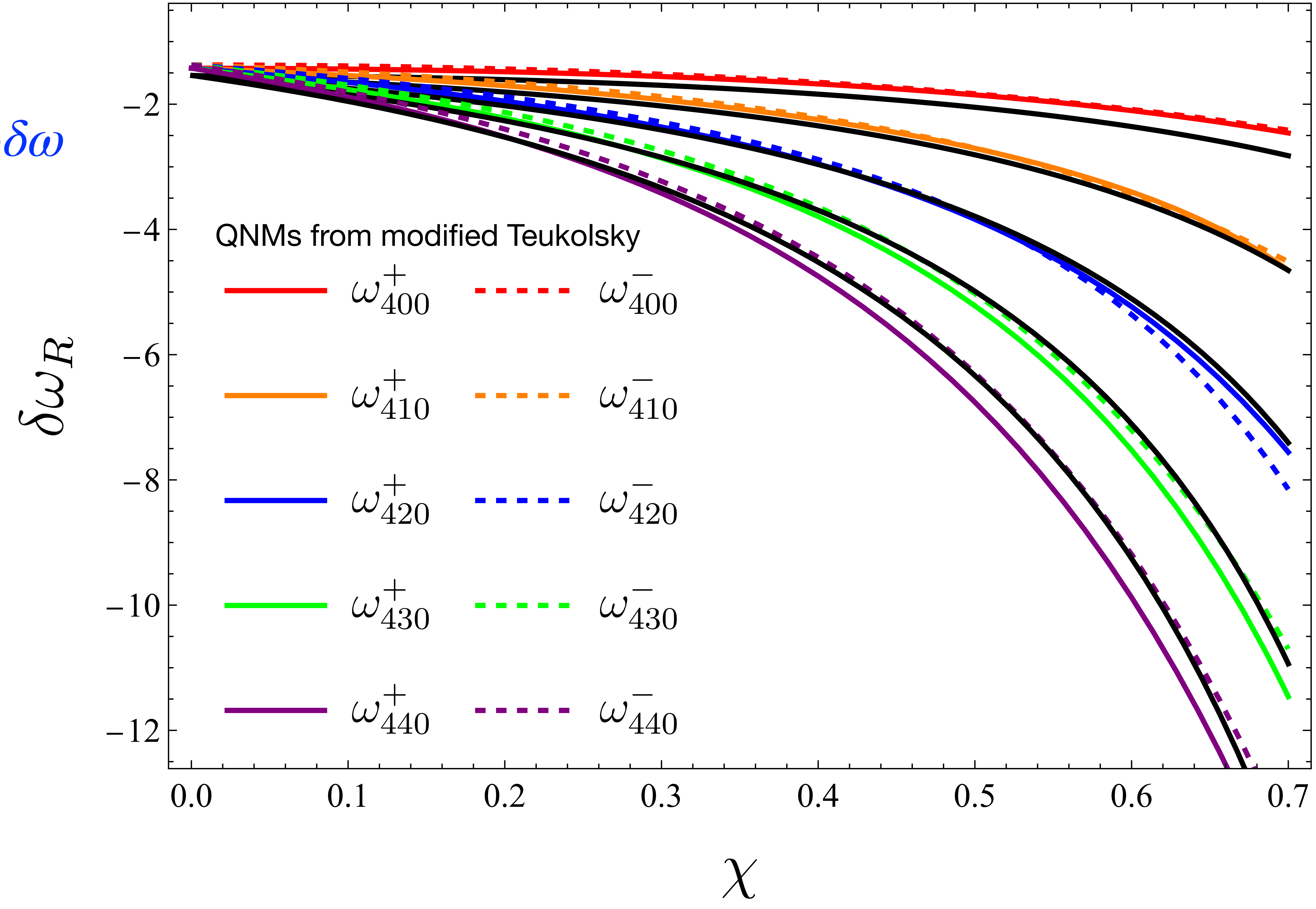
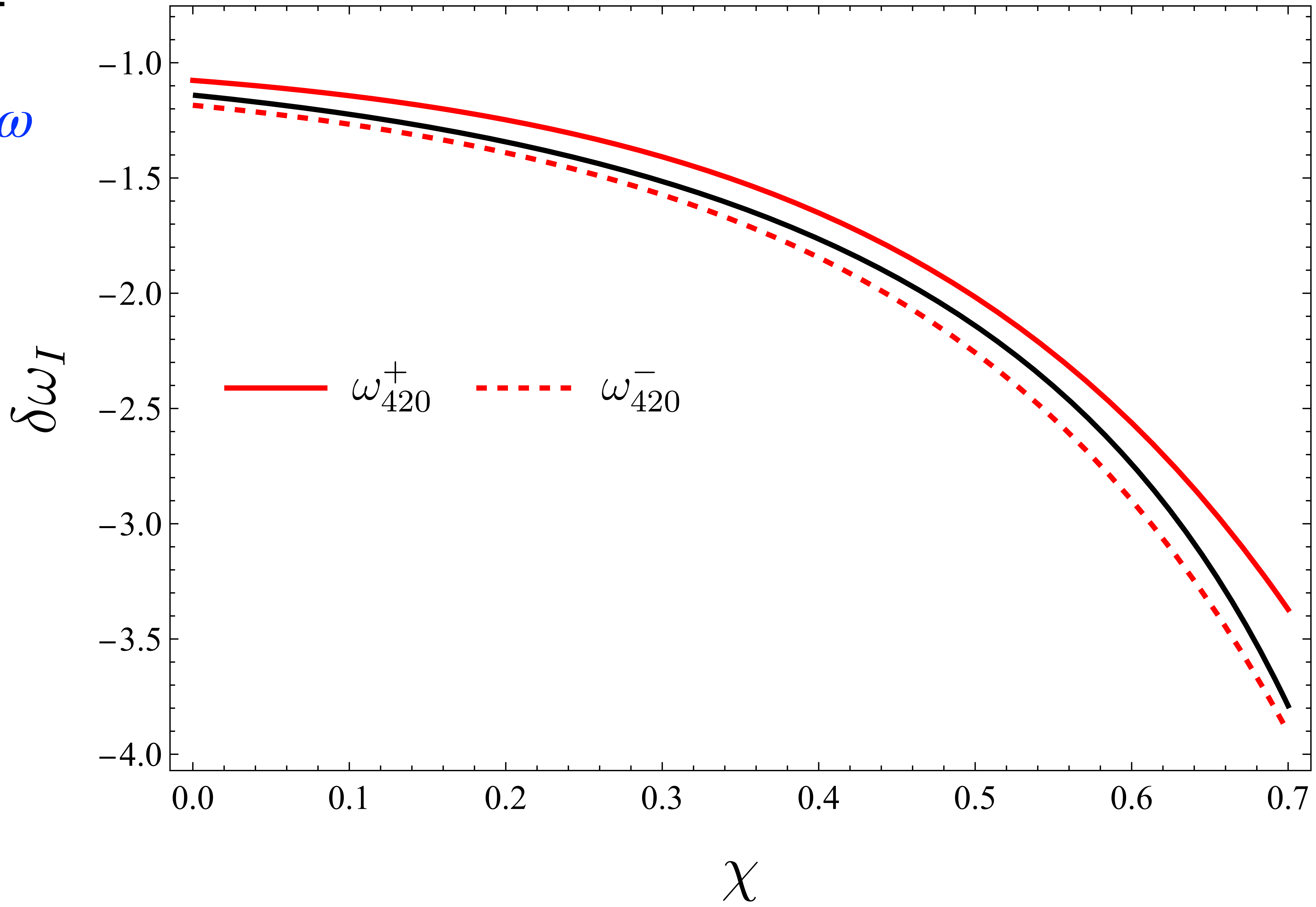


Eikonal formula

Comparison with modified Teukolsky

Imaginary part

$$\omega = \omega^{\text{Kerr}} + \frac{\epsilon}{M^7}\delta\omega$$



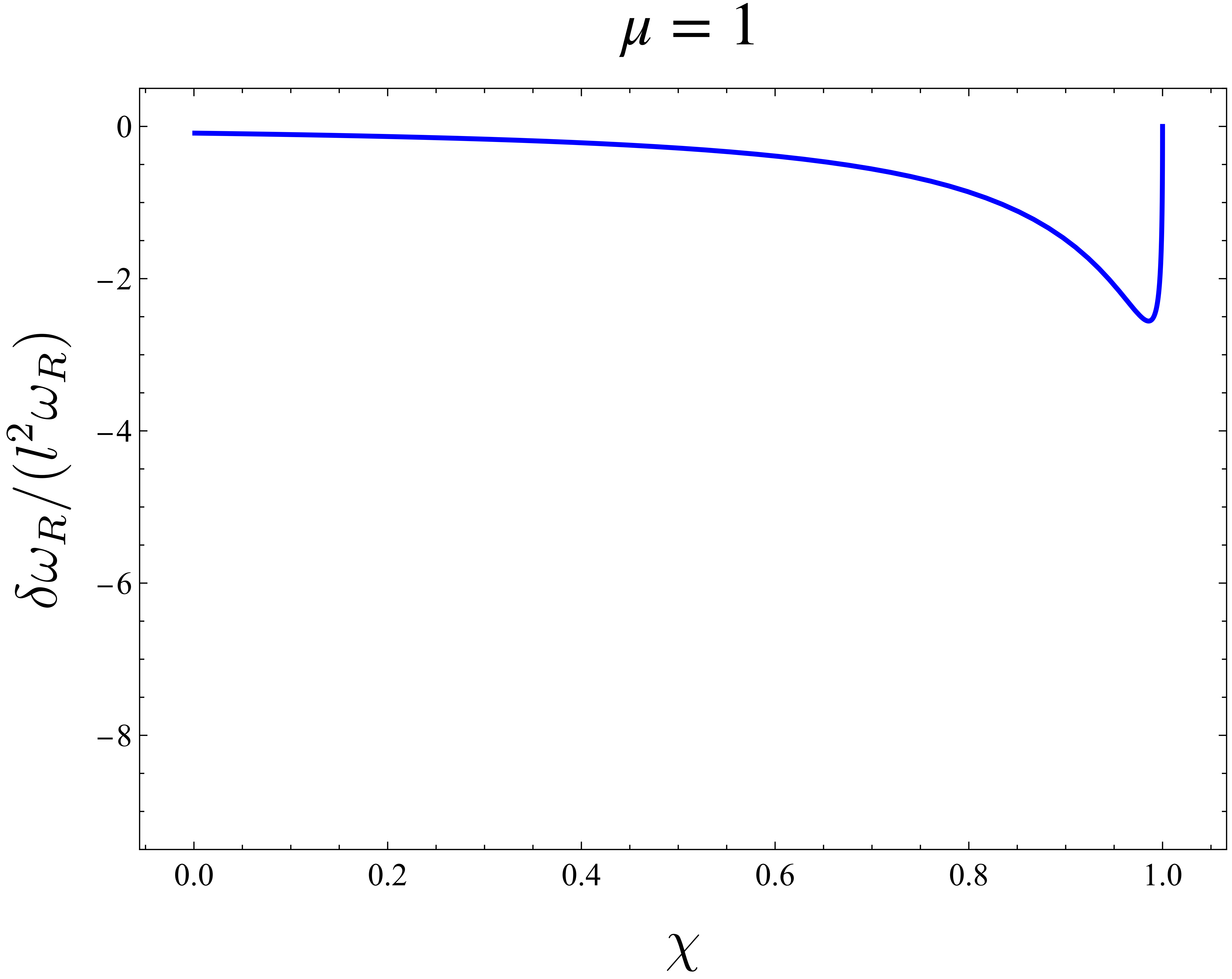
Eikonal formula

Results for high rotation

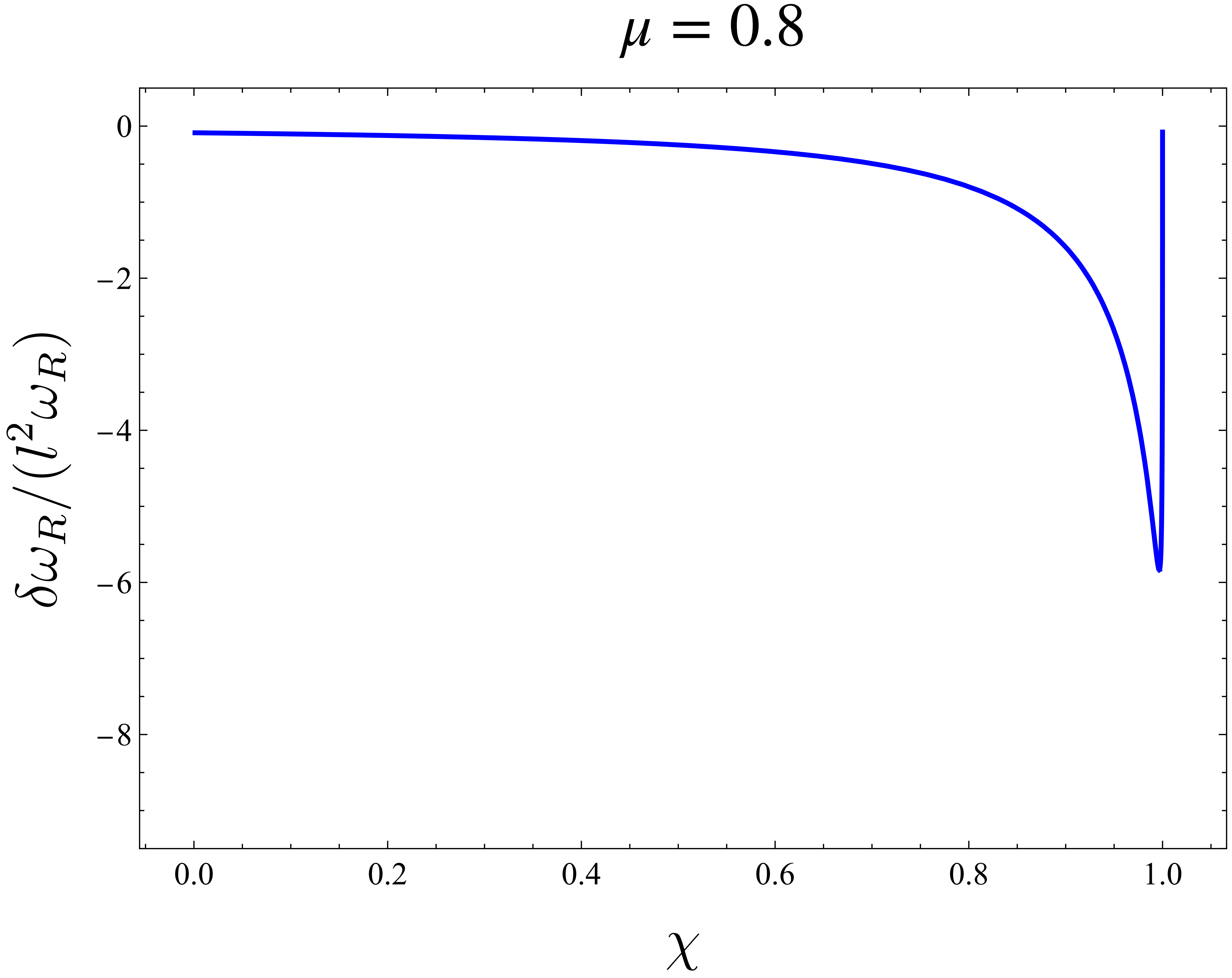
Generalities

- Result depends on $\mu = m/\ell$ and on $\chi = J/J_{\rm max}$
- For $\mu > \mu_{\rm thr} \approx 0.74$ we have "**zero damping modes**" in the extremal limit
- For $\mu < \mu_{\rm thr}$ the modes are damped
- There are also ZDMs for $\mu < \mu_{\rm thr}$, but these are not captured by the WKB analysis [Yang+ '12, '13]

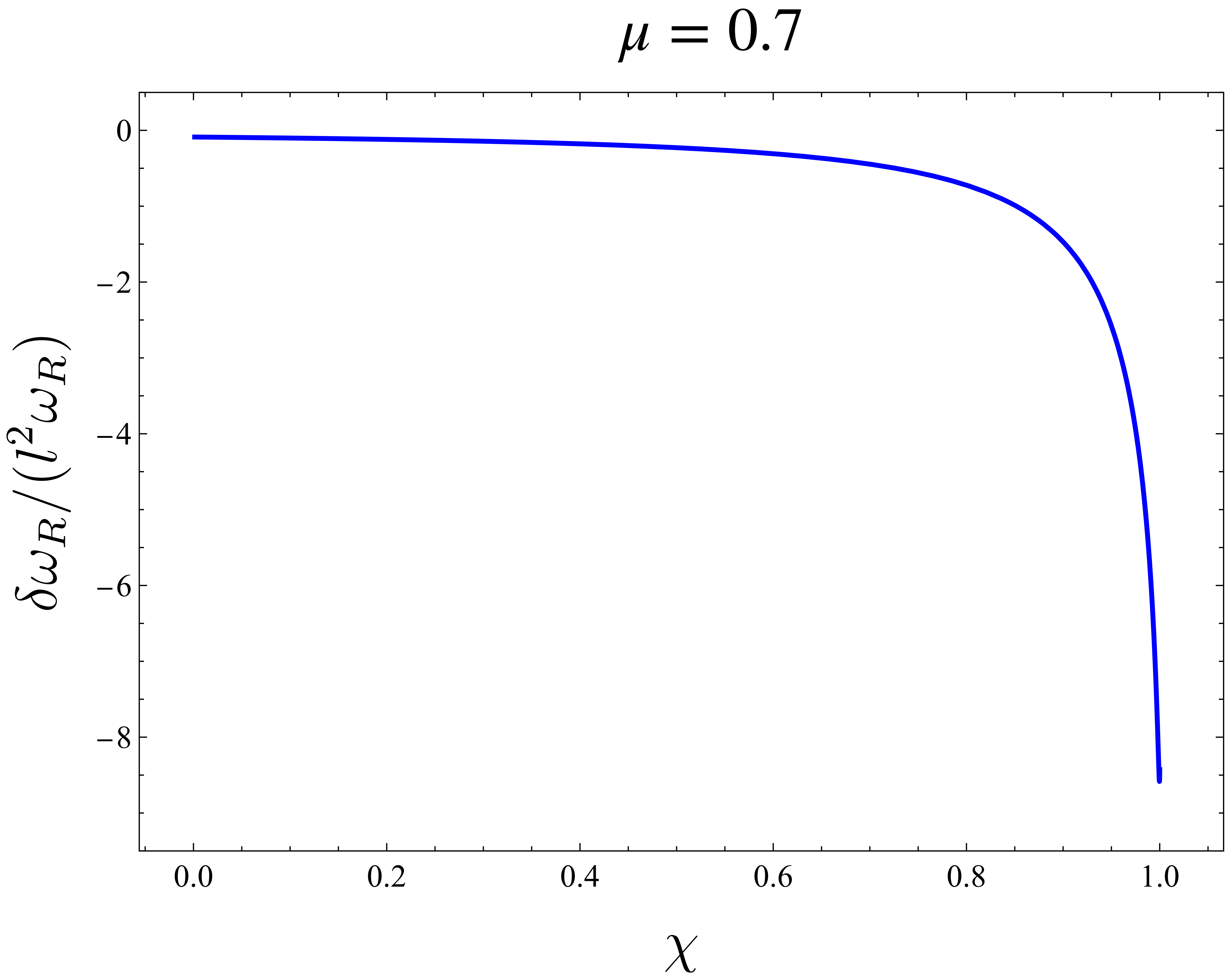
Real part: relative correction



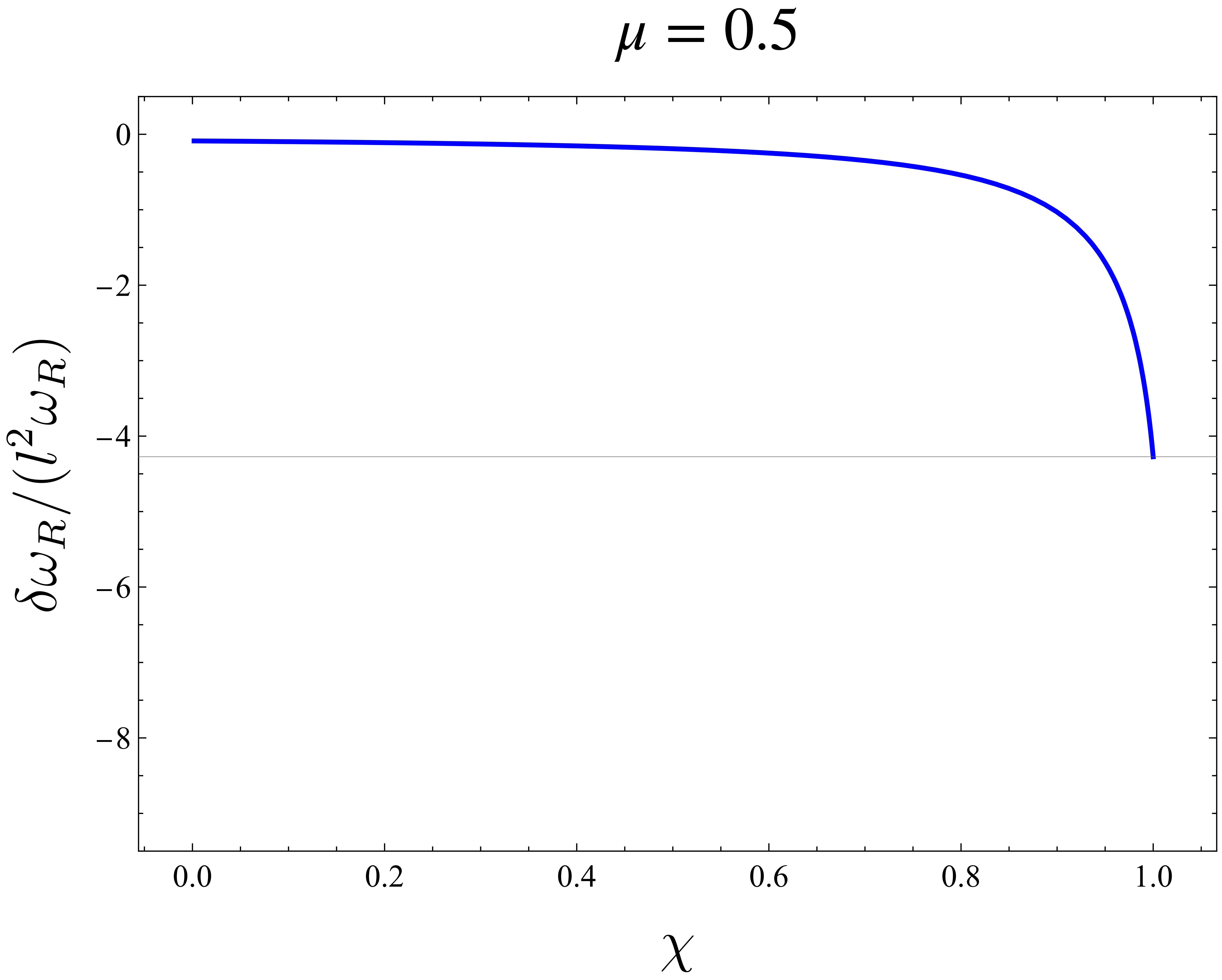
Real part: relative correction



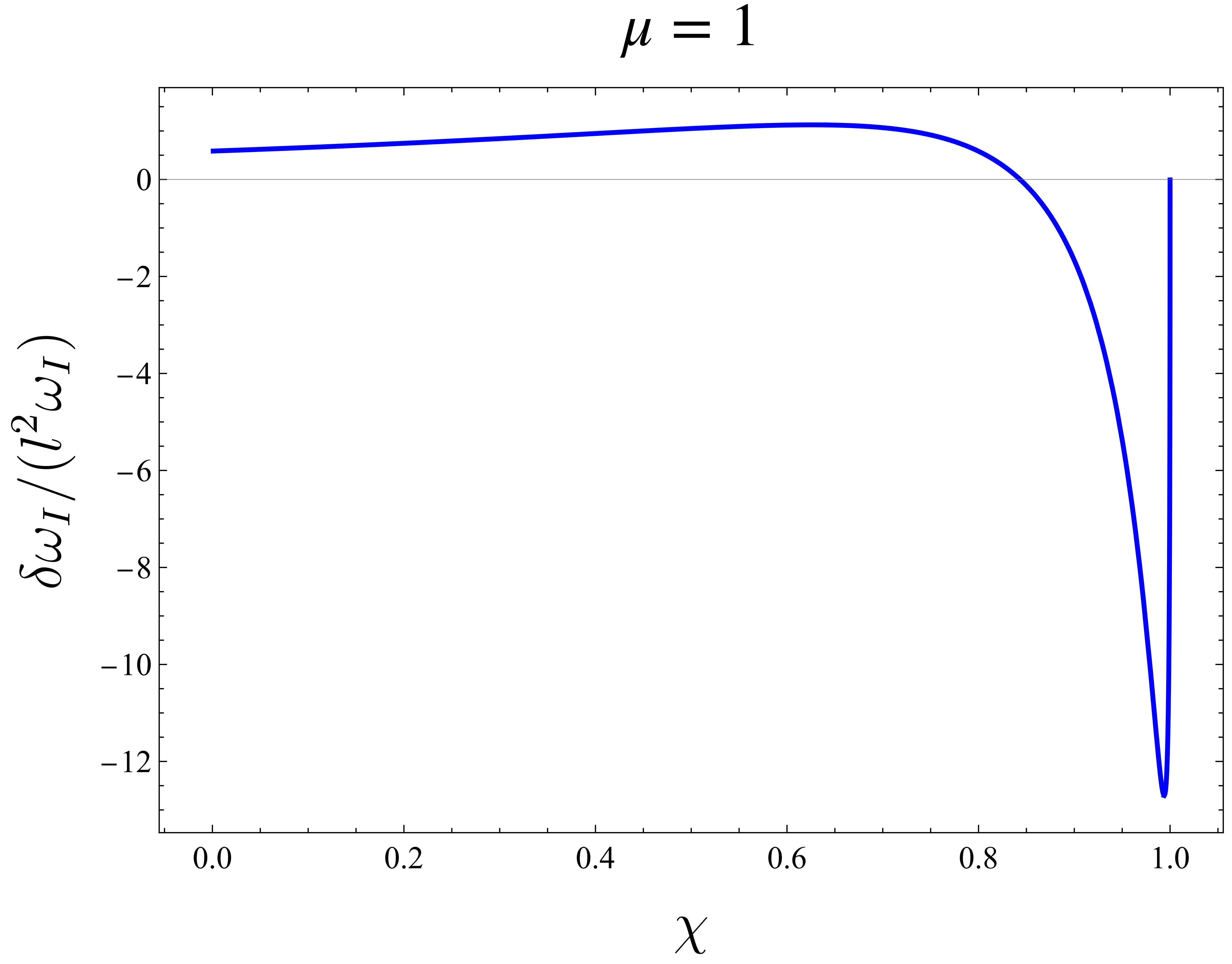
Real part: relative correction



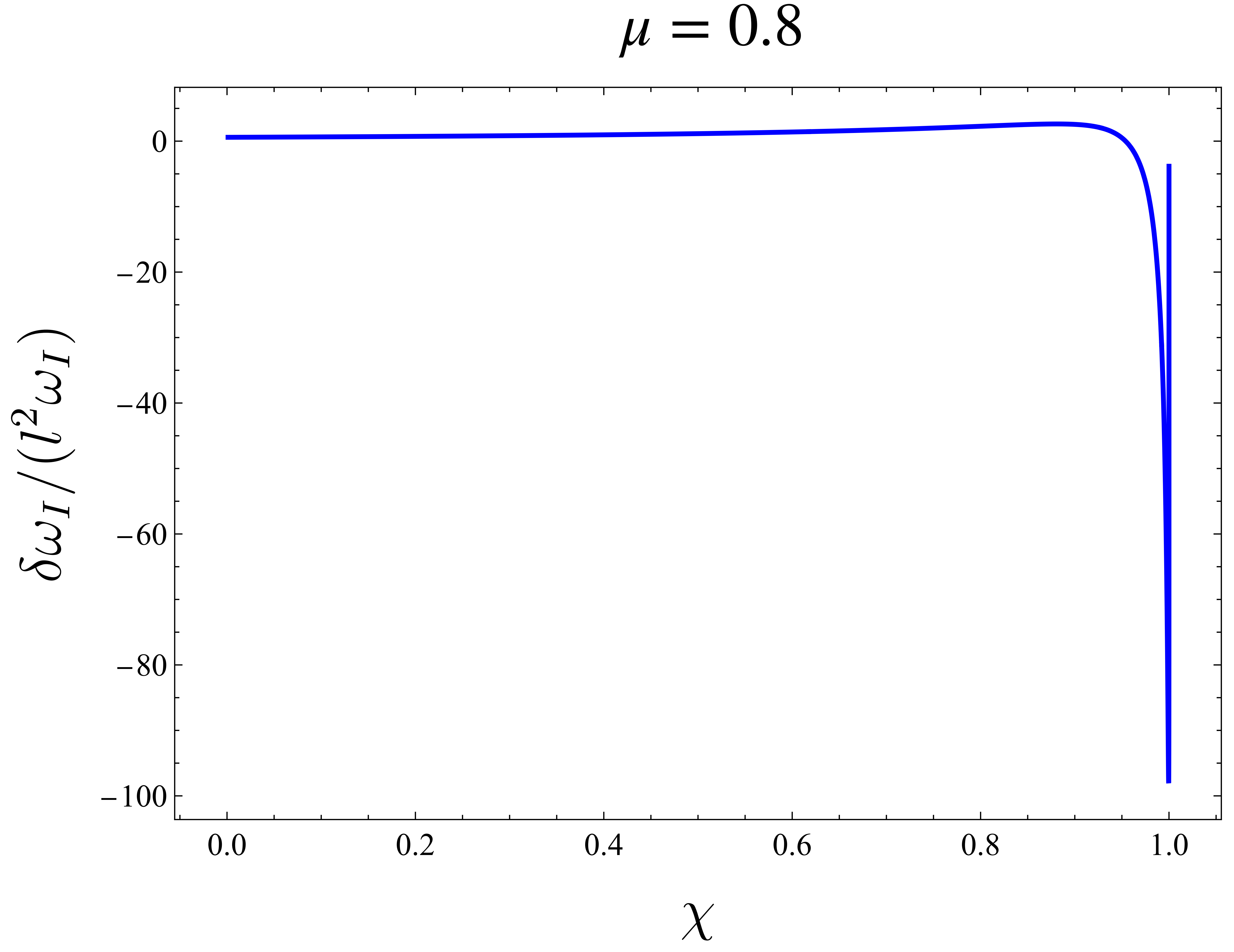
Real part: relative correction



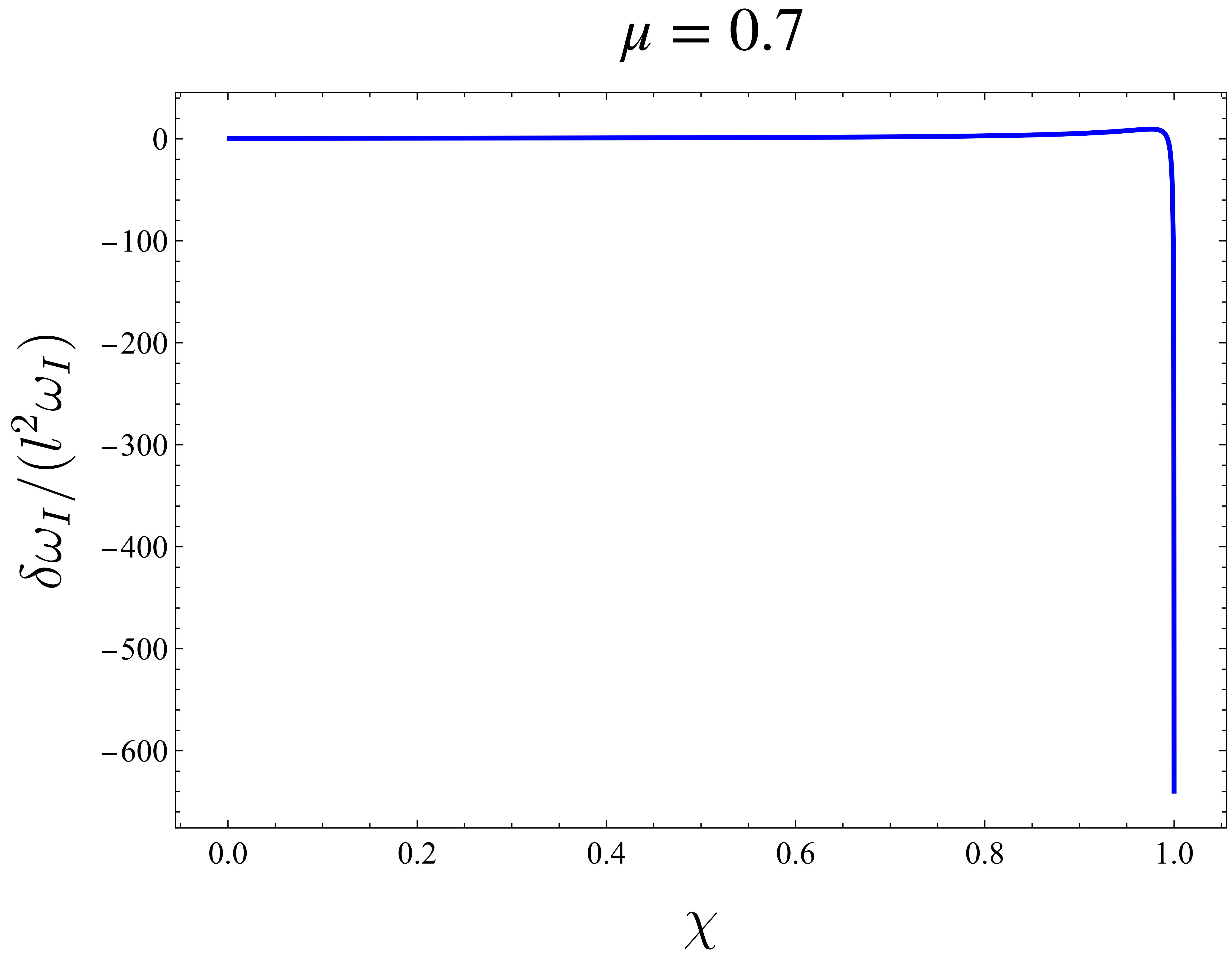
Imaginary part: relative correction



Imaginary part: relative correction

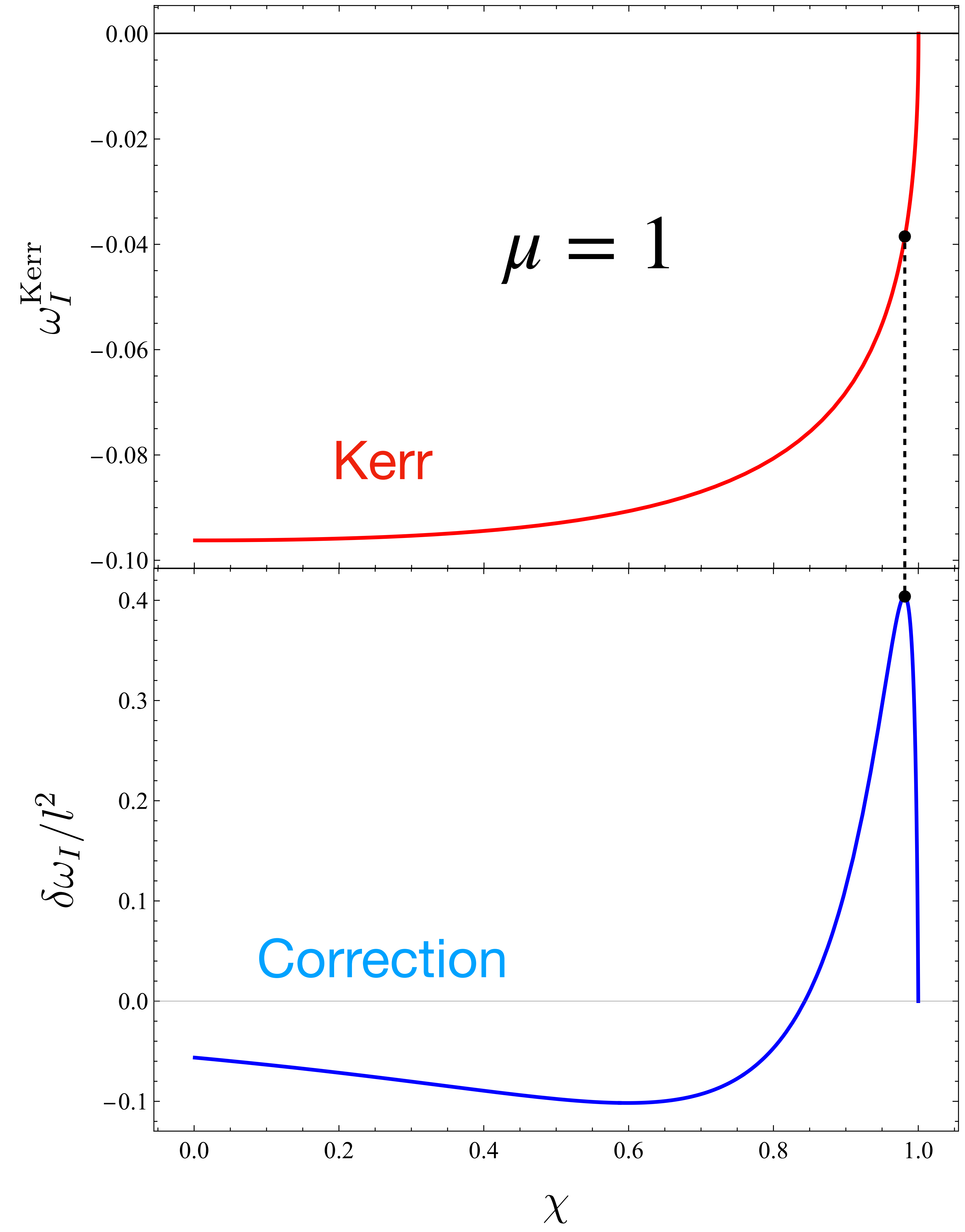


Imaginary part: relative correction



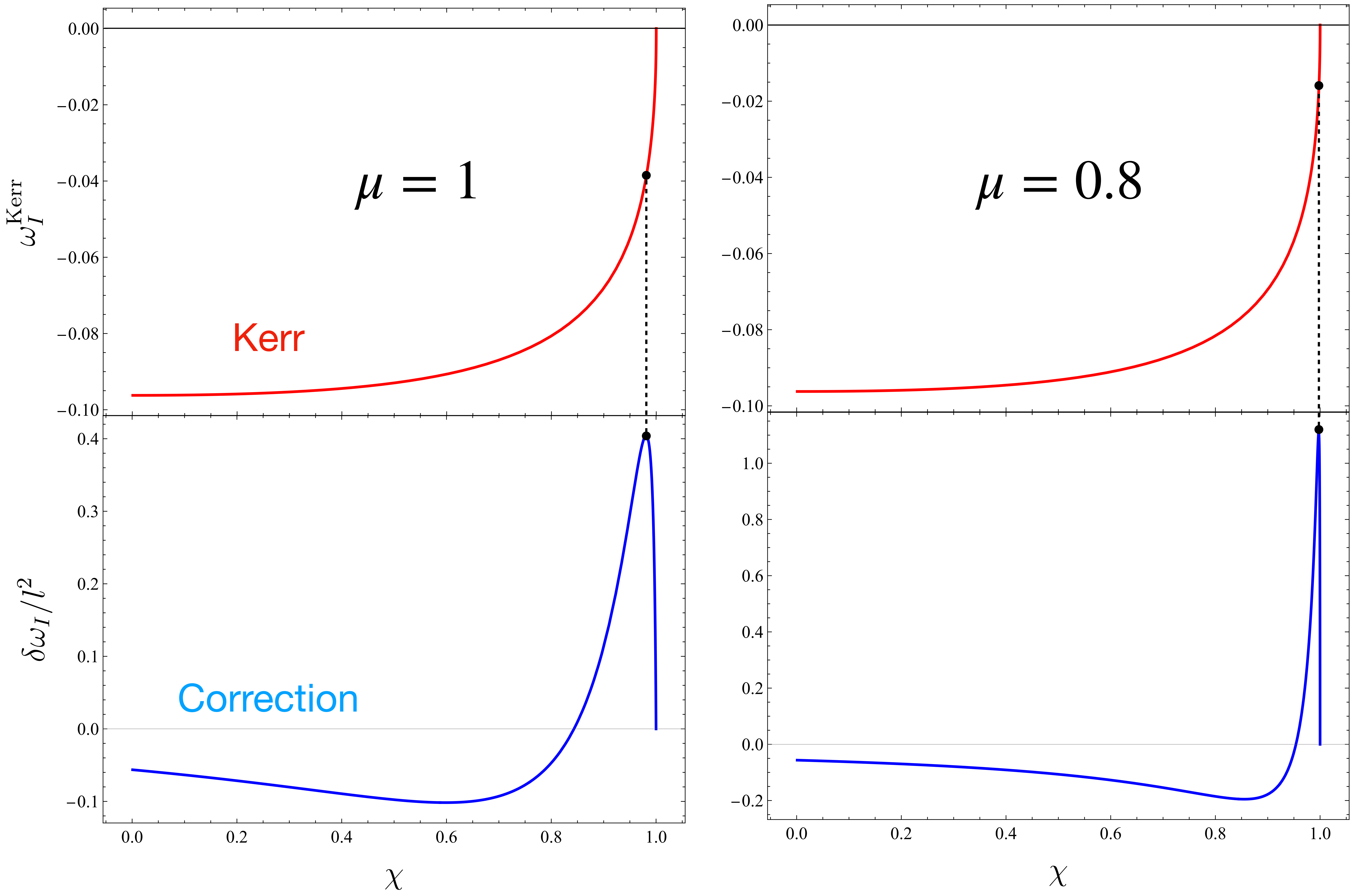
Imaginary part: GR vs correction

$$\omega_I = \omega_I^{\mathrm{Kerr}} + \frac{\epsilon}{M^7}\delta\omega_I$$



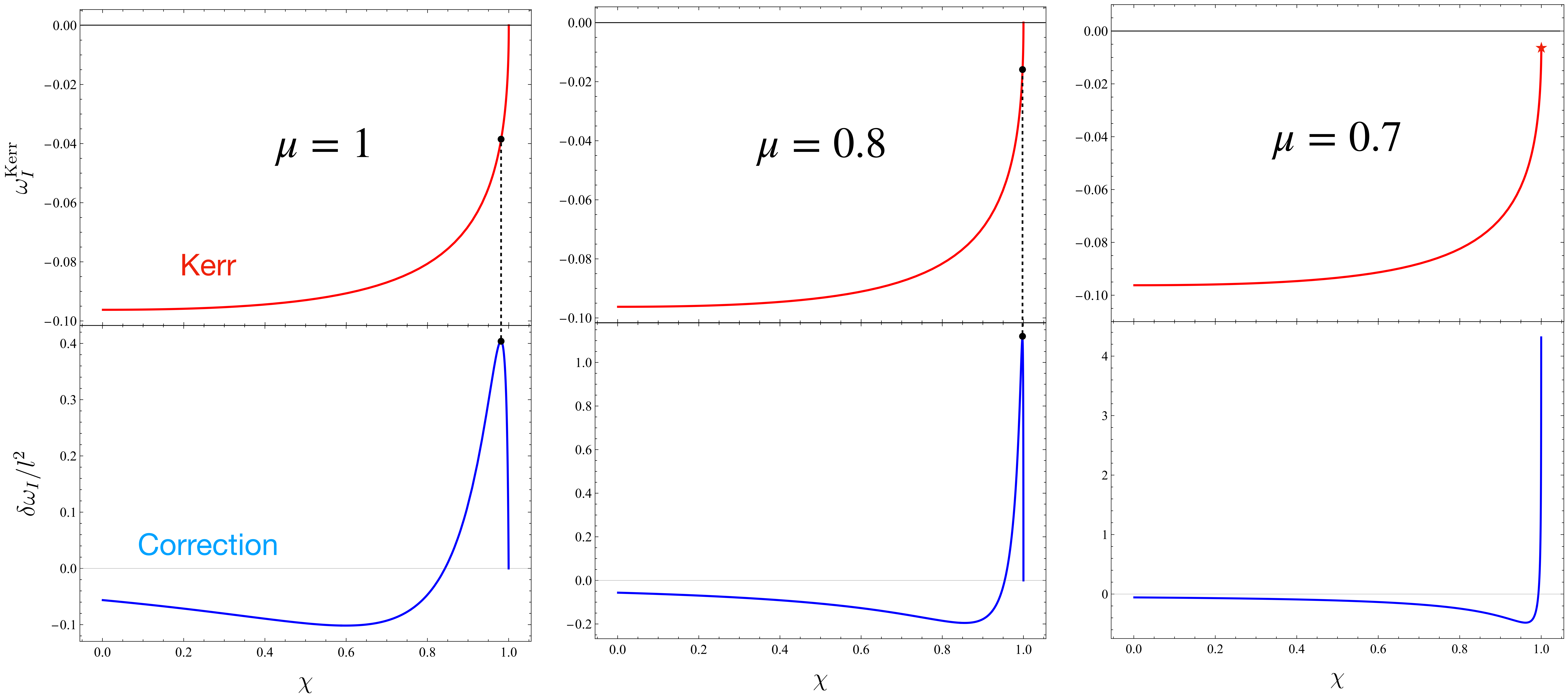
Imaginary part: GR vs correction

$$\omega_I = \omega_I^{\rm Kerr} + \frac{\epsilon}{M^7}\delta\omega_I$$



Imaginary part: GR vs correction

$$\omega_I = \omega_I^{\mathrm{Kerr}} + \frac{\epsilon}{M^7}\delta\omega_I$$



Results for high rotation

Summary

For $\mu \approx \mu_{\text{thr}}$ and $\chi \approx 1$, we have

$$M\omega_I^{\text{Kerr}} \ll 1, \qquad \delta\omega_I \text{ grows a lot}$$

- Could the corrections overcome the GR part?
- Instability for $\epsilon > 0$?
- In general: the corrections to GR grow by orders of magnitude as we approach extremality

Conclusions

Specific remarks

- First computation of **gravitational QNMs with high rotation** beyond GR
- **Key development: effective scalar equation** for eikonal perturbations in "isospectral" theories
- Master equation could have more applications: **time domain simulations?**
- **Future work:** extension for non-isospectral theories

Conclusions

General remarks

- Beyond-GR effects **increase dramatically** for high rotation
- Highly-rotating BHs have long-lived modes: **high-precision spectroscopy**

Conclusions

General remarks

- Beyond-GR effects **increase dramatically** for high rotation
- Highly-rotating BHs have long-lived modes: **high-precision spectroscopy**

Highly rotating BHs → **Golden events to test new physics**

More work is needed!

Thank you

Bonus slides

Why test EFT corrections

EFT is the main hypothesis for beyond-GR physics

Conditions for a theory to be **viable:**

1. It's not ruled out by other experiments
2. It has full predictive power
3. It CAN be tested with GWs

Very few "alternatives" to GR remain. EFT is the best motivated one

Observability of higher-derivative corrections

Relative corrections to GR = Const × Δ

$$\Delta = \frac{\ell^4 (GM)^2}{r^6}$$

$$\Delta_{\text{Sun}} \sim \left(\frac{\ell}{5 \times 10^8 \text{km}}\right)^4, \quad \Delta_{\text{Earth}} \sim \left(\frac{\ell}{2 \times 10^8 \text{km}}\right)^4, \quad \Delta_{BH}(10 M_\odot) \sim \left(\frac{\ell}{40 \text{km}}\right)^4$$

30 orders of magnitude increase

In addition, "Const" can become large in special cases (high rotation)