Hi! I'm Felix Lichtner

MAX PLANCK INSTITUTE
FOR GRAVITATIONAL PHYSICS
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Astrophysical and Cosmological Relativity
Max Planck Institute for Gravitational Physics

- PhD student at the Max Planck Institute for Gravitational Physics in Potsdam
- Main focus: Description of neutron star tides using effective field theory

About me

- Hobbies: Cooking, Guitar (New)
- Game with most hours: Elden Ring
- Currently watching: Naruto

Current Project:

Effective Gravitoelectric Lagrangian for Neutron Star Dynamical Tides

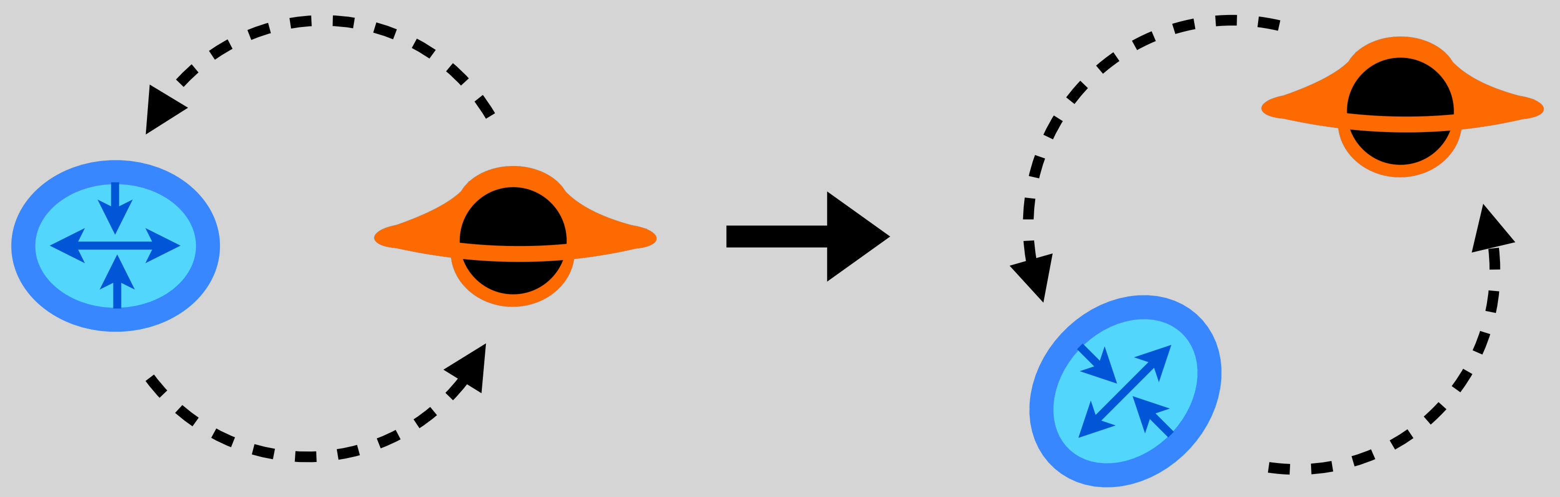
Together with Raj Patil & Jan Steinhoff

PhD School Nordita **08.04.2026**

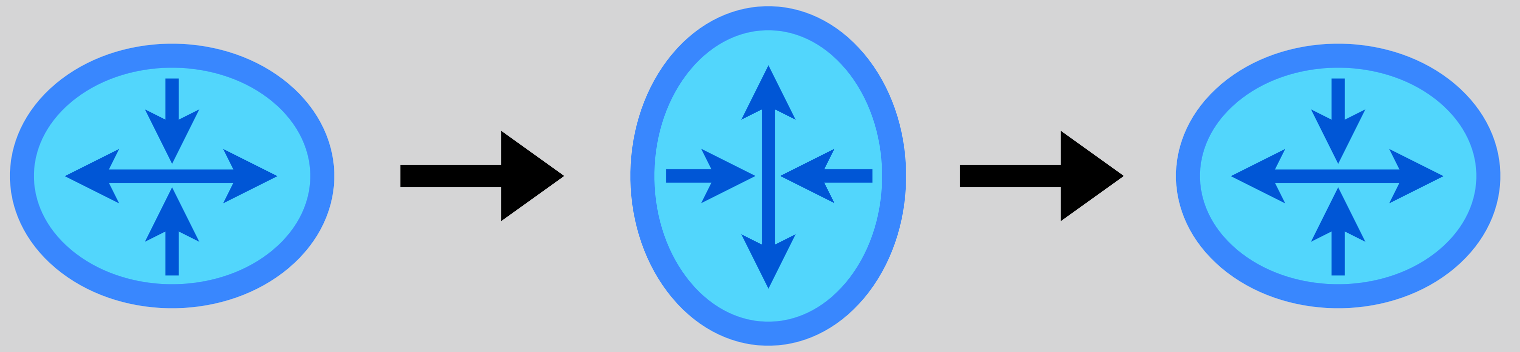
Binary Neutron Stars Experience Tides

- Binary systems of neutron stars exhibit a rich phenomenology which alters the phasing and structure of emitted gravitational waves
- The extension of the NS permits tidal deformation which can be **adiabatic** or **dynamic**

Adiabatic tides follow their companion:



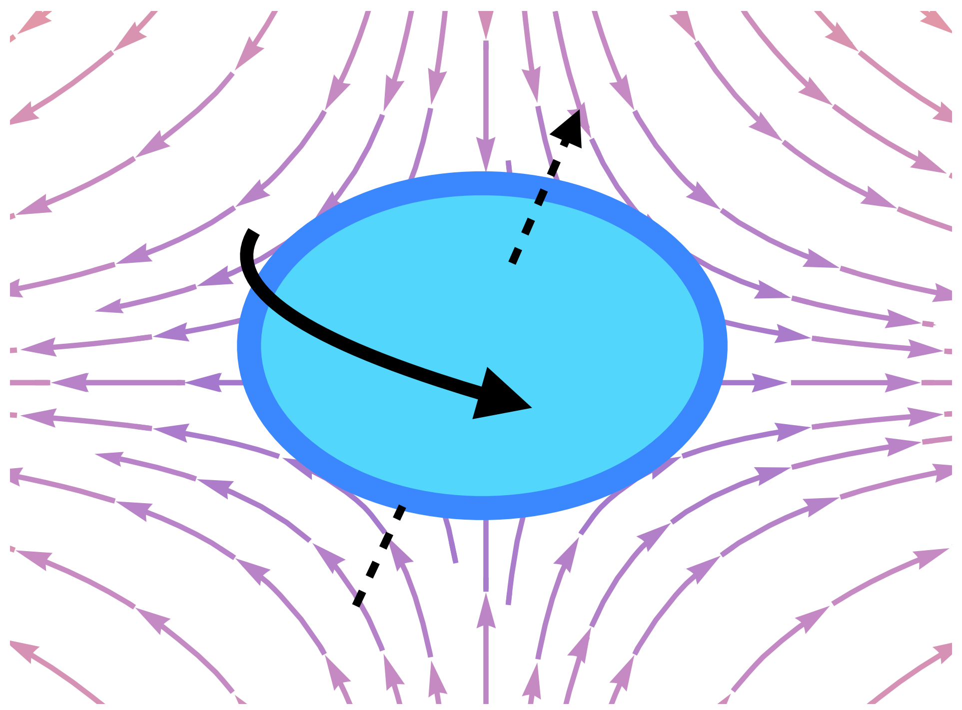
Dynamical tides can oscillate independently:

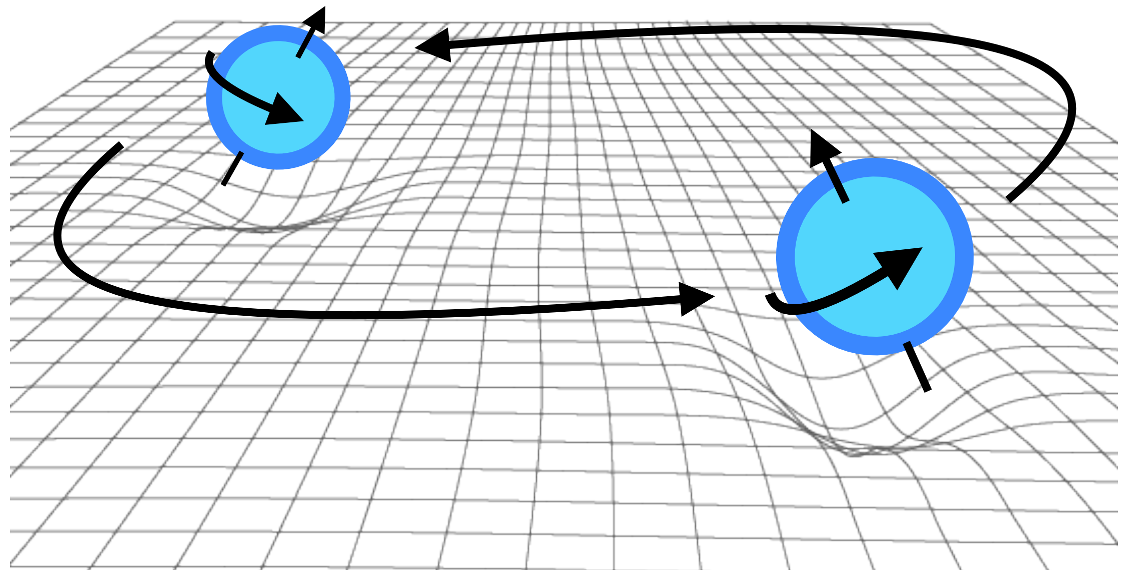


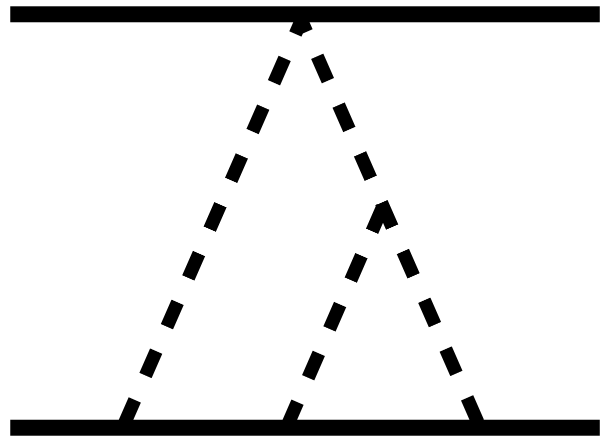
$\omega_{DT} \sim \omega_{orbit} \implies$ Tidal resonance

- Neutron stars can be systematically described using the tools of **effective field theory (EFT)**

EFT of single NS → EFT of binary NS + GR → Feynman Diagrams → Effective Hamiltonian, Fluxes and Tails, etc.





$\cdots +$  $+ \cdots$

Effective Hamiltonian

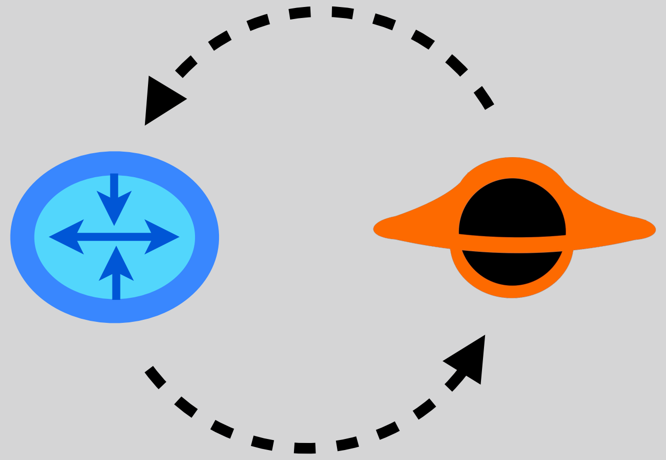
Fluxes and Tails

etc.

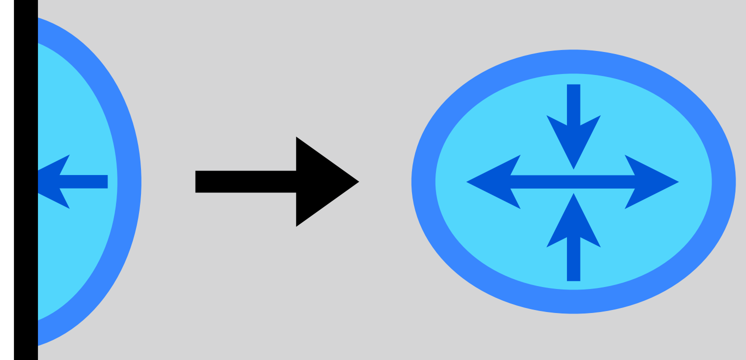
Binary Neutron Stars Experience Tides

- Binary systems of neutron stars exhibit a rich phenomenology which alters the phasing and structure of emitted gravitational waves
- The extension of the NS

Adiabatic tides follow



cillate independently:

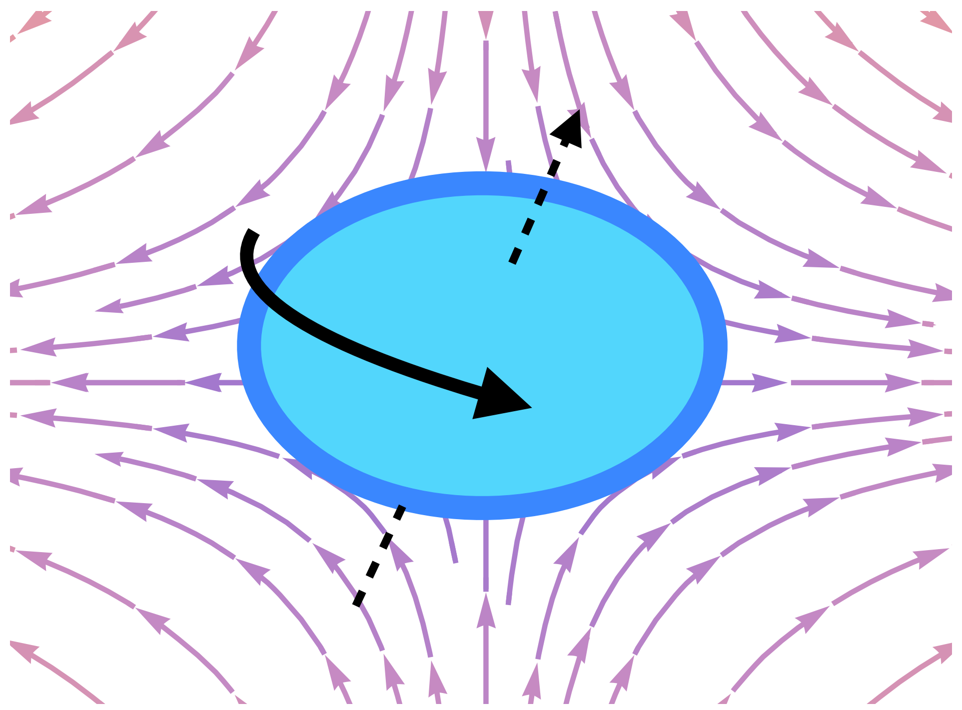


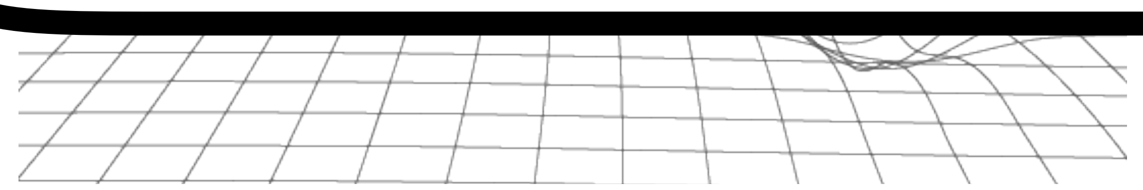
Tidal resonance

- Neutron stars can be sys

(EFT)

EFT of single NS





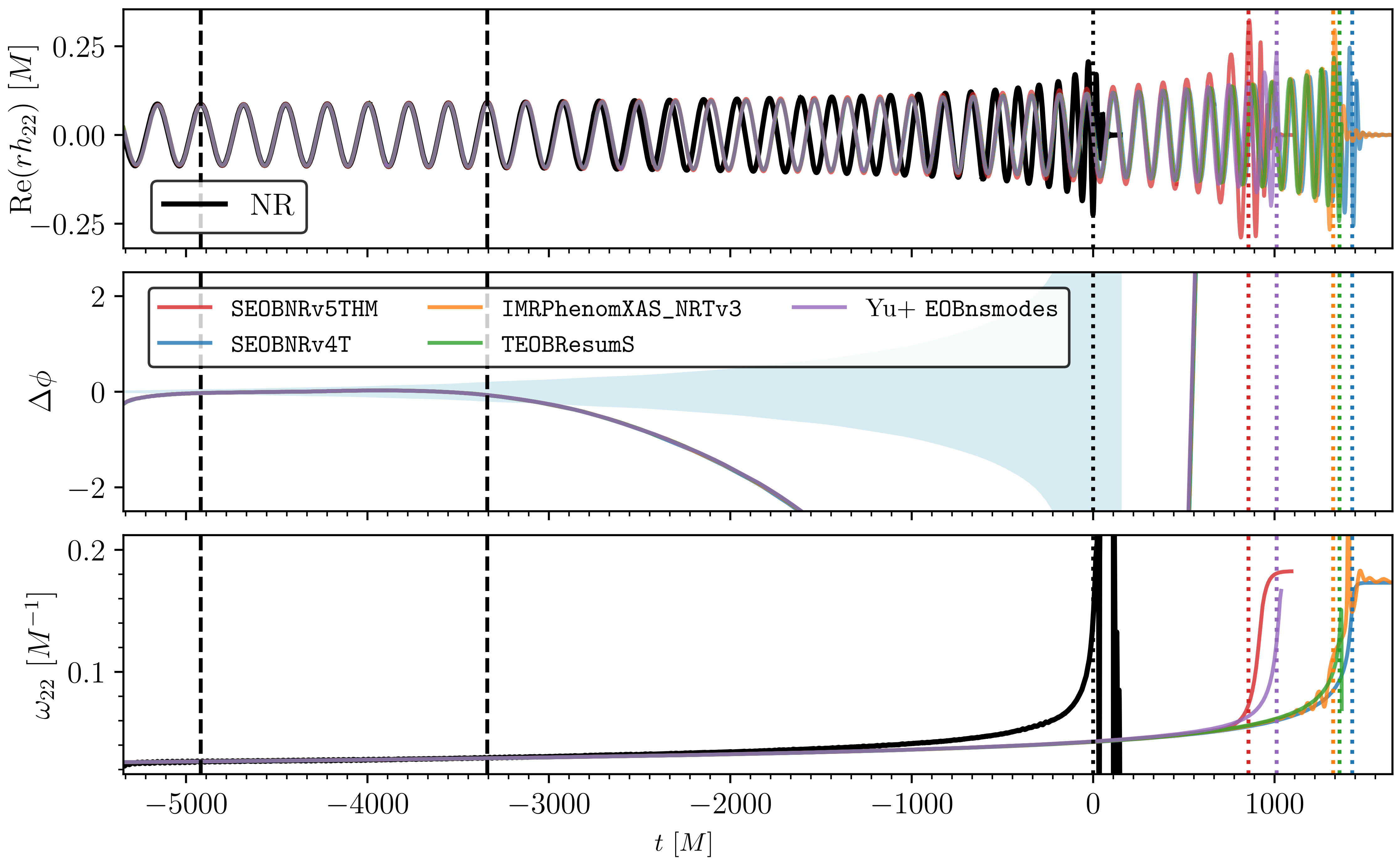
…

Effective Hamiltonian

Fluxes and Tails

etc.

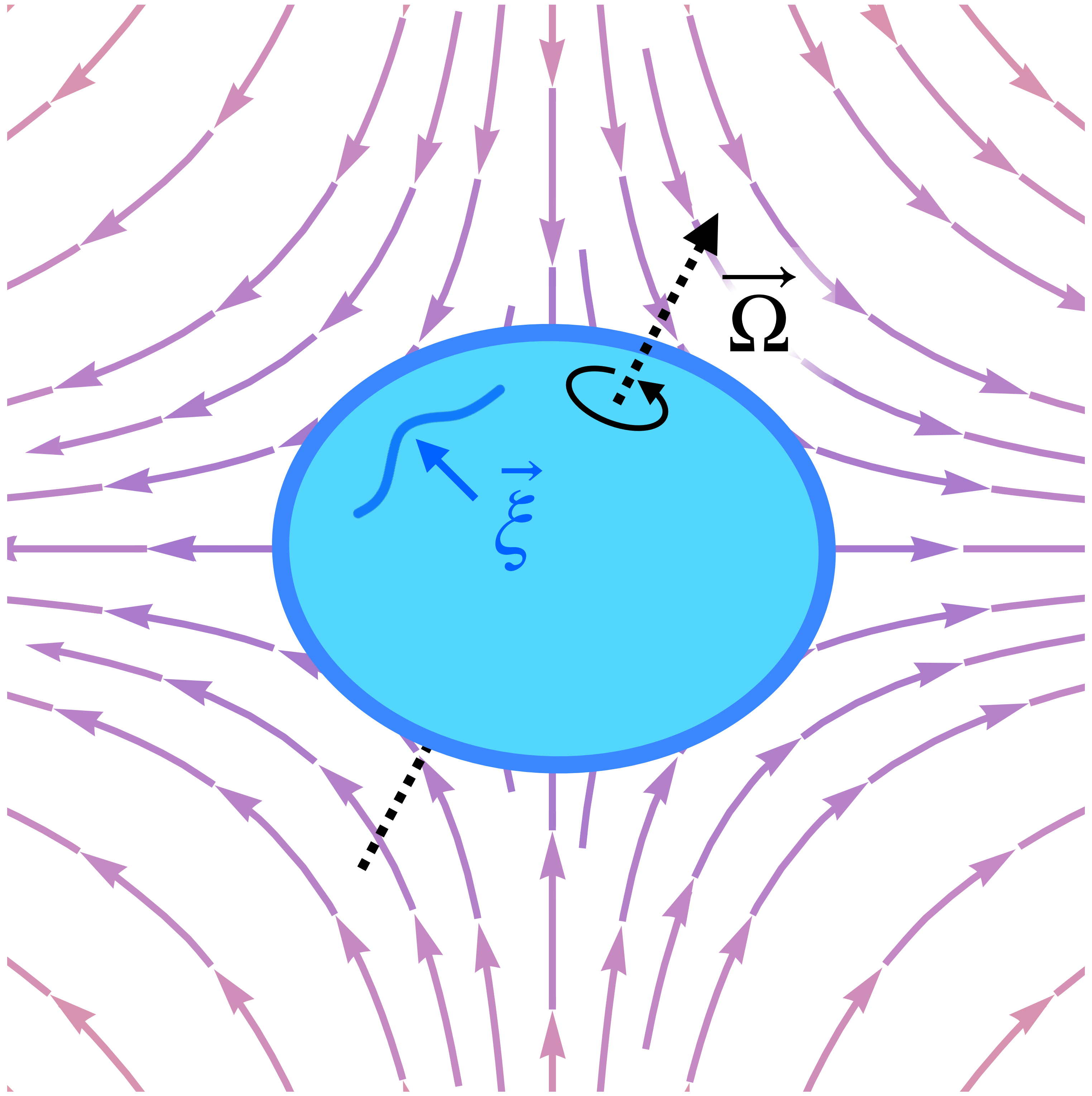
Discrepancies at High Spin



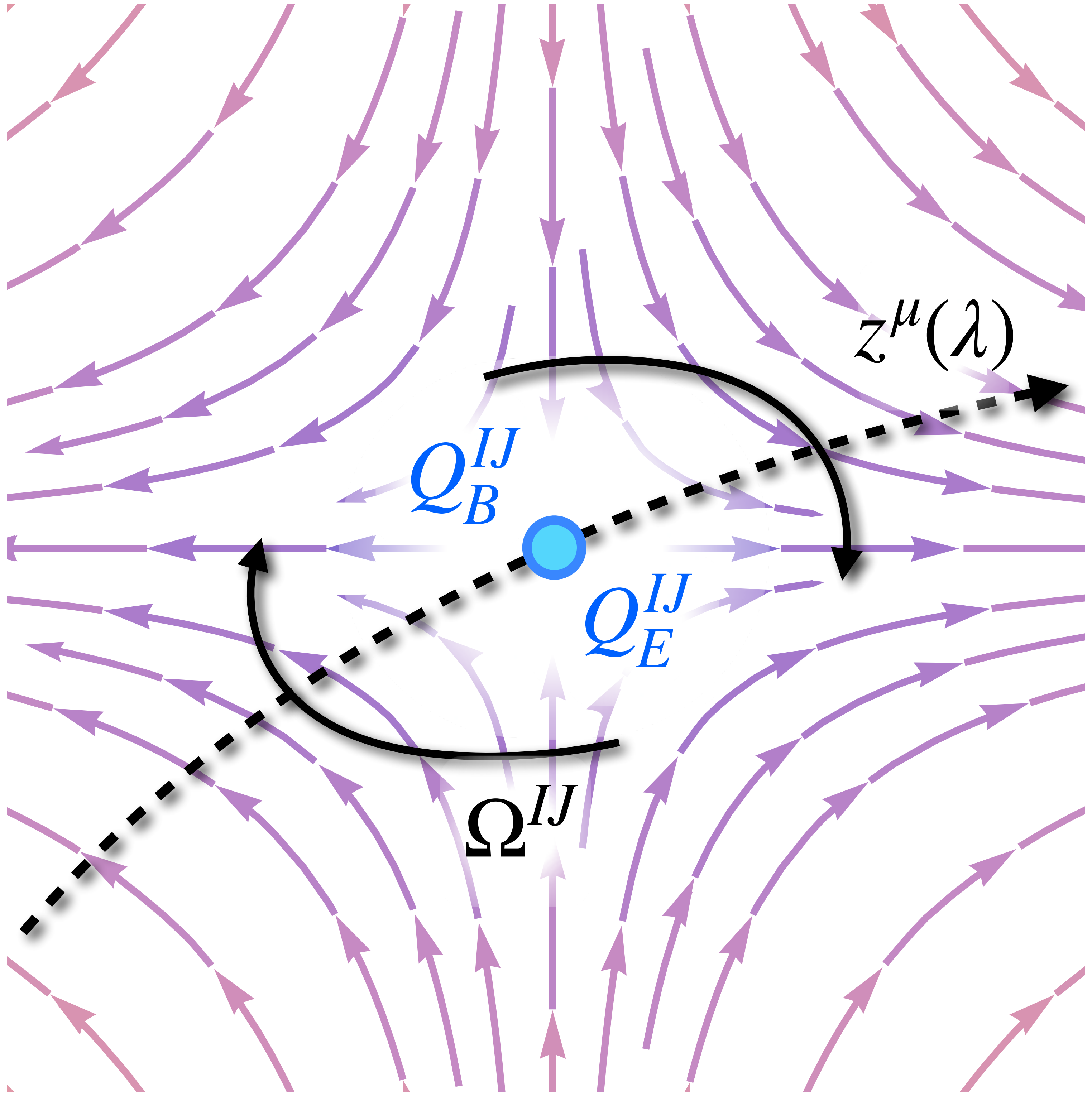
Private communications [Haberland, Kuan, Steinhoff]

From a Perfect Fluid to a Worldline

Newtonian Description



Effective Worldline Description



The Newtonian NS quadrupole behaves like a driven harmonic oscillator:

$$\mathscr{L}_{DT}^{E} = \frac{1}{4\lambda\omega_f^2}\left[\dot{Q}_E^{IJ}\dot{Q}_E^{IJ} - \omega_f^2 Q_E^{IJ}Q_E^{IJ}\right] - \frac{1}{2}E^{IJ}Q_E^{IJ} + C_\Omega \Omega^{IJ} Q_E^{IK}\dot{Q}_E^{JK}$$

[Steinhoff, Hinderer, Buonanno, Taracchini; 2016]
[Steinhoff, Hinderer, Dietrich, Foucart; 2021]

We use a fully relativistic effective description:

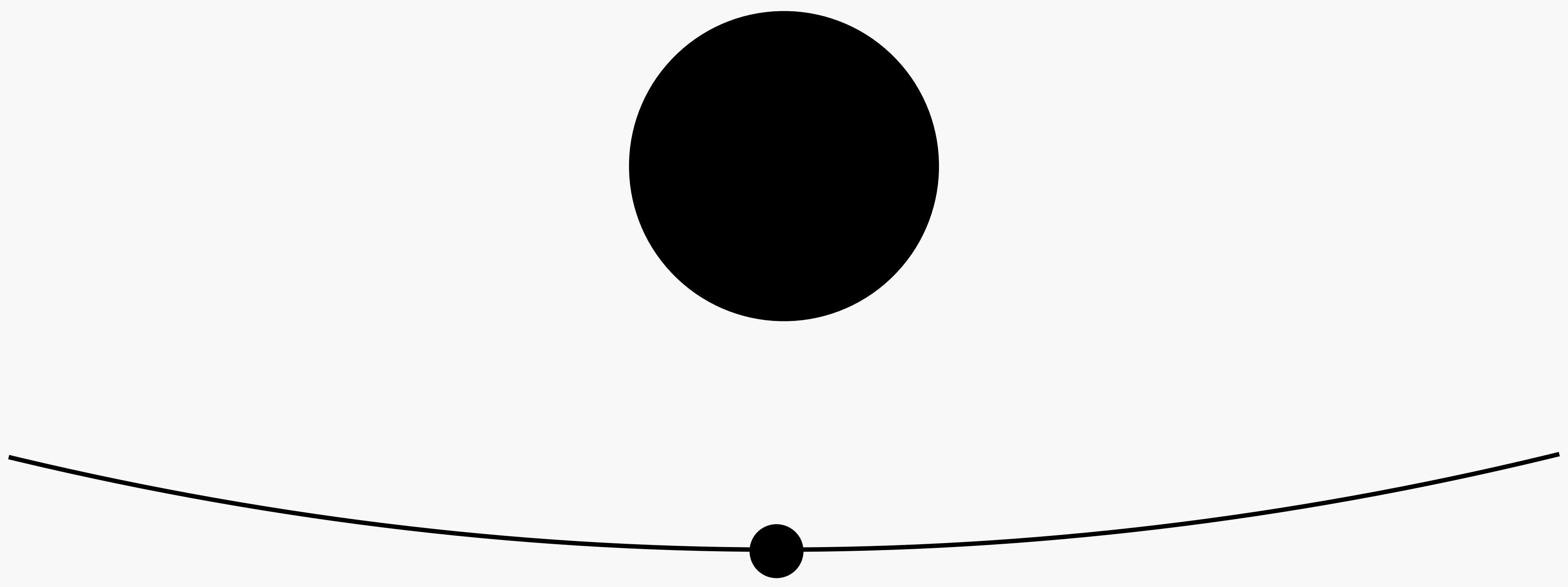
$$\mathscr{L}_{eff} = \sqrt{-\dot{z}_\mu \dot{z}^\mu}\left[-m + \frac{I}{4}\Omega_{AB}\Omega^{AB} + \mathscr{L}_{DT}^{E} + \cdots\right]$$

PM-exact probe motion from Magnusian

Based on [Jitze Hoogeveen, 26xx.xxxxx]

Jitze Hoogeveen, Humboldt Universität zu Berlin

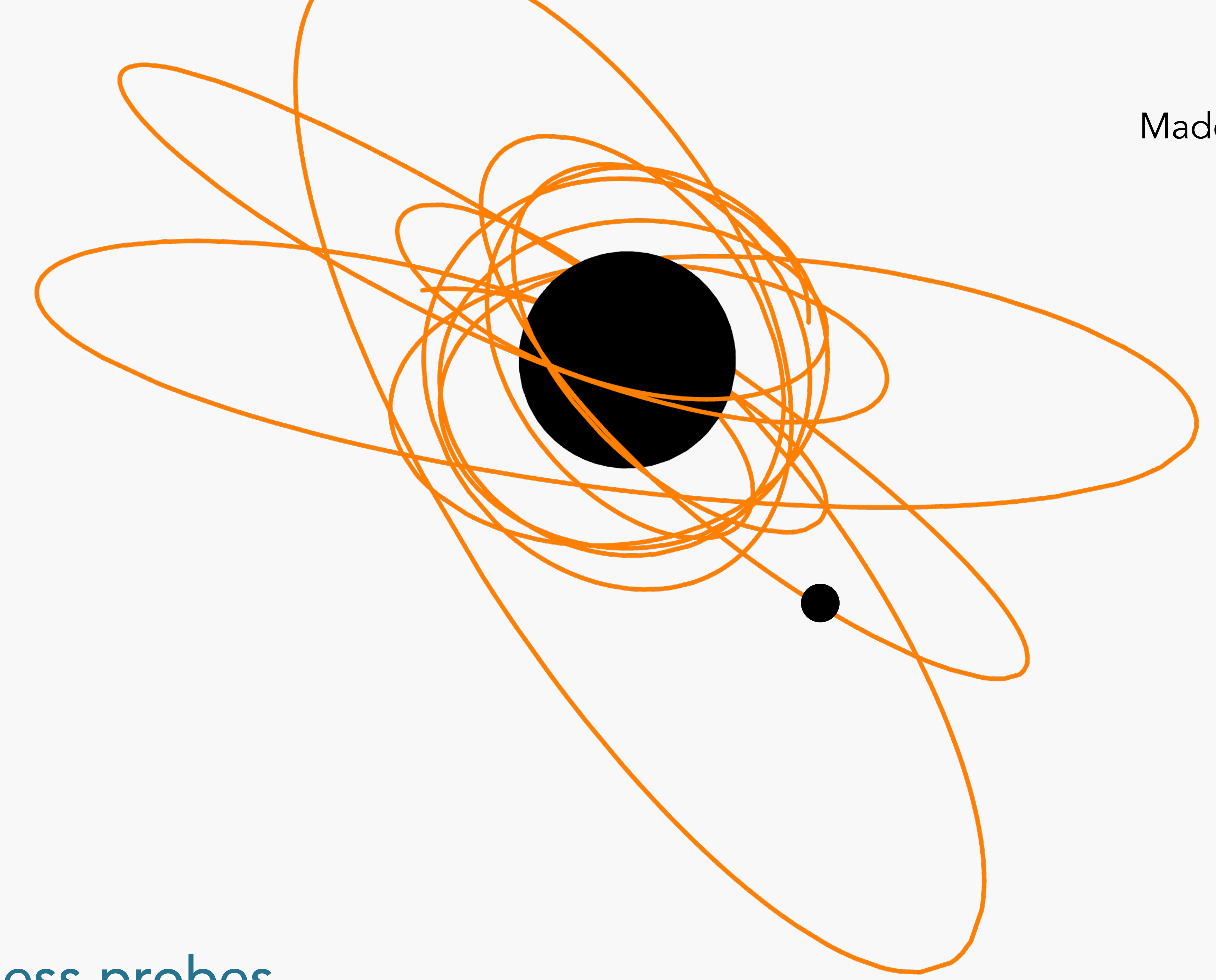
Stockholm, 8/4 2026



$$\ddot{x}^{\mu} = -\Gamma^{\mu}_{\rho\sigma}\dot{x}^{\rho}\dot{x}^{\sigma}$$

$$\{E, L, K\}$$ [Carter; 1968]

Integrable EOM



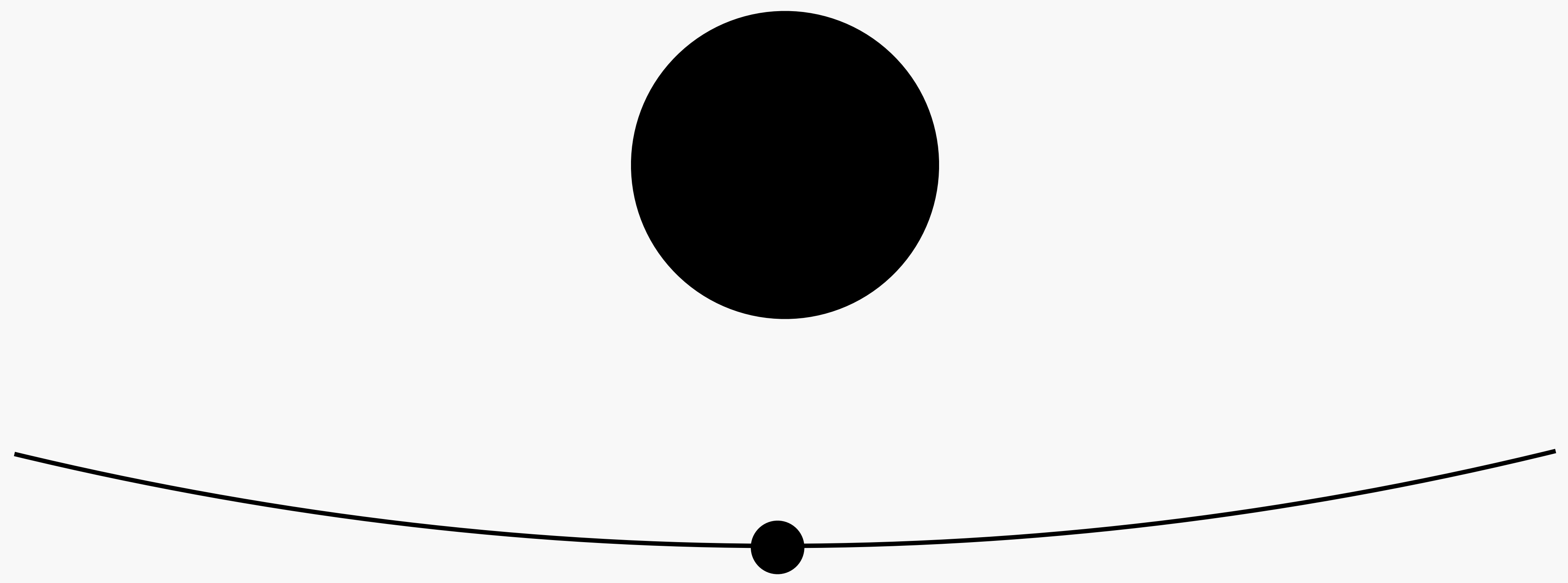
Made with BHPT (KerrGeodesics)
bhptoolkit.org

Spinless probes

[Mino; 2003], [Fujita, Hikida; 2009], [Hackmann; 2010], [Cieślik et.al; 2023]

Spinning probes @ $\mathcal{O}(s^2)$

[Rüdiger; 1981-1983], [Compére, Druart, Vines; 2023], [Ramond; 2024], [Witzany, Piovano; 2023], [Skoupý, Witzany; 2024]

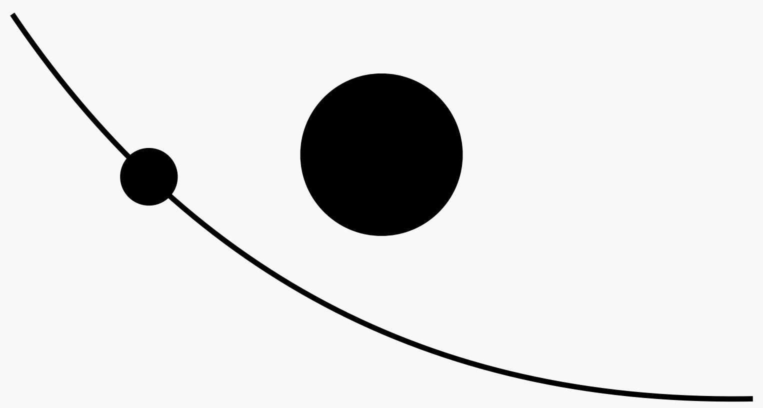


Scattering trajectories

- **Explicit solutions** - [Bini, Geralico, Vines; 2017], [Bini, Geralico; 2018], [Damgaard, **JH**, Luna, Vines; 2023], [Gonzo, Shi; 2024], [**JH**, Jakobsen, Plefka; 2025], [Aoude, Helset; 2025]
- **Integrability @ $\mathcal{O}(s^4)$** - [Akpinar, Brown, Gonzo, Zeng; 2025]

Scattering observables from integrable system

Magnusian N for probes



[Damgaard, Plante, Vanhove; 2021],
[Damgaard, Hansen, Planté, Vanhove; 2023],
[Gonzo, Shi; 2024], [Gonzo, Lewis, Pound; 2024],
[Kim, Kim, Kim, Lee; 2024], [Kim; 2025],
[Alessio, Gonzo, Shi; 2025],
[Kim, Patil, Schoeppner, Steinhoff; 2025],
[Haddad, Jakobsen, Mogull, Plefka; 2025],
[Para-Matrinez, He; 2025]

$$\Delta\mathcal{O} = \sum_{n=1} \frac{1}{n!}\{N, \{N, ..., \{N, \mathcal{O}\}...\}\}$$

$$N = \log(-i\hbar\hat{S})$$

Integrable systems

$$N = I_r = \int_{r_m}^{\infty} dr\, p_r$$

[Gonzo, Shi; 2024]

$$p_r = p_r(r; E, L, s_{||}, K)$$

only function of r

How to compute I_r ?

Magnusian to all PM orders - [Jitze Hoogeveen, 26xx.xxxxx]

Generic separable theory

$$N = I_r = \int_{r_m}^{\infty} dr\, p_r \qquad\qquad p_r^2 = p_\infty^2 - \frac{L^2 f(r)}{r^2} - U(r)$$

[Damgaard, **JH**, Luna, Vines; 2023]

Magnusian to all PM orders - [Jitze Hoogeveen, 26xx.xxxxx]

Generic separable theory

$$N = I_r = \int_{r_m}^{\infty} dr\, p_r$$

arbitrary theory-specific function

$$\underline{p_r^2 = p_\infty^2 - \frac{L^2 f(r)}{r^2}} - U(r)$$

[Damgaard, **JH**, Luna, Vines; 2023]

asymptotically flat

arbitrary scattering potential

Magnusian to all PM orders - [Jitze Hoogeveen, 26xx.xxxxx]

Generic separable theory

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$$p_r^2 = \underline{p_\infty^2 - \frac{L^2 f(r)}{r^2}} - U(r)$$

[Damgaard, **JH**, Luna, Vines; 2023]

asymptotically flat

arbitrary scattering potential

Expand I_r in $U(r)$ (preliminary)

$$\frac{dI_r}{dX} = \frac{p_\infty}{2} \sum_{n=0}^{\infty} \int_0^{\infty} du \left(\frac{d}{du^2}\right)^n \tilde{h}(r) \frac{r^{2n}\tilde{U}(r)^n}{n! p_\infty^{2n}}$$

Valid at all PM orders

Magnusian to all PM orders - [Jitze Hoogeveen, 26xx.xxxxx]

Generic separable theory

$$N = I_r = \int_{r_m}^{\infty} dr\, p_r \qquad p_r^2 = p_\infty^2 - \frac{L^2 f(r)}{r^2} - U(r)$$

[Damgaard, **JH**, Luna, Vines; 2023]

Expand I_r in $U(r)$ (preliminary)

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Valid at all PM orders

Simple integrals!

Kerr: Elliptical integrals at all PM

Mirrors $\mathscr{O}(s^4)$ results [**JH**, Jakobsen, Plefka; 2025]

[Akpinar, Brown, Gonzo, Zeng; 2025]?

Observables on the way!

Tidal heating and torquing on noncircular, planar binary black hole dynamics

D. Chiaramello, R. Gamba, E. Shukla, S. Albanesi

https://doi.org/10.1103/PhysRevD.111.024024
https://arxiv.org/abs/2603.28982

April 2026

Horizon absorption

Or tidal heating and torquing

- BHBs lose energy, angular momentum to GWs, mainly escaping toward infinity
- However some interact with the BHs themselves, being **absorbed through their horizons**
- **PN theory**: leading order energy flux to infinity is $F_\infty \propto v^{10}$

$v =$ relative velocity

- Horizon flux starts at higher order:

➡ 2.5PN beyond F_∞ for spinning BHs ($O(v^{15})$)

➡ 4PN beyond F_∞ for nonspinning BHs: ($O(v^{18})$)

- Known analytically to 1.5PN on circular orbits for comparable-mass binaries, 11PN for a test mass orbiting Kerr

Analytical computation

Horizon fluxes for comparable mass binaries valid on **generic orbits**.

$$r = \text{ relative separation}$$
$$p_r, p_\varphi = \text{ canonical EOB momenta}$$
$$\sigma_1 = \sqrt{1-\chi_1^2}$$
$$B_2(\chi_1) = \Im\left[\psi^{(0)}\left(3+2\mathrm{i}\frac{\chi_1}{\sigma_1}\right)\right]$$
$$\Omega_{\mathrm{H}}^1 = \frac{\chi_1}{2m_1 r_{\mathrm{H}}^1} = \frac{\chi_1}{2m_1(1+\sigma_1)}$$

$$\begin{aligned}\frac{\dot m_1}{M} =& -\frac{8}{5}\nu^2\left(\frac{m_1}{M}\right)^3\frac{\chi_1}{r^6}\Bigg\{\left(1+3\chi_1^2\right)\frac{p_\varphi}{r^2}+\frac{1}{c^2}\frac{p_\varphi}{r^2}\Bigg\{\left(1+3\chi_1^2\right)\left[\frac{p_\varphi^2}{r^2}\left(\frac{3}{4}+\frac{m_1}{2M}-4\nu\right)-p_r^2\left(\frac{7m_1}{2M}+6\nu\right)\right.\\
&\left.-\left(1-\frac{m_1}{M}-2\nu\right)\frac{2}{r}\right]+\frac{5}{4}\frac{p_\varphi^2}{r^2}\Bigg\}+\frac{1}{r^2c^3}\Bigg\{\left(1+3\chi_1^2\right)\left[\chi_1\left(10\frac{m_1}{M}p_r^2+\frac{p_\varphi^2}{3r^2}\left(\frac{m_1}{M}+9\nu\right)+\frac{1}{2r}\left(4\frac{m_1}{M}+\nu\right)\right)\right.\\
&-2\frac{m_1}{M}\left(4\frac{p_\varphi^2}{r^2}+9p_r^2\right)B_2\left(\chi_1\right)+\chi_2\left(\frac{p_\varphi^2}{2r^2}\left(6\nu-5\frac{m_2}{M}\right)+\frac{1}{2r}\left(4\frac{m_2}{M}-3\nu\right)-\frac{m_2}{M}p_r^2\right)-\frac{64m_1}{3M}\frac{p_\varphi p_r}{r}\\
&\left.-\frac{m_1\chi_1}{2M}\left(1+\sigma_1\right)\left(8\frac{p_\varphi^2}{r^2}+19p_r^2\right)\right]-46\frac{m_1}{M}\chi_1p_r^2(1+\sigma_1)-\frac{p_\varphi^2}{3r^2}\frac{m_1}{M}\chi_1(71+66\sigma_1)-\frac{5}{2}\frac{m_2}{M}\chi_2\frac{p_\varphi^2}{r^2}\\
&-\underbrace{\frac{2m_1(1+\sigma_1)}{M\chi_1}}_{\frac{1}{\Omega_{\mathrm{H}}^1}}\left(\frac{p_\varphi^2}{r^2}+3p_r^2\right)\Bigg\}\Bigg\}\end{aligned}$$

$$\begin{aligned}\frac{\dot S_1}{M^2} =& -\frac{8}{5}\nu^2\left(\frac{m_1}{M}\right)^3\frac{\chi_1}{r^6}\Bigg\{1+3\chi_1^2+\frac{1}{c^2}\Bigg\{\left(1+3\chi_1^2\right)\left[\frac{p_\varphi^2}{2r^2}\left(\frac{5}{2}+\frac{m_1}{M}-5\nu\right)-\frac{1}{2}p_r^2\left(1+5\frac{m_1}{M}+11\nu\right)\right.\\
&\left.-\left(1-2\frac{m_1}{M}-3\nu\right)\frac{1}{r}\right]+\frac{5}{4}\frac{p_\varphi^2}{r^2}\Bigg\}+\frac{1}{r^2c^3}\Bigg\{\left(1+3\chi_1^2\right)\left[\chi_1p_\varphi\left(-\frac{11m_1}{3M}+3\nu-4\frac{m_1}{M}\sigma_1\right)-16\frac{m_1}{M}rp_r\right.\\
&\left.+\chi_2p_\varphi\left(-\frac{7}{2}\frac{m_2}{M}+3\nu\right)-8\frac{m_1}{M}p_\varphi B_2(\chi_1)\right]-\frac{m_1}{3M}p_\varphi(71+66\sigma_1)\chi_1-\frac{5m_2}{2M}\chi_2p_\varphi-\underbrace{\frac{2m_1p_\varphi(1+\sigma_1)}{M\chi_1}}_{\sim\frac{\dot\varphi}{\Omega_{\mathrm{H}}^1}}\Bigg\}\Bigg\}\end{aligned}$$

- Correct scaling: $\dot m \sim \dot\varphi \dot S$ to LO
- Correct quasi-circular limit
- Correct test-mass limit

- Up to NLO all vanish if $\chi_1 = 0$, as expected
- Only surviving terms reconstruct correct non-spinning LO

Analytical computation

$$
\begin{aligned}
\frac{\dot{m}_1}{M} = & -\frac{16}{5}\nu^2\left(\frac{m_1}{M}\right)^4\frac{1+\sigma_1}{r^6}\boxed{\left[\Omega_{\rm H}^1-\frac{1}{c^3}\left(\frac{p_\varphi}{r^2}+3\frac{p_r^2}{p_\varphi}\right)\right]}\Bigg\{\left(1+3\chi_1^2\right)\frac{p_\varphi}{r^2}+\frac{1}{c^2}\frac{p_\varphi}{r^2}\Bigg[-\frac{2}{r}\left(1+3\chi_1^2\right)\left(\frac{m_2}{M}-2\nu\right) \\
& -\frac{1}{2}p_r^2\left(1+3\chi_1^2\right)\left(\frac{7m_1}{M}+12\nu\right)+\frac{p_\varphi^2}{r^2}\left(\left(1+3\chi_1^2\right)\left(\frac{3}{4}+\frac{m_1}{2M}-4\nu\right)+\frac{5}{4}\right)\Bigg] \\
& +\frac{1}{r^2c^3}\Bigg[\left(1+3\chi_1^2\right)\Bigg[\chi_1\left(\frac{10m_1}{M}p_r^2+\frac{p_\varphi^2}{3r^2}\left(\frac{m_1}{M}+9\nu\right)+\frac{1}{2r}\left(\frac{4m_1}{M}+\nu\right)\right)-\frac{2m_1}{M}\left(4\frac{p_\varphi^2}{r^2}+9p_r^2\right)B_2\left(\chi_1\right) \\
& +\chi_2\left(\frac{p_\varphi^2}{2r^2}\left(6\nu-\frac{5m_2}{M}\right)+\frac{1}{2r}\left(\frac{4m_2}{M}-3\nu\right)-\frac{m_2}{M}p_r^2\right)-\frac{64m_1}{3M}\frac{p_\varphi p_r}{r}-\frac{m_1\chi_1}{2M}\left(1+\sigma_1\right)\left(8\frac{p_\varphi^2}{r^2}+19p_r^2\right)\Bigg] \\
& -\frac{28m_1}{M}\chi_1 p_r^2(1+\sigma_1)-\frac{p_\varphi^2}{3r^2}\frac{m_1}{M}\chi_1(53+48\sigma_1)-\frac{5m_2\chi_2}{2M}\frac{p_\varphi^2}{r^2}\Bigg]\Bigg\}
\end{aligned}
$$

$$
\begin{aligned}
\frac{\dot{S}_1}{M^2} = & -\frac{16}{5}\nu^2\left(\frac{m_1}{M}\right)^4\frac{1+\sigma_1}{r^6}\boxed{\left(\Omega_{\rm H}^1-\frac{p_\varphi}{r^2c^3}\right)}\Bigg\{1+3\chi_1^2+\frac{1}{c^2}\Bigg[p_r^2\left(1+3\chi_1^2\right)\left(-3+\frac{5m_2}{2M}-\frac{11}{2}\nu\right) \\
& -\frac{p_\varphi^2}{2r^2}\left(\left(1+3\chi_1^2\right)\left(\frac{m_2}{M}+\frac{5}{2}\nu\right)+\frac{3}{2}\left(4+7\chi_1^2\right)\right)-\frac{1+3\chi_1^2}{r}\left(\frac{2m_2}{M}-1-3\nu\right)\Bigg] \\
& +\frac{1}{r^2c^3}\Bigg[\left(1+3\chi_1^2\right)\left(\chi_1 p_\varphi\left(-\frac{11m_1}{3M}+3\nu-\frac{4m_1\sigma_1}{M}\right)+\chi_2 p_\varphi\left(-\frac{7m_2}{2M}+3\nu\right)-\frac{8m_1}{M}p_\varphi B_2(\chi_1)\right. \\
& \left.-\frac{16m_1}{M}rp_r\right)-\frac{m_1}{3M}p_\varphi(53+48\sigma_1)\chi_1-\frac{5m_2}{2M}\chi_2 p_\varphi\Bigg]\Bigg\}
\end{aligned}
$$

- In BHPT this factor parametrizes the superradiance regime, where energy, momentum are *extracted* from the BH

- Known on circular orbits:
  $\dot{M} = \Omega \dot{S} \propto (\Omega_{\rm H} - \Omega)$

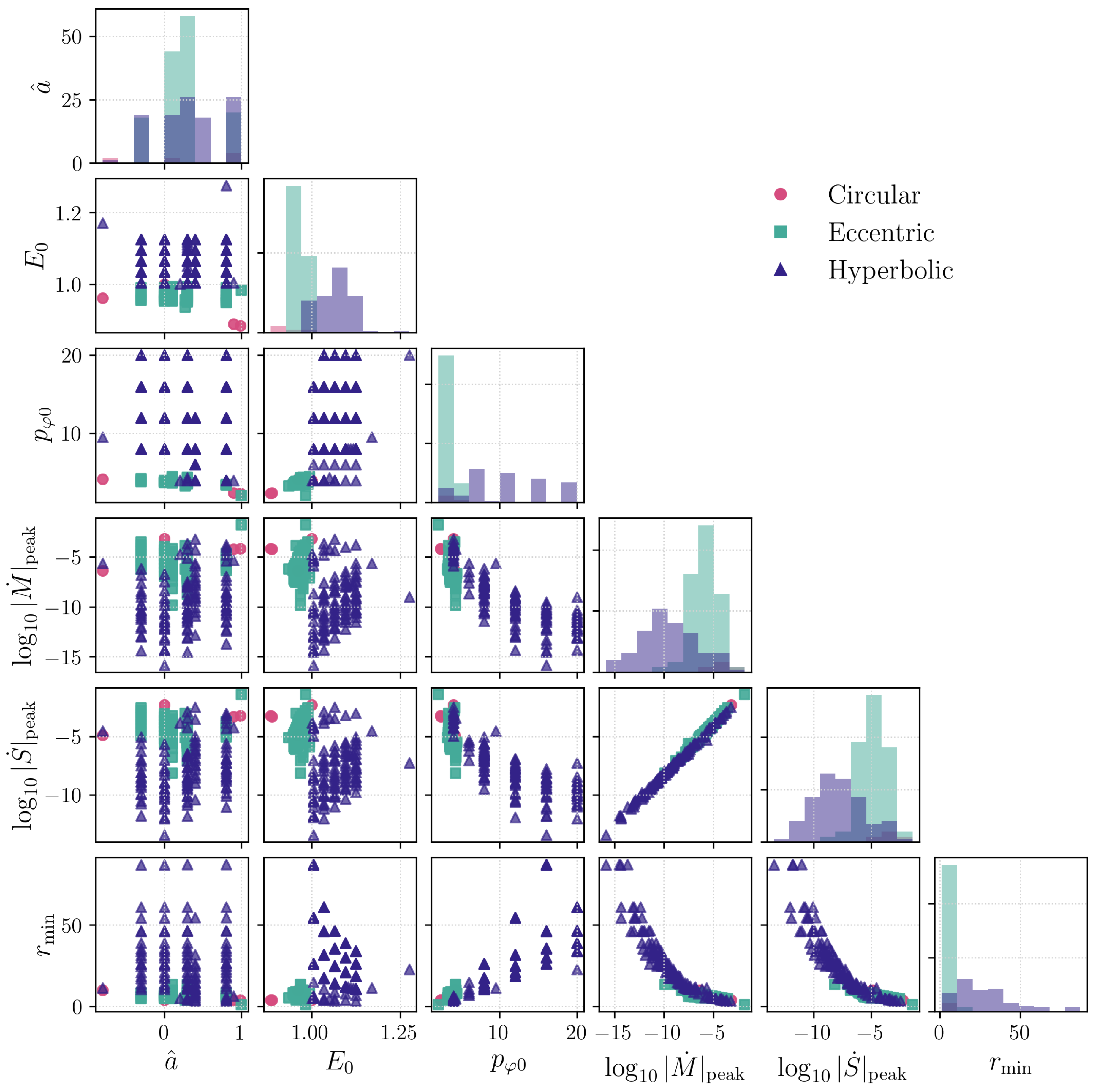
- On generic orbits, they are **different for the energy and angular momentum fluxes**

Numerical fluxes

- >200 simulations, with circular, eccentric, hyperbolic (geodesic) orbits of a **test-mass in Kerr** geometry
- Solve Teukolsky equation in time domain for ψ_0 Newman-Penrose scalar
- Compute **horizon fluxes** with Poisson's formalism

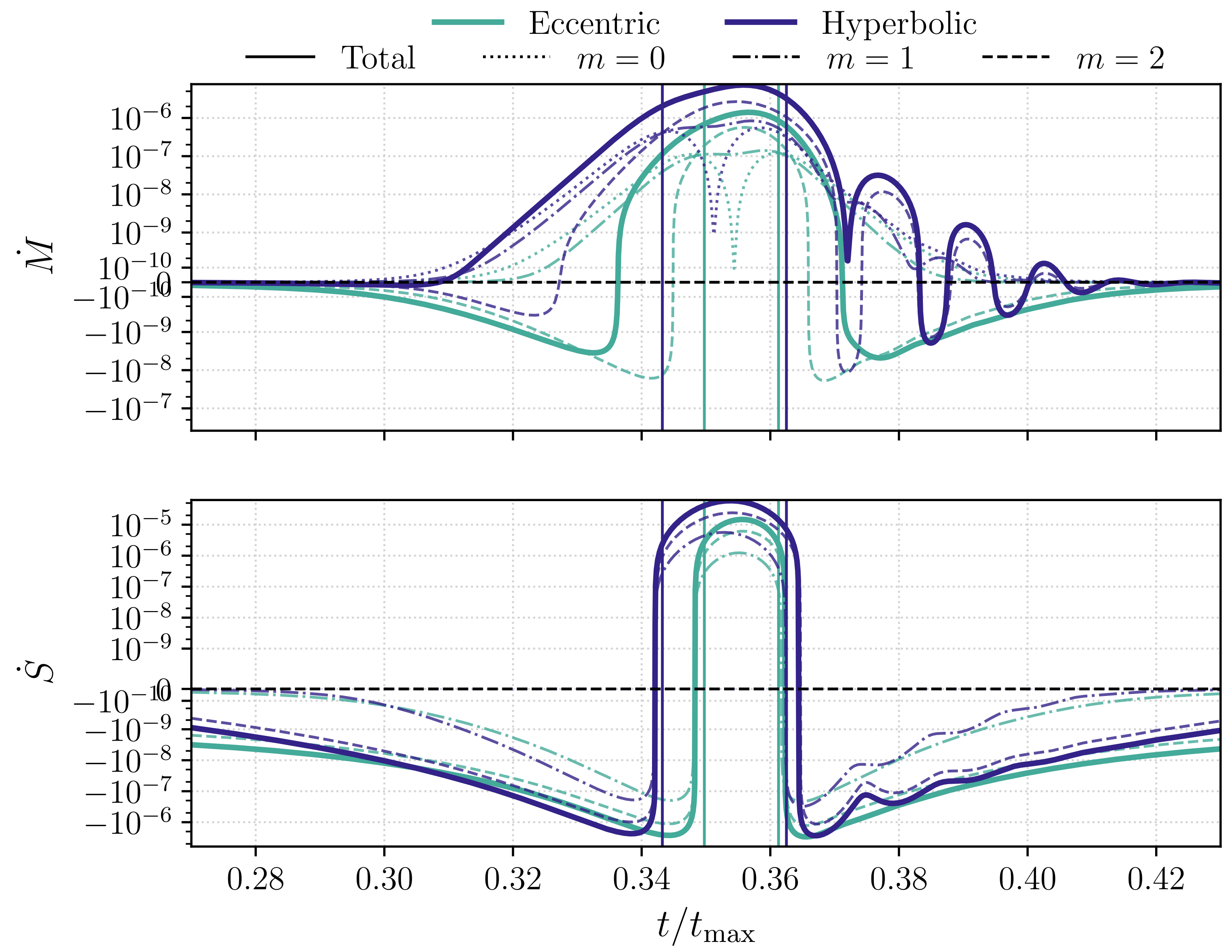
Tests:

1. Can we reliably predict the sign of the fluxes?
2. Can we reproduce their values?

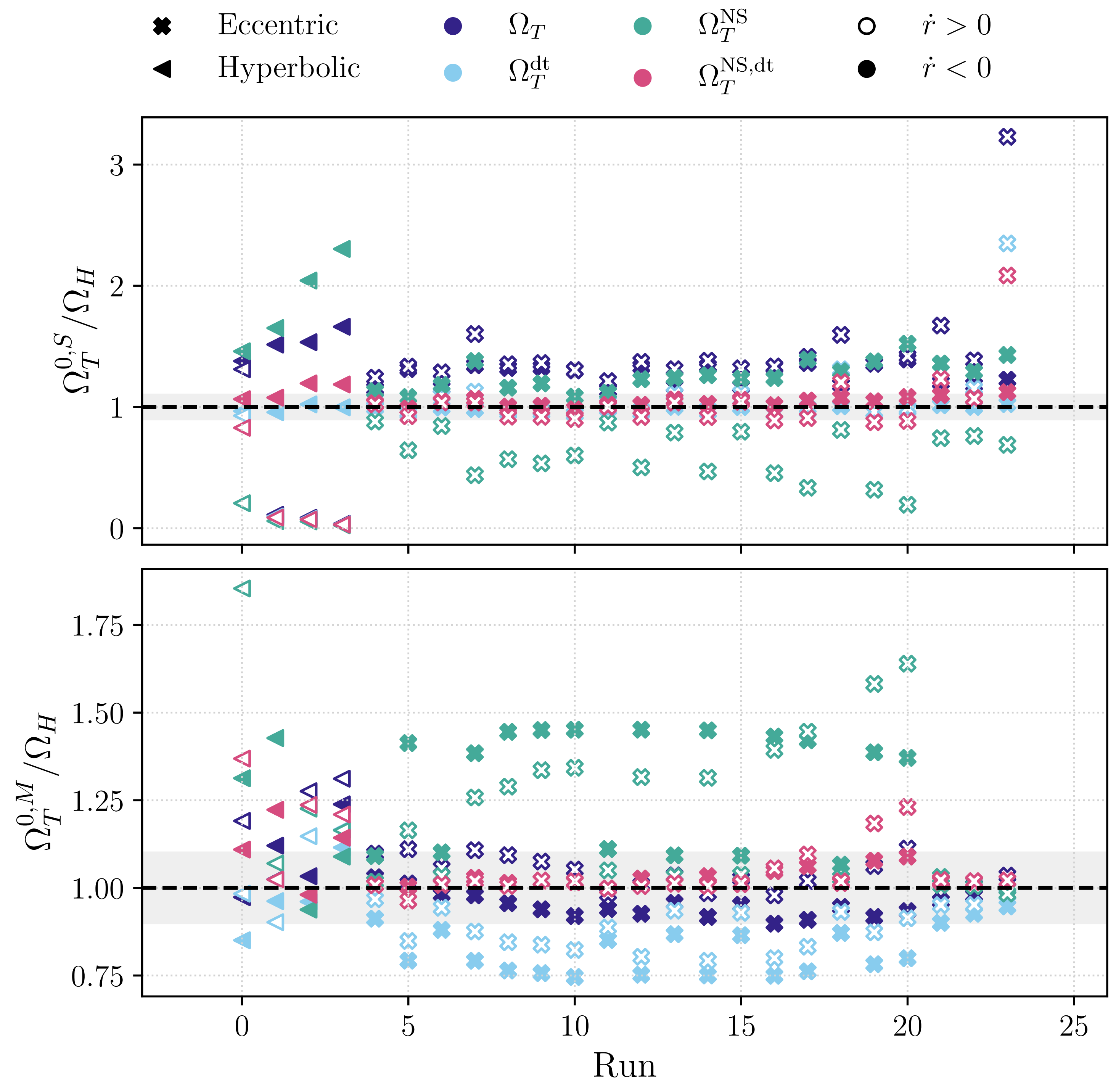


1. Surprisingly well

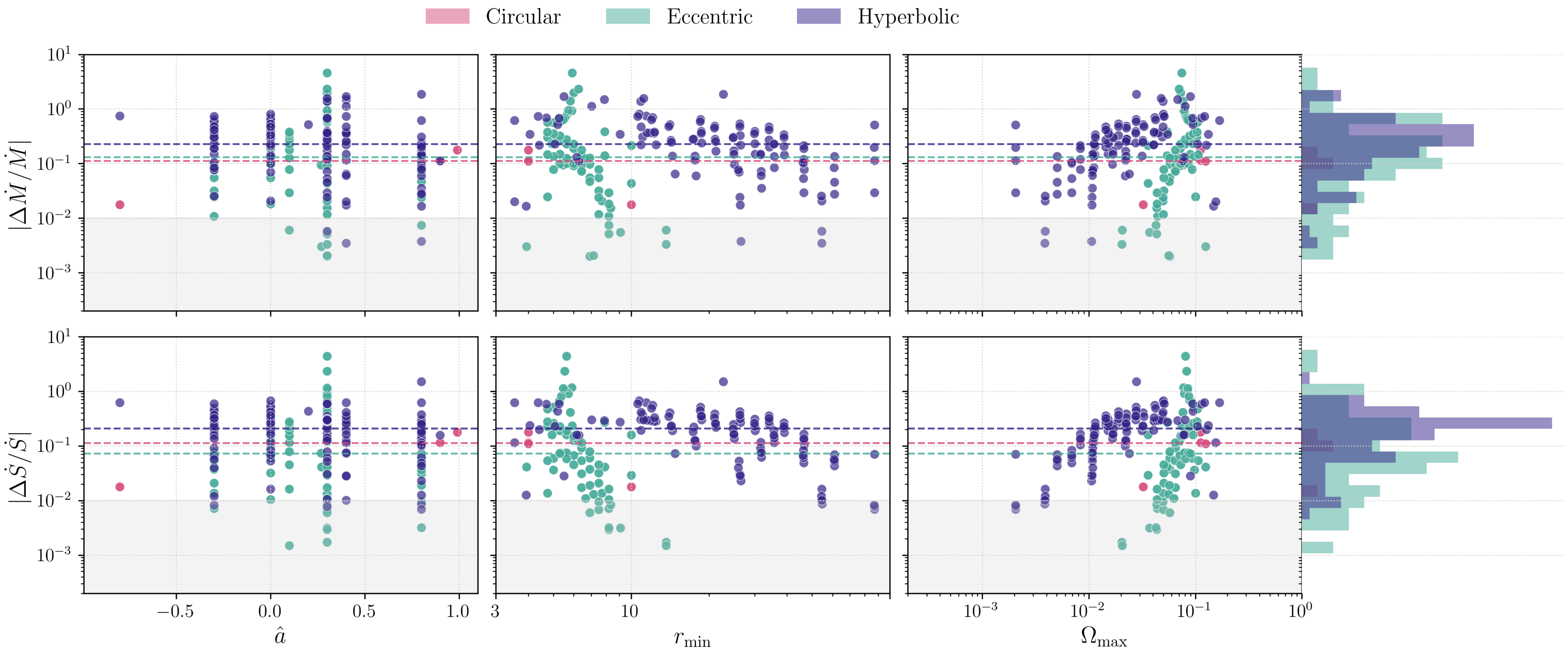
- Numerical fluxes behave as expected (energy flips before momentum)
- (Except for **quasi-normal bursts…**)



- Model for **superradiance factor** with non-spinning corrections tracks sign changes in numerical fluxes quite well
- Predicted within 10% in 70% of cases



2. Not surprisingly not so well



- With sophisticated **factorization and resummation**, good results on circular and low-eccentricity orbits
- Error grows with $\Omega^{\max}$; hyperbolic orbits particularly hard to model

Thank you

RTG 2575:
Rethinking
Quantum Field Theory

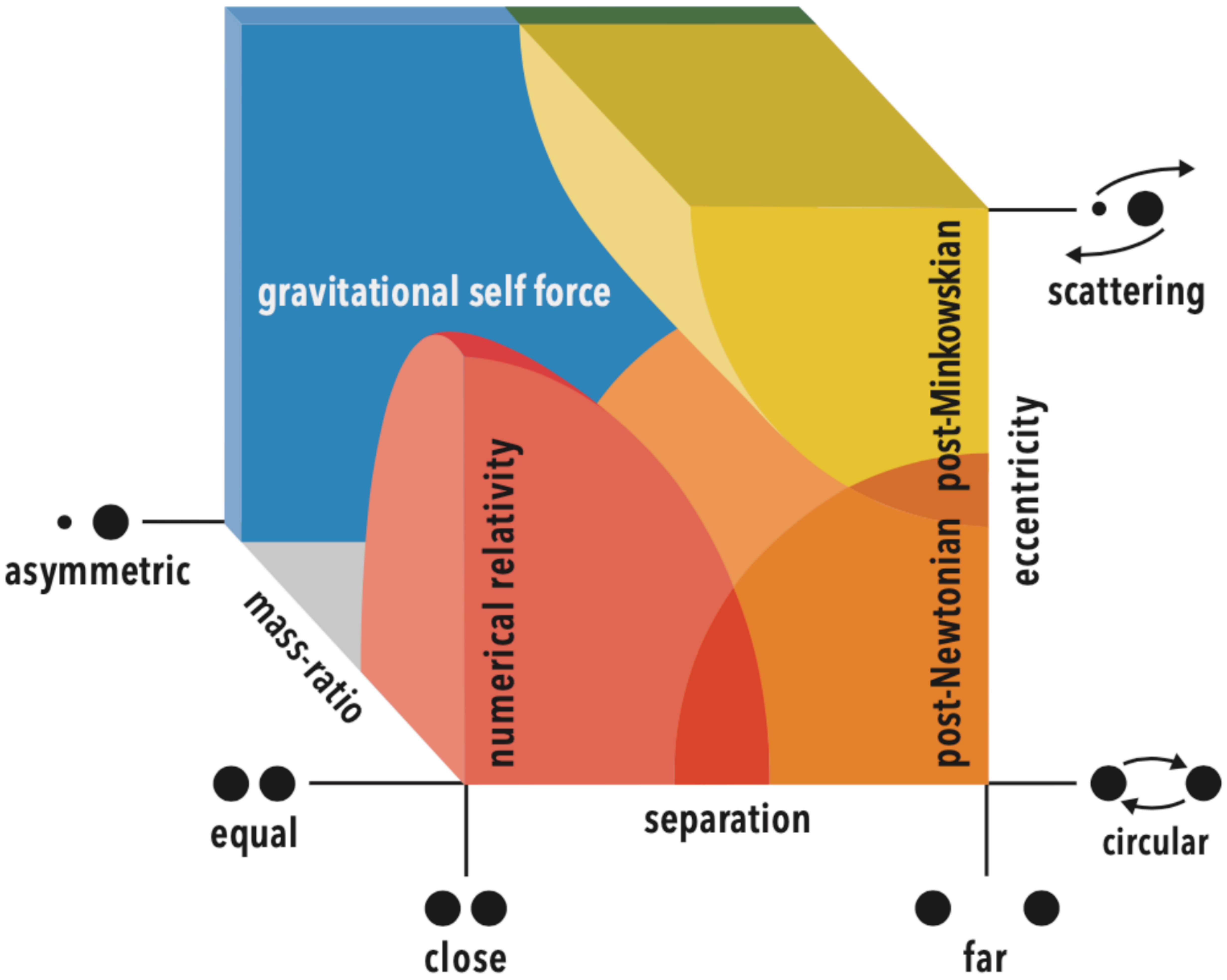
HUMBOLDT-UNIVERSITÄT ZU BERLIN

DFG Deutsche Forschungsgemeinschaft

Black Hole Response Theory and the Shockwave Limit

Lara Bohnenblust, **Carl Jordan Eriksen**, Jitze Hoogeveen,
Gustav Uhre Jakobsen, Jan Plefka

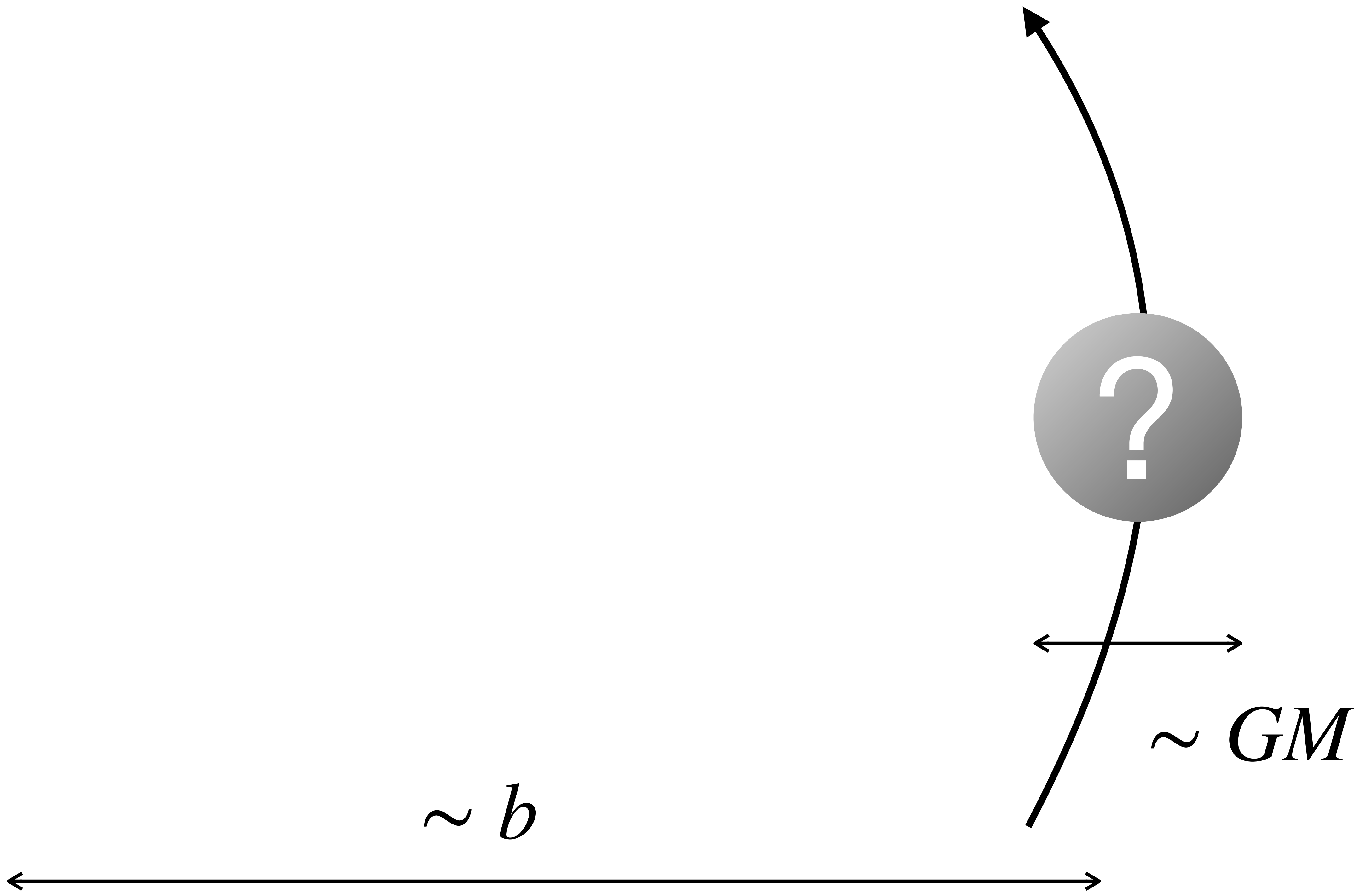
08.04.2026
Nordita PhD School
Stockholm



Credit: Ana Carvalho

Goldberger, Rothstein [0409156]
Levi, Steinhoff [1506.05056]
Porto [1601.04914]
Saketh, Steinhoff, Vines, Buonanno [2212.13095]

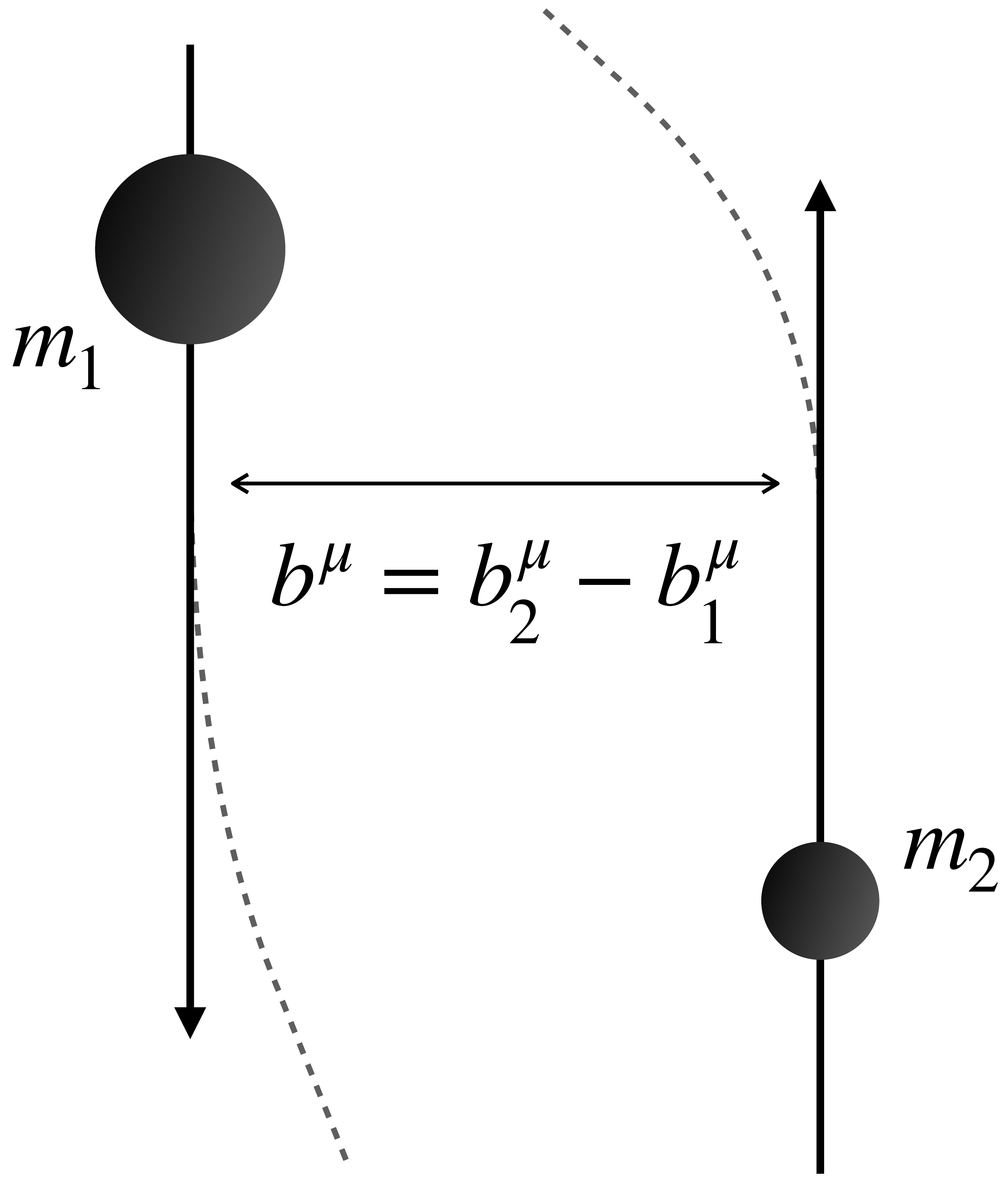
Worldline EFT



Mogull, Plefka, Steinhoff [2010.02865]
Jakobsen, Mogull, Plefka, Sauer [2207.00569]

Perturbative two-body dynamics with WQFT

PN	PM	SF
γ	$\frac{Gm_i}{b}$	$\frac{m_2}{m_1}$



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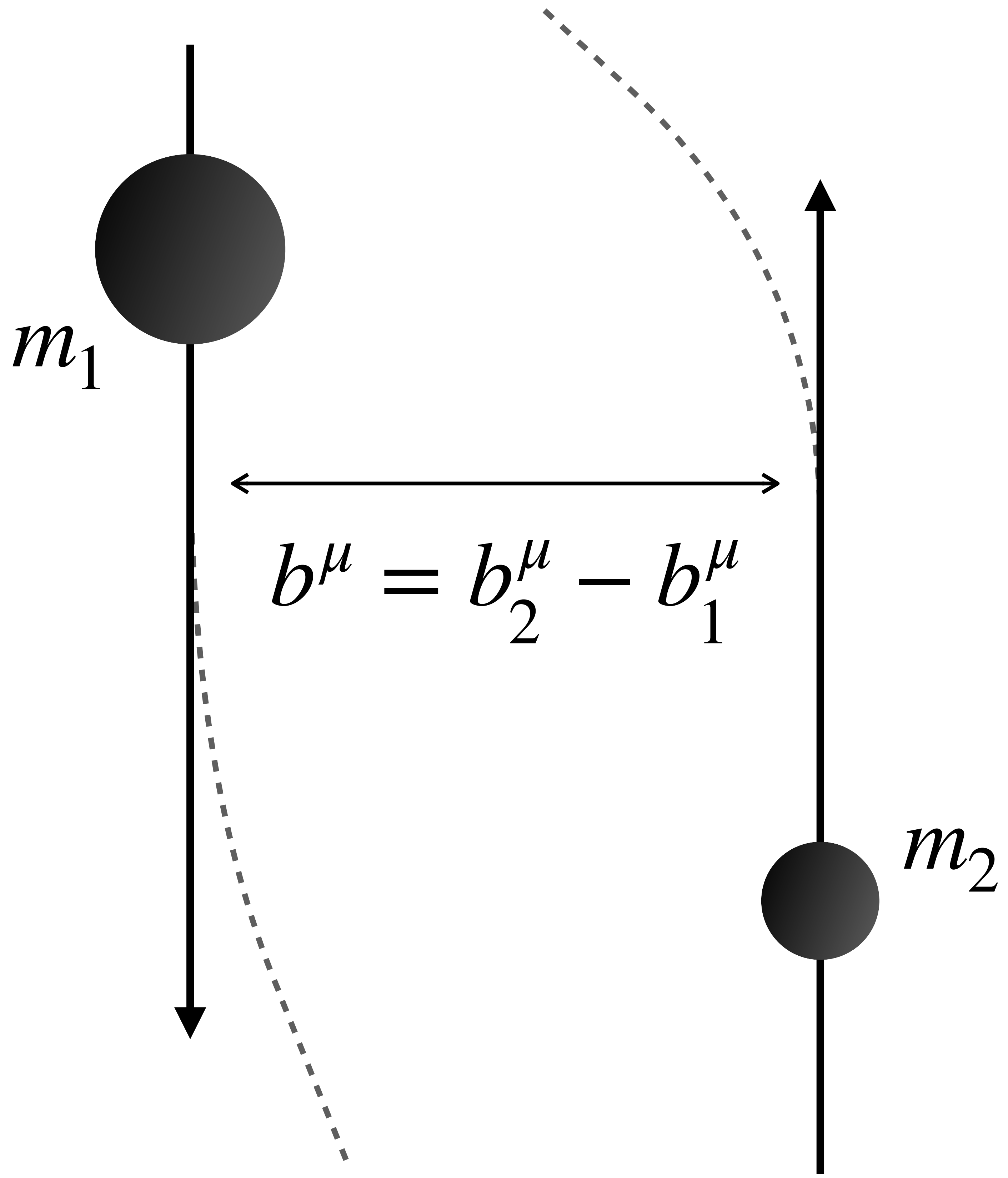
PN	PM	SF
γ	$\dfrac{Gm_i}{b}$	$\dfrac{m_2}{m_1}$

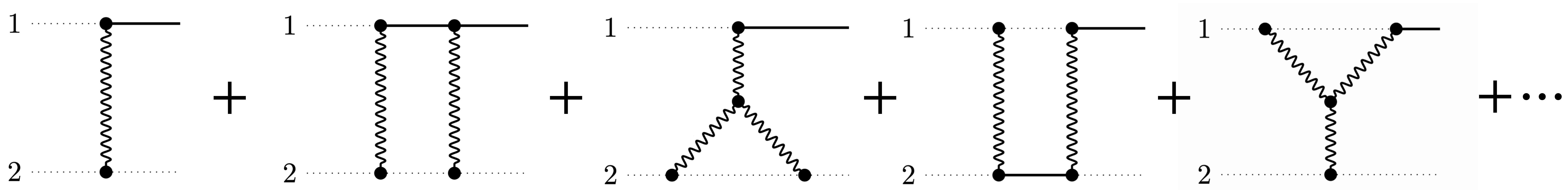


tree-level one-point fcts. solve classical EoMs!

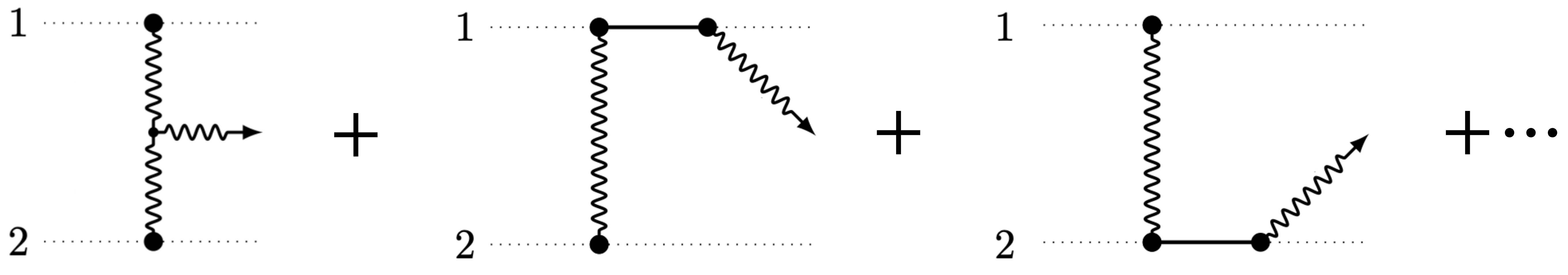
$$\langle X \rangle = \int \mathscr{D}[h, z_i]\, X \exp \mathrm{i}(S_{\mathrm{EH}}[h] + S_{\mathrm{wl},1}[h, z_1] + S_{\mathrm{wl},2}[h, z_2])\Big|_{\mathrm{tree}} \sim \frac{\delta Z[J]}{\delta J}\Big|_{\mathrm{tree}}$$

Perturbative two-body dynamics with WQFT

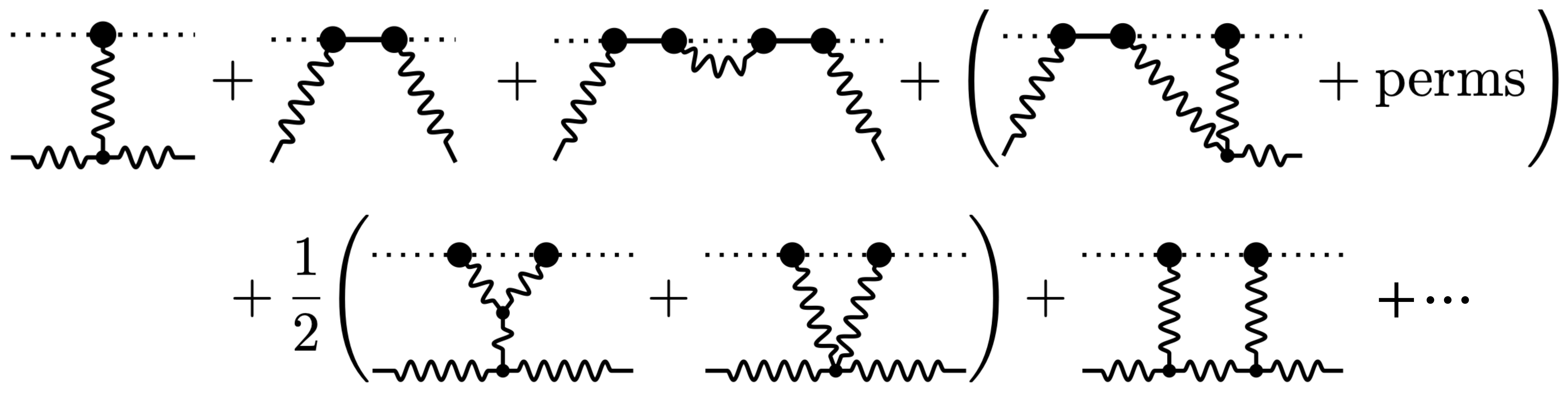
Impulse: $\Delta p_1^\mu =$



Waveform: $k^2\langle h_{\mu\nu}(k)\rangle =$

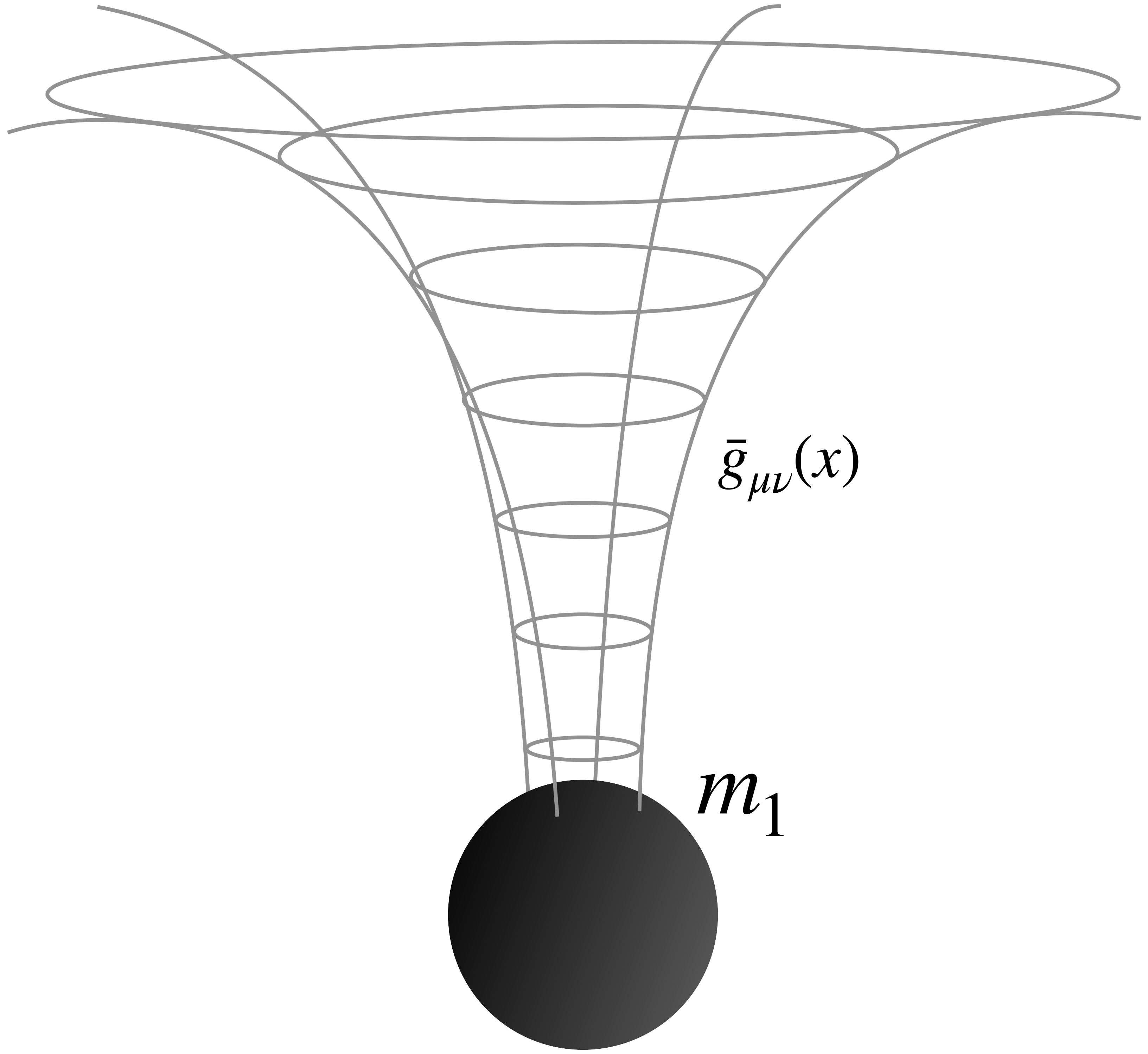


Compton: $k_1^2 k_2^2 \langle h_{\mu_1\nu_1}(k_1) h_{\mu_2\nu_2}(k_2)\rangle =$



Black hole response

$$Z[T] = \exp \mathrm{i} W[T]$$



$$\mathrm{i}W[\mathcal{T}^{(\pm)}] = -\mathrm{i}\int_{k_1} \mathcal{T}^{(-)\alpha\beta}(k_1)\mathcal{R}_{\alpha\beta}(k_1) - \int_{k_1,k_2} \mathcal{T}^{(+)\alpha\beta}(k_1)\mathcal{T}^{(-)\mu\nu}(k_2)\mathcal{R}_{\alpha\beta\mu\nu}(k_1,k_2)$$
$$+ \frac{\mathrm{i}}{2}\int_{k_1,k_2,k_3} \mathcal{T}^{(+)\alpha\beta}(k_1)\mathcal{T}^{(+)\mu\nu}(k_2)\mathcal{T}^{(-)\rho\sigma}(k_3)\mathcal{R}_{\alpha\beta\mu\nu\rho\sigma}(k_1,k_2,k_3) + \ldots$$

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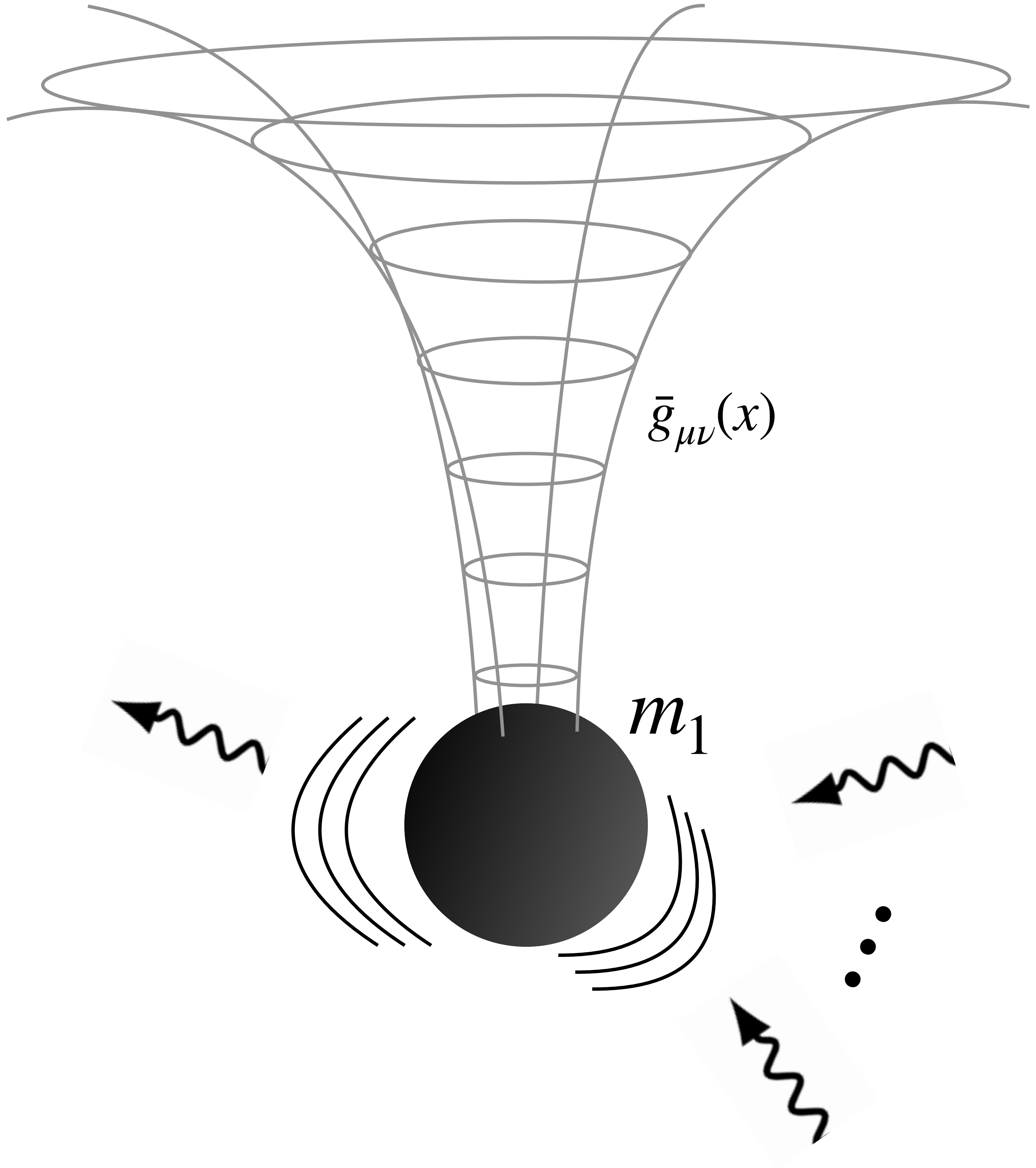

Encode response of black hole to external stimuli

Black hole response

$$Z[T] = \exp \mathrm{i}W[T]$$

"Compton amplitude" / linear BHPT

metric

$$\mathrm{i}W[\mathcal{T}^{(\pm)}] = -\mathrm{i}\int_{k_1} \mathcal{T}^{(-)\alpha\beta}(k_1)\mathcal{R}_{\alpha\beta}(k_1) - \int_{k_1,k_2} \mathcal{T}^{(+)\alpha\beta}(k_1)\mathcal{T}^{(-)\mu\nu}(k_2)\mathcal{R}_{\alpha\beta\mu\nu}(k_1,k_2)$$
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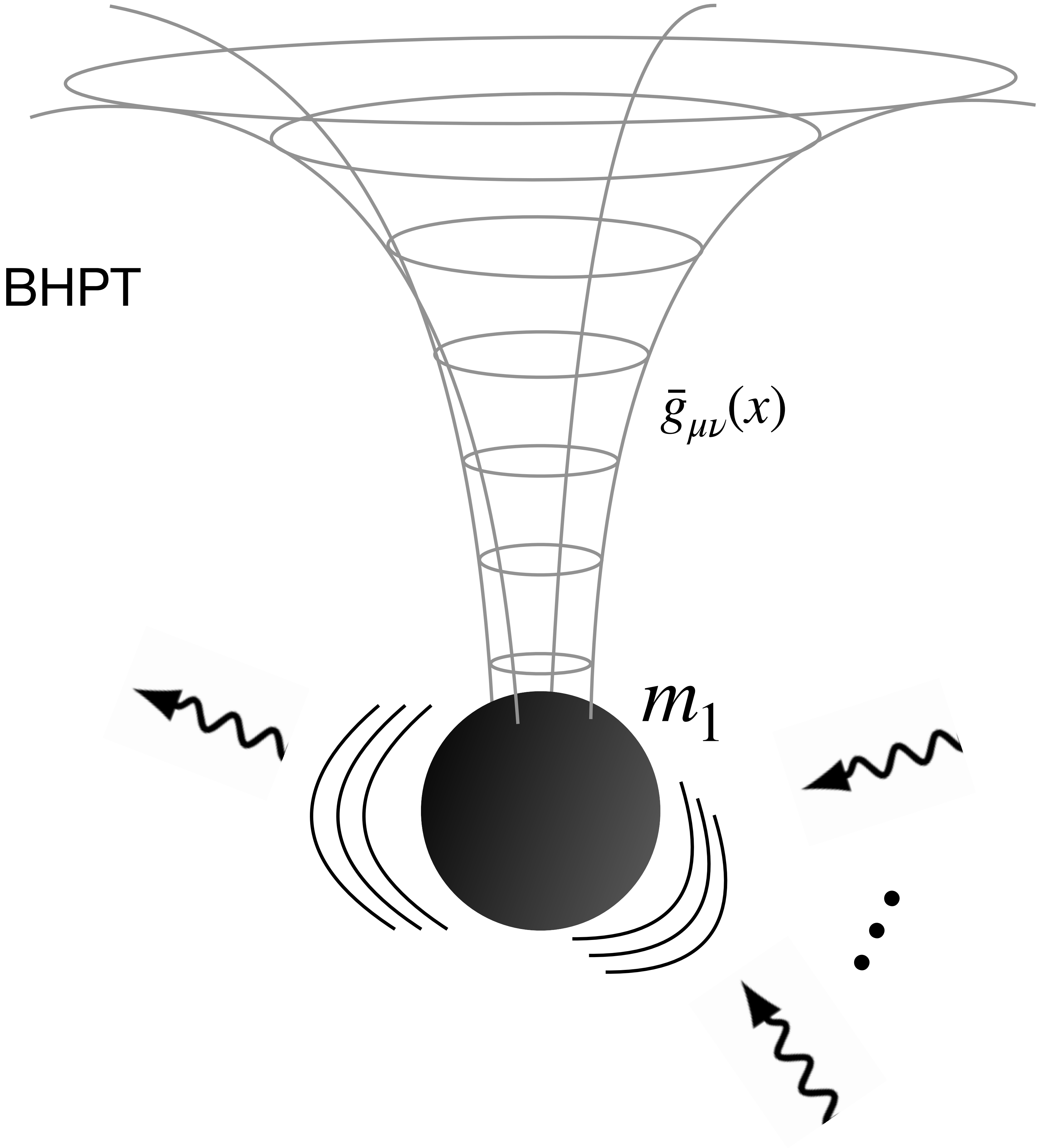
non-linear BHPT



Encode response of black hole to external stimuli

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$$Z[T] = \exp \mathrm{i}W[T]$$

“Compton amplitude” / linear BHPT

metric

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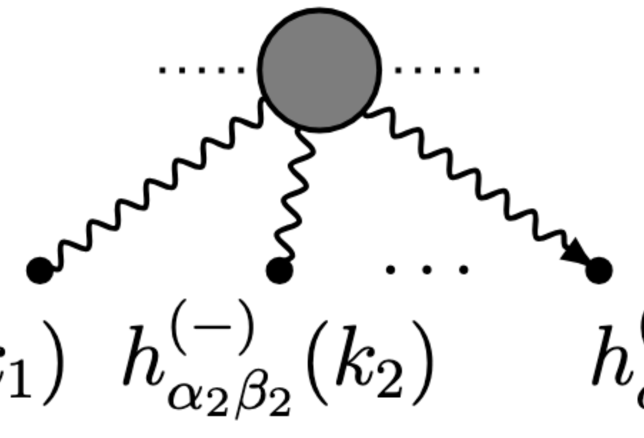
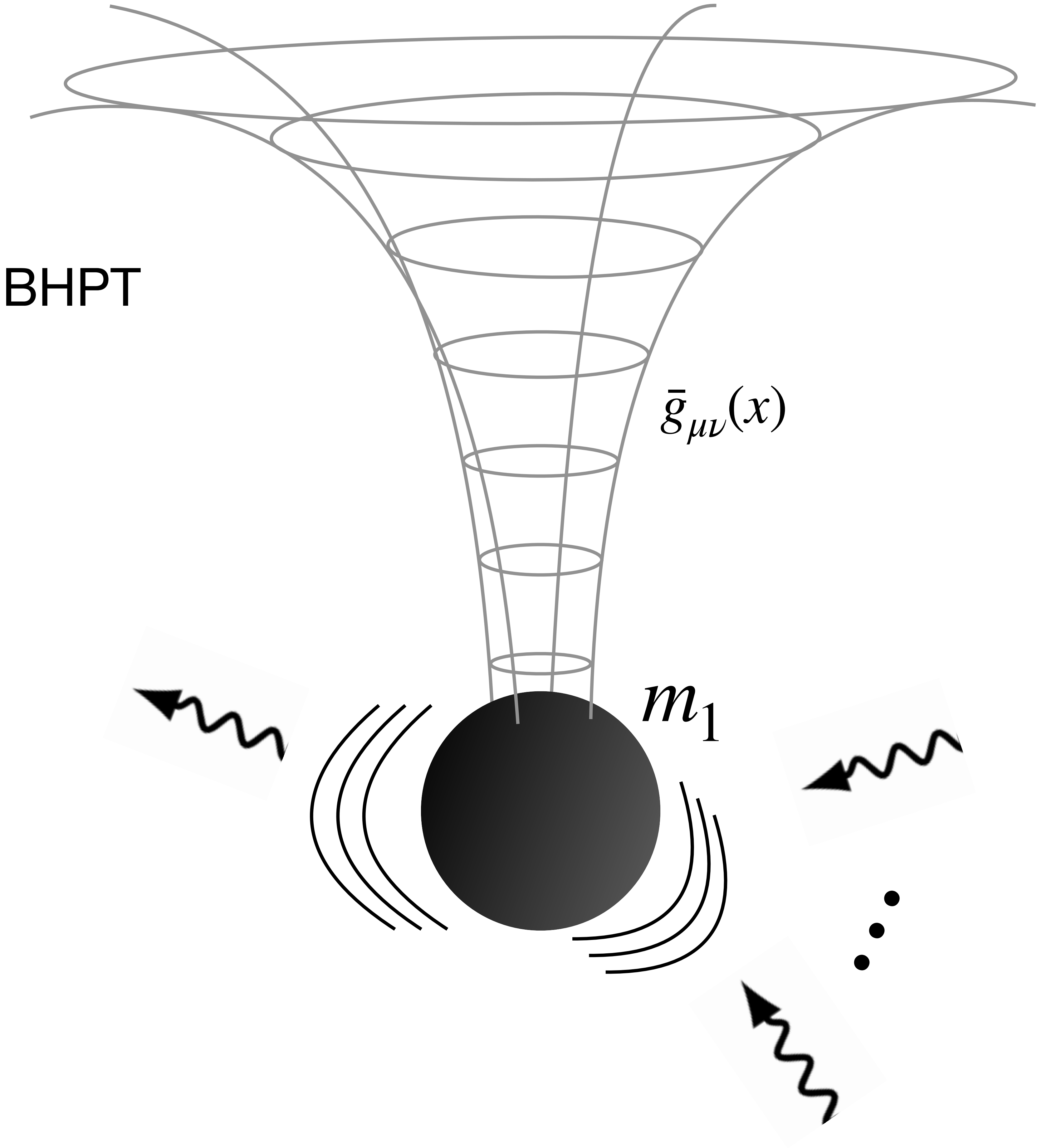
non-linear BHPT

$$\mathcal{R}_{\alpha_1\beta_1\alpha_2\beta_2\cdots\alpha_n\beta_n}(k_1,k_2,\ldots,k_n) \;=$$



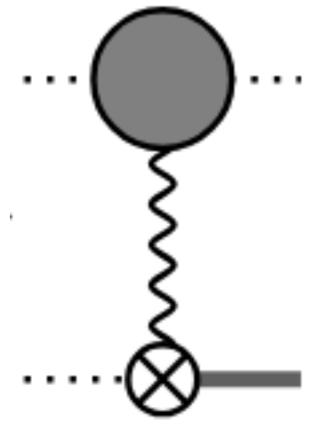


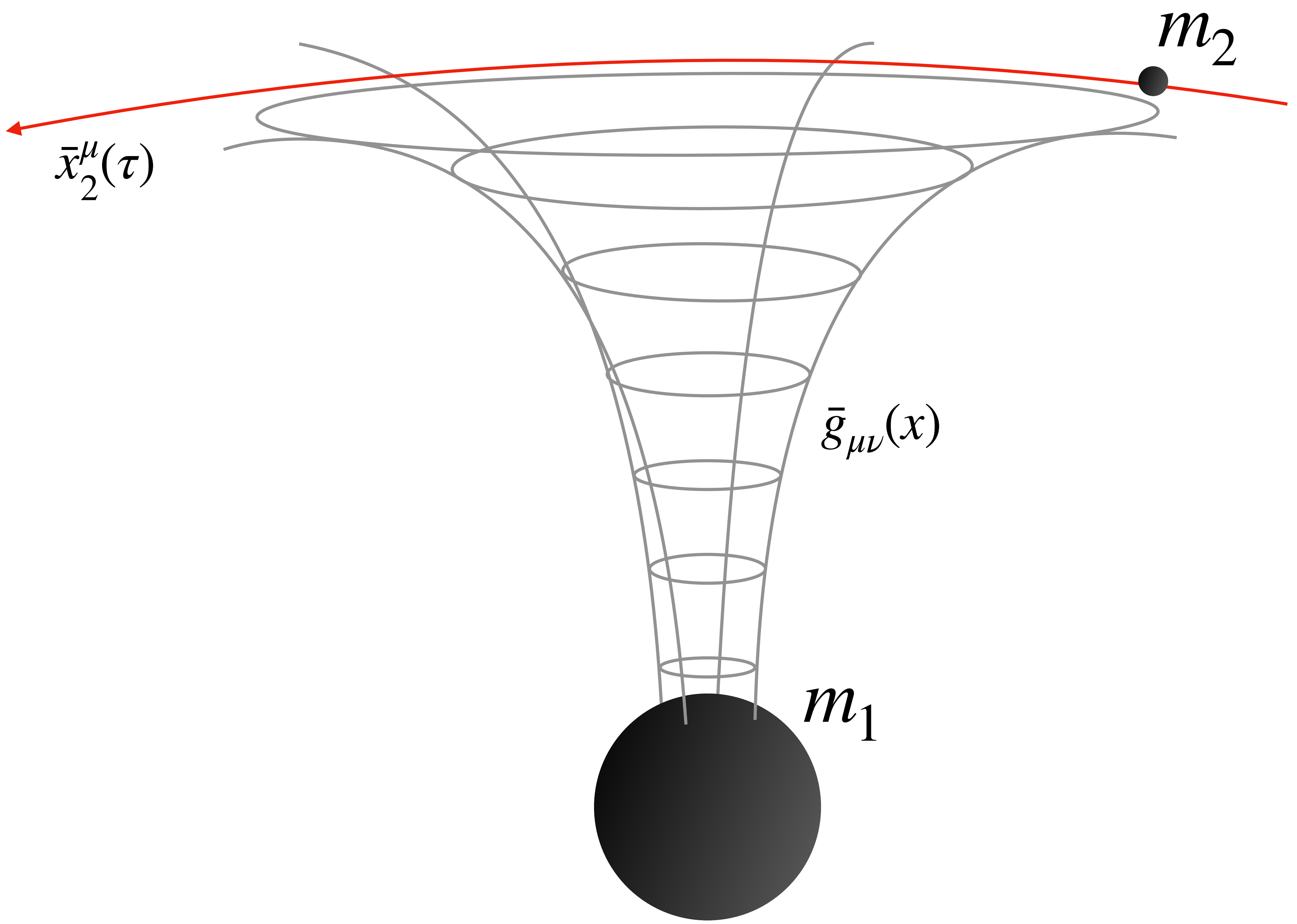
Encode response of black hole to external stimuli

Cheung et al. [2406.14770]
Kosmopoulos, Solon [2308.15304]

Self-force expansion

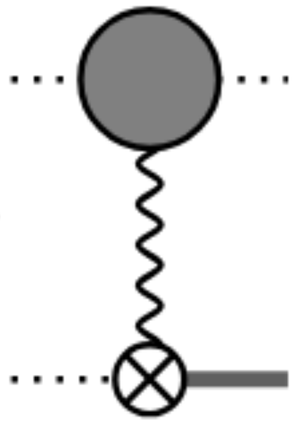
$$x_2^\mu(\tau) = \bar{x}_2^\mu(\tau) + z_2^\mu(\tau) \quad :$$



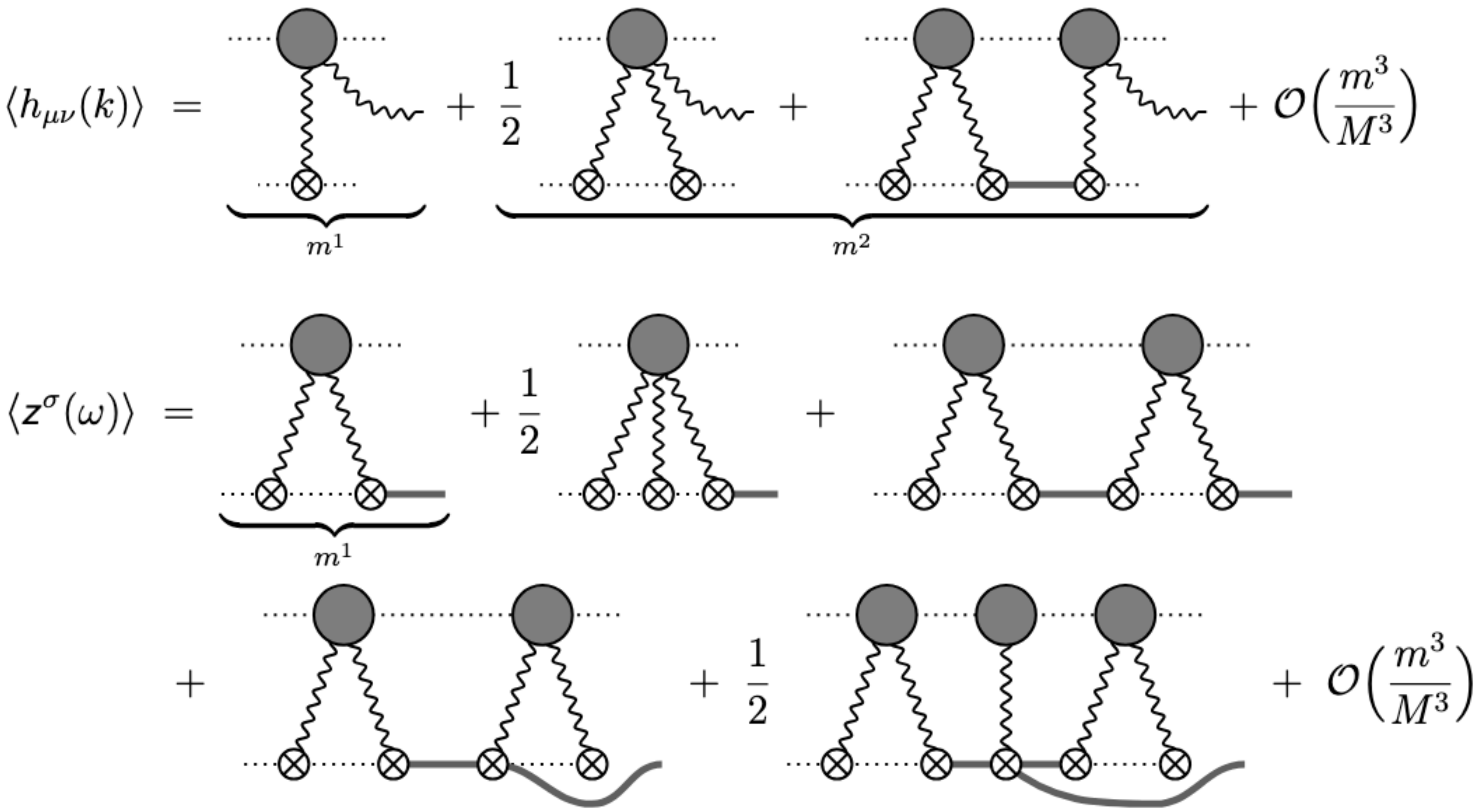


Self-force expansion

$$x_2^\mu(\tau) = \bar{x}_2^\mu(\tau) + z_2^\mu(\tau) \quad :$$

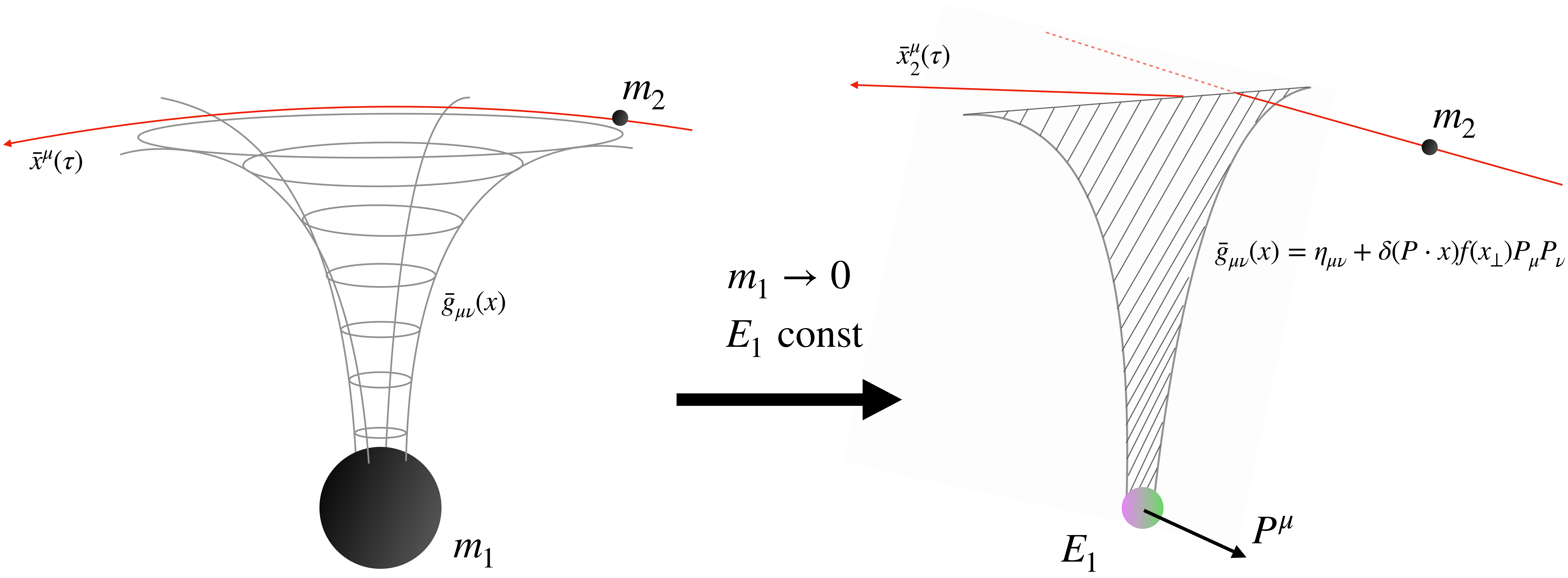


Integrating out leads to

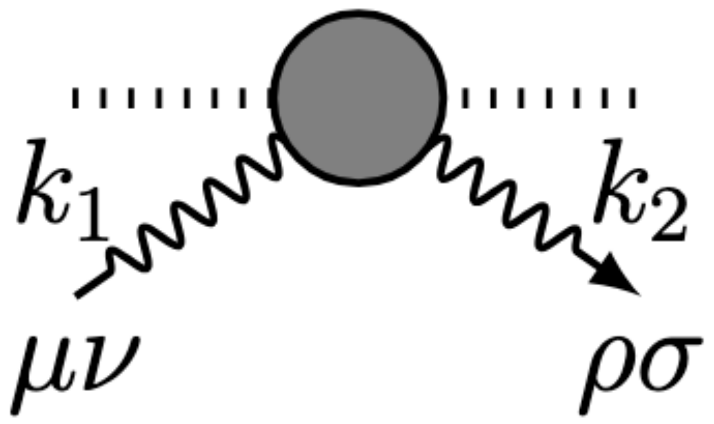


Aichelburg, Sexl (1971)
Dray, 't Hooft (1985)

The shockwave limit



The shockwave limit



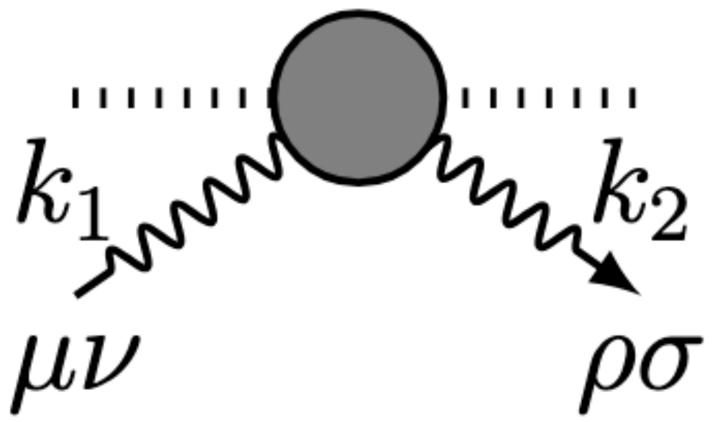
$$= -2\mathrm{i}(P\cdot k_1)\hat{\delta}(P\cdot q)A^{(2h_1,2h_2)}\int \mathrm{d}^{D-2}\boldsymbol{x}_\perp\, \mathrm{e}^{-\mathrm{i}\boldsymbol{q}_\perp\cdot\boldsymbol{x}_\perp}\left[\mathrm{e}^{-2\mathrm{i}G(P\cdot k_1)f(\boldsymbol{x}_\perp^2)}-1\right]$$

$$A^{(2h_1,2h_2)} \equiv \frac{(P\cdot F_1^{(h_1)}\cdot F_2^{(h_2)}\cdot P)^2}{(P\cdot k_1)^4}$$

$$W = 2G(P\cdot k_1)$$

Raj, Venugopalan [2311.03463]

The shockwave limit



$$= -2\mathrm{i}(P\cdot k_1)\hat{\delta}(P\cdot q)A^{(2h_1,2h_2)}\int \mathrm{d}^{D-2}\boldsymbol{x}_\perp\, \mathrm{e}^{-\mathrm{i}\boldsymbol{q}_\perp\cdot\boldsymbol{x}_\perp}\left[\mathrm{e}^{-2\mathrm{i}G(P\cdot k_1)f(\boldsymbol{x}_\perp^2)}-1\right]$$

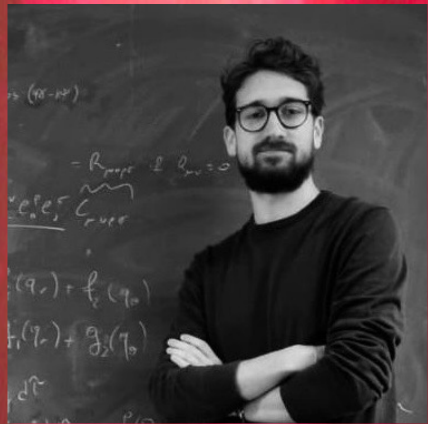
$$\xrightarrow{D\to 4} \mathrm{e}^{-\mathrm{i}W/\epsilon}\,\hat{\delta}(P\cdot q)W\frac{\Gamma(1-\mathrm{i}W)}{\Gamma(1+\mathrm{i}W)}\frac{8\pi(P\cdot k_1)A^{(2h_1,2h_2)}}{\boldsymbol{q}_\perp^2(\boldsymbol{q}_\perp^2L^2)^{-\mathrm{i}W}}$$

$$A^{(2h_1,2h_2)} \equiv \frac{(P\cdot F_1^{(h_1)}\cdot F_2^{(h_2)}\cdot P)^2}{(P\cdot k_1)^4}$$

$$W = 2G(P\cdot k_1)$$

Davide Panella

Joint PhD student at NBI & University of Perugia - II year



- Supervisors:
  Prof. Gianluca Grignani, Prof. Troels Harmark

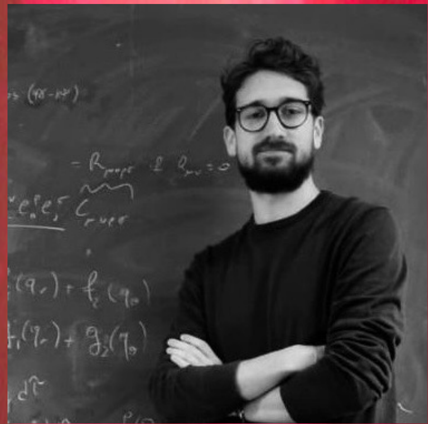
- Contacts:
  davide.panella@nbi.ku.dk
  davide.panella@dottorandi.unipg.it

Davide Panella

Joint PhD student at NBI & University of Perugia - II year

Inter fan

Currently developing uncle lore



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Chess loser

Gin tonic lover

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KØBENHAVNS UNIVERSITET

INFN Istituto Nazionale di Fisica Nucleare

A.D. 1308 unipg UNIVERSITÀ DEGLI STUDI DI PERUGIA

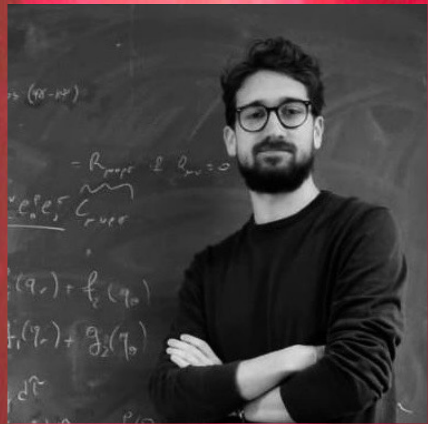
Davide Panella

Joint PhD student at NBI & University of Perugia - II year

- **Research interests:**
  I'm interested in studying hierarchical triple systems in strong gravity regime modelling tidal perturbation on coalescing binaries dynamics.

  I am working on both secular and non-secular phenomena, such as ZLK mechanism and precession resonances.

  As an outlook, I plan to include tidal perturbations in gravitational wave modelling, using Post-Newtonian framework and Effective-One-Body approach.



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  davide.panella@dottorandi.unipg.it

- **Main Collaborators:**
  Prof. Gianluca Grignani, Prof. Troels Harmark, Prof. Marta Orselli, Marta Cocco, Elisa Grilli, Dr. Daniele Pica, Dr. Andrea Placidi

- "Observable signature of magnetic tidal coupling in hierarchical triple systems" M. Cocco, G. Grignani, T. Harmark, M. Orselli, **DP**, and D. Pica.
  arXiv: 2510.24897

Poster next week!

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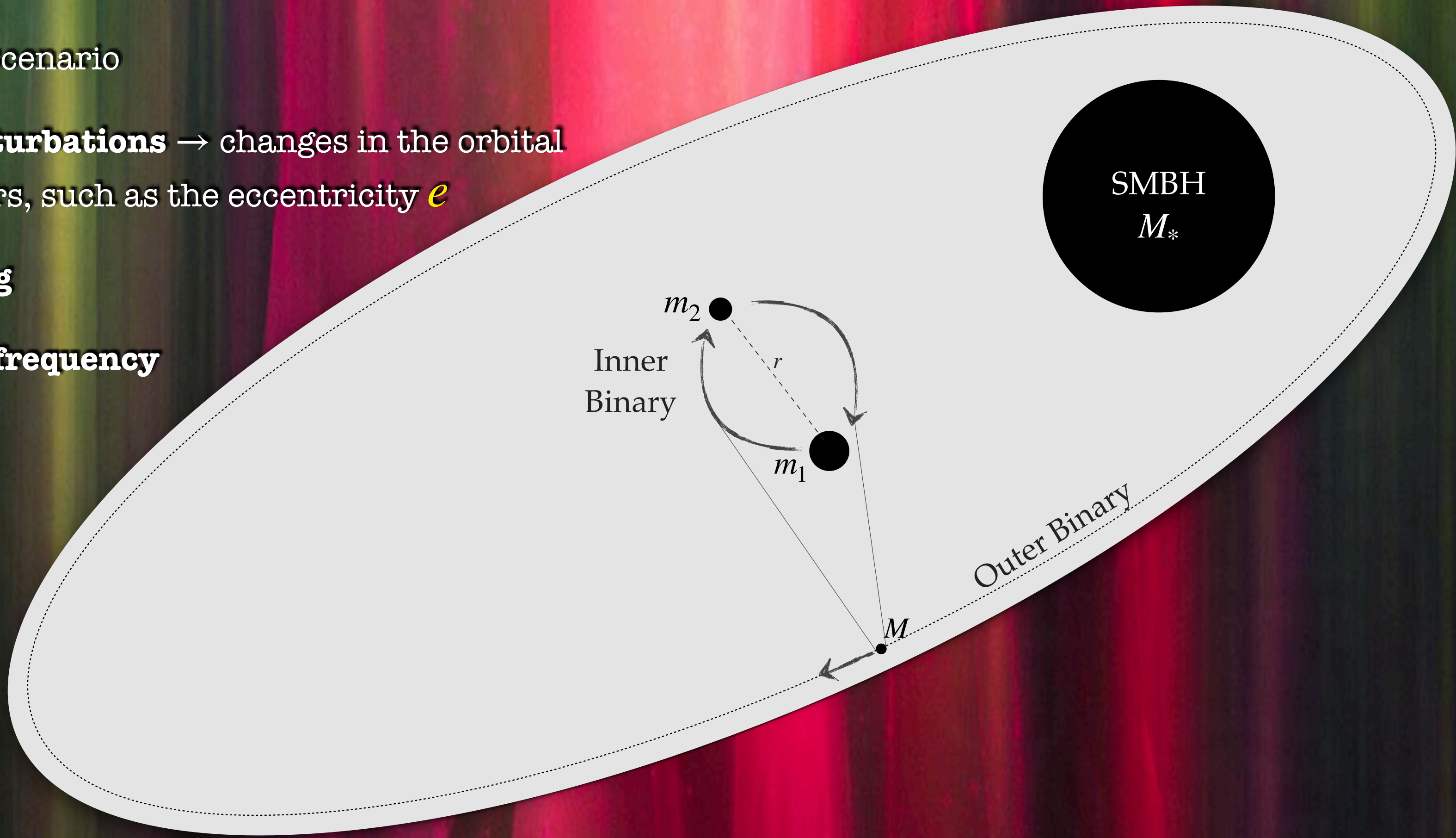
Tidal effects in hierarchical triple systems

Why?

- Realistic scenario
- **Tidal perturbations** → changes in the orbital parameters, such as the eccentricity e
- **Dephasing**
- **GW peak frequency**



Tidal effects in hierarchical triple systems

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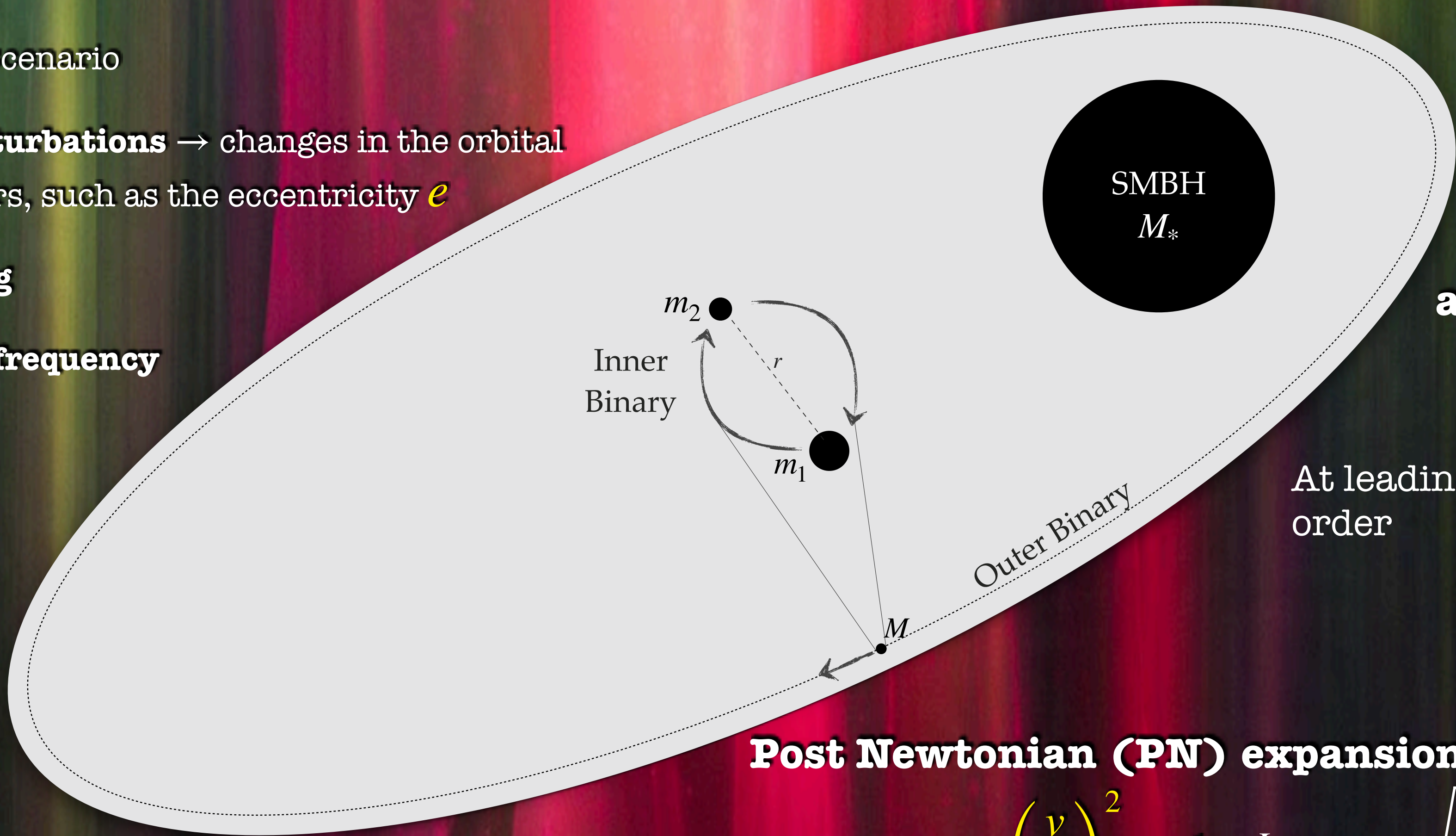


How?

Small-tide approximation

$$\frac{r}{\mathcal{R}} \ll 1$$

At leading quadrupolar order

Electric $\mathcal{E}_{ij}$

Magnetic $\mathcal{B}_{ij}$

Post Newtonian (PN) expansion

$$\left(\frac{v}{c}\right)^2 \ll 1 \qquad L_I = -m_I c\sqrt{-G_{\mu\nu}\frac{dx_I^\mu}{d\tau}\frac{dx_I^\nu}{d\tau}}$$

Tidal effects in hierarchical triple systems

- **The resulting Hamiltonian, up to quadrupolar order, at the 0.5 PN order is given by:**

$$H_{inner} = \underbrace{\frac{p^2}{2\mu} - \frac{GM\mu}{r} + \frac{1}{2}\mu c^2 x^i x^j \mathcal{E}_{ij}}_{0PN} + \underbrace{\frac{2}{3}c^2 \frac{m_1 - m_2}{M} \frac{p^i}{c} x^k x^l \epsilon_{ijk} \mathcal{B}^j{}_l}_{0.5PN}$$

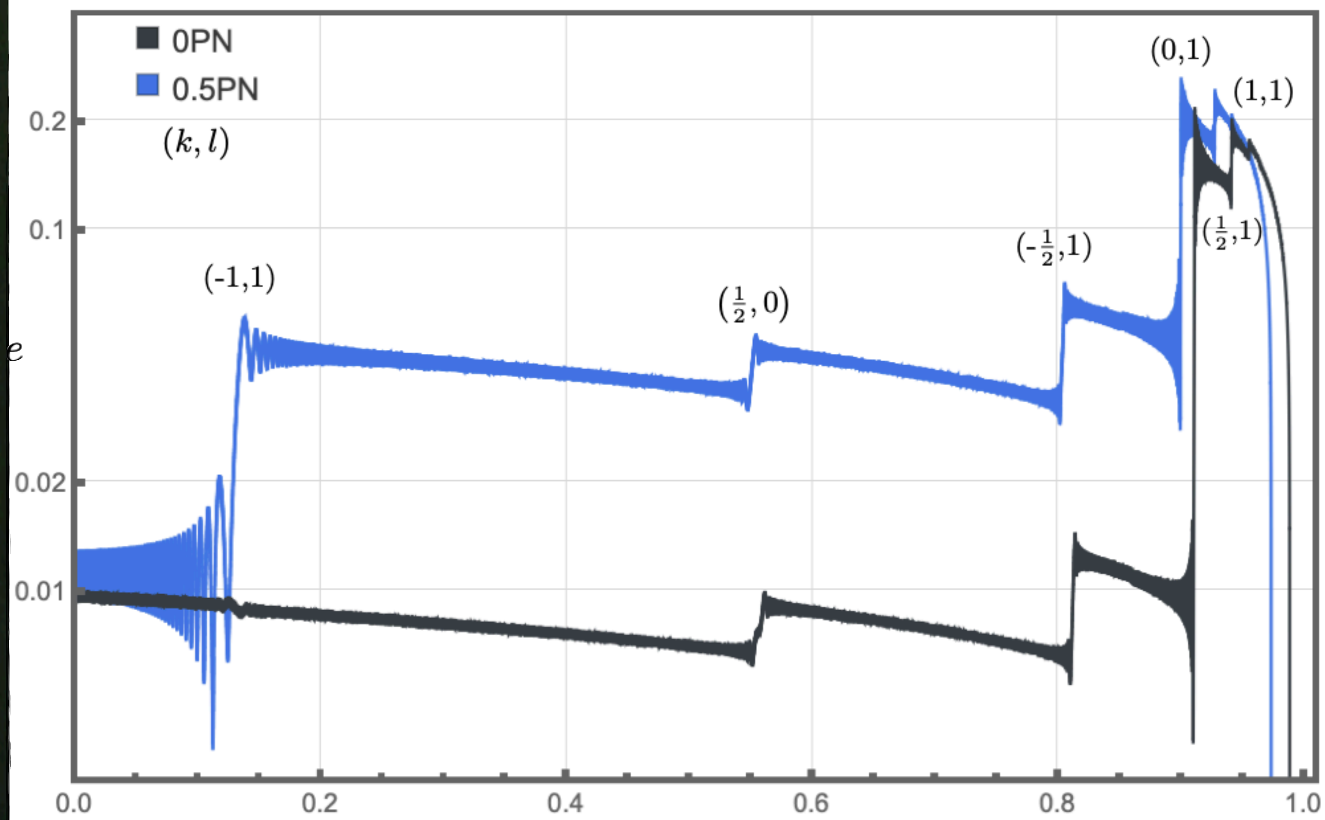
(**DP** et al, 2025)

- Coupling not only to positions, but also to velocities!
- Purely relativistic → test of GR in a strong-gravity regime

- Non secular effect: **precession resonances**

Whenever the periastron precession frequency $\dot{\gamma}$ becomes commensurable with characteristic frequencies of the external orbital motion occurs a resonant peak in the binary eccentricity e

Magnetic tidal signature in precession resonances



(**DP** et al, 2025)

$\hat{t}/t_{\rm RR}$

$M_* = 4\times10^6 M_\odot$, $m_1 = 25 M_\odot$, $m_2 = 1.5 M_\odot$, $\hat{e} = 0.08$, $\hat{a} = 10 GM_*/c^2 \sim 0.4$AU, $t_{\rm RR} \sim 6$ yrs, $GW_{peakfrequency} \sim 0.06$Hz, $a_0 \sim 0.0003$ AU , $e_0 = 0.01$, $\gamma_0 = 0^\circ$, $I_0 = 20^\circ$, $\vartheta_0 = 0^\circ$, $\Psi_0 = 0^\circ$

TABLE I. Resonances condition at the first order in $\hat{e}$

$$\dot{\gamma} = k\,\Omega_{\hat{r}} + l\,\Omega_{\hat{\Psi}}, \quad k \in \mathbb{Z}/2,\ l \in \mathbb{Z}$$

$\mathscr{E}_{ij}$ (0PN)	$\mathscr{B}_{ij}$ (0.5PN)
$\dot{\gamma} = \frac{1}{2}\,\Omega_{\hat{r}}$	
$\dot{\gamma} = -\frac{1}{2}\,\Omega_{\hat{r}} + \Omega_{\hat{\Psi}}$	$\boxed{\dot{\gamma} = -\Omega_{\hat{r}} + \Omega_{\hat{\Psi}}}$
$\dot{\gamma} = \Omega_{\hat{\Psi}}$	$\dot{\gamma} = \Omega_{\hat{\Psi}}$
$\dot{\gamma} = \frac{1}{2}\,\Omega_{\hat{r}} + \Omega_{\hat{\Psi}}$	$\boxed{\dot{\gamma} = \Omega_{\hat{r}} + \Omega_{\hat{\Psi}}}$

First evidence of magnetic tidal coupling in resonant dynamics!

- New resonances
- Shorter merger time
- GW peak frequency within LISA band
- Dephasing potentially detectable


Tack!

Gong show: Sofiya Sianiuta

PhD student in Theoretical Physics at Uppsala University

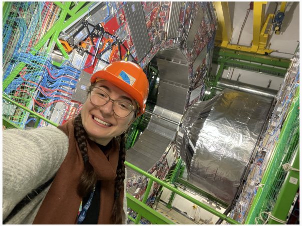
Project: Scattering Amplitudes Methods for Gravitational Waves
Supervisor: Prof. Chia-Hsien Shen (PI of ERC AmpEFT project)
Co-supervisor: Prof. Henrik Johansson

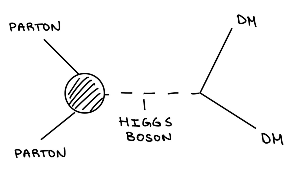
April 8, 2026

erc
European Research Council
Established by the European Commission

Background

- M.Sc.at NTNU
- Exchange year, UniBo
- Master's thesis (NTNU ∪ UiO)
  - Supersymmetric Standard Model
  - Cross section for dark matter searches at LHC
  - Analytic loop-level (in QCD) calculations and numerical analysis
  - Supervisor: Prof. Are Raklev





Current research

- Feel like a “child in a candy store”
- Current flavour: Tidal deformations
- Inspired by work of Caron-Huot *et al.* [2503.13593]
  - Compton amplitude, generalizing to spin-1.

Gravitational Wave Scattering via the Born Series:
Scalar Tidal Matching to $\mathcal{O}(G^7)$ and Beyond

Simon Caron-Huot,[1] Miguel Correia,[1] Giulia Isabella,[2] and Mikhail Solon[2]

Screenshot of [2503.13593]

Photo by April Walker on Unsplash

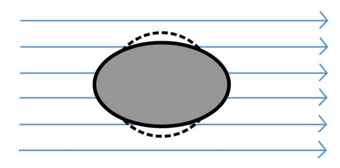


Illustration by me.

What I am also curious about

- Shell-EFT, along the lines of Kosmopoulus *et al.* [2512.04002].
- Recoil (radiation-reaction sector).
- Formal properties of the WQFT
  - Symplectic formulation
  - Magnusian $S = \exp(iN)$ relation
- Outside of GW/ tangential topic:
  - Energy-energy correlators

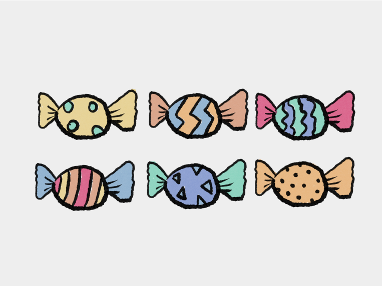


Illustration by Annie Spratt on Unsplash

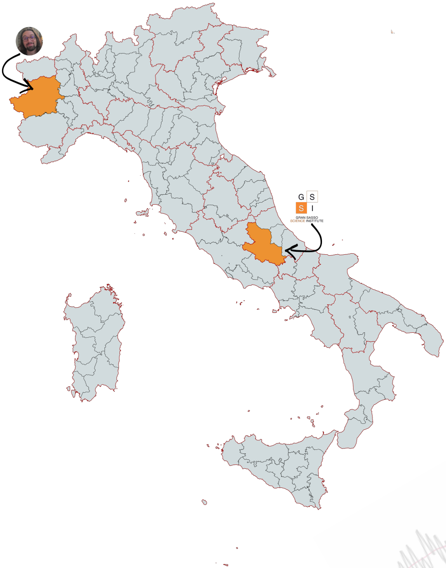
Gong Show Presentation

Luca Nagni

8th April 2026

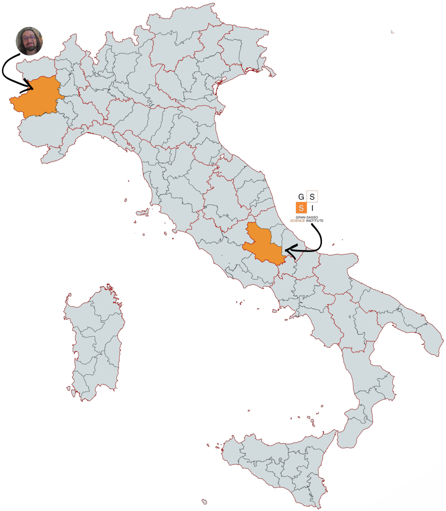
Nordita PhD School

Myself



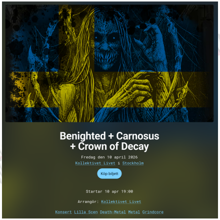
Myself

Myself

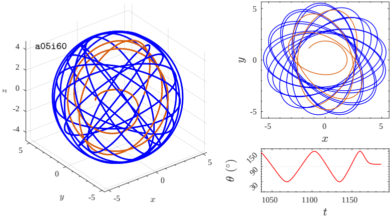


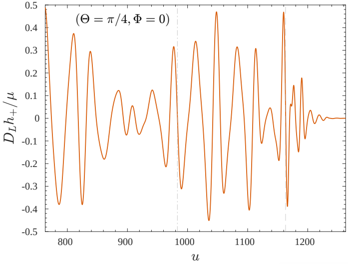
Myself


G S
S I
GRAN SASSO
SCIENCE INSTITUTE


Benighted + Carnosus
+ Crown of Decay
Fredag den 10 april 2026
Kollektivet Livet i Stockholm
Köp biljett
Startar 10 apr 19:00
Arrangör: Kollektivet Livet
Konsert Lilla Scen Death-Metal Metal Grindcore

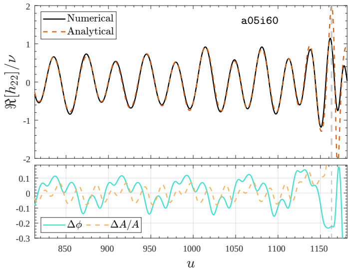
Current Research Interests





Perturbation theory in Kerr spacetime: dynamics and waveform emission following non-equatorial plunge.

Current Research Interests



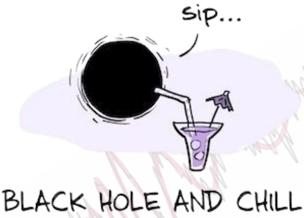
$$h_{\ell m}^{\mathrm{EOB}} = T_{\ell m} \sum_{\epsilon=0,1} h_{\ell m}^{(N,\epsilon)} \hat{S}_{\mathrm{eff}}^{(\epsilon)} \left[\rho_{\ell m}^{(\epsilon)}\right]^{\ell} e^{i\delta_{\ell m}^{(\epsilon)}}$$

Model the numerical waveform with an analytical, EOB-like factorization

Prospects

Why I'm Here

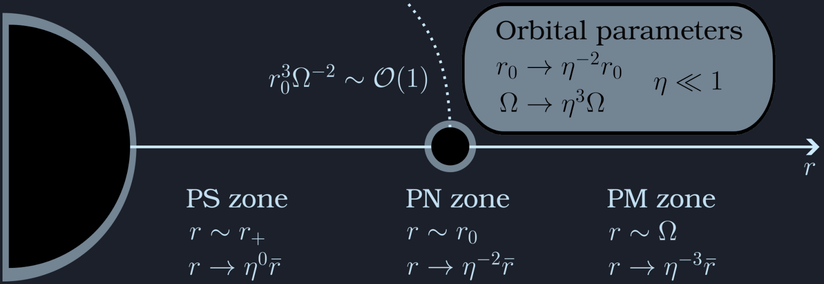
- Always wanted to visit Stockholm
- Topics covered, especially interested in learning something more about the GSF approach to EMRIs
- Discuss physics, meet new people!



Self Force + Weak Field (PN/PM)

Problem: Don't have analytic solution

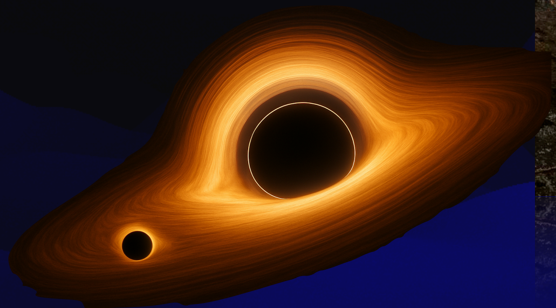
- Numerics
- Expansions $\leftarrow$ This is what I do



Gong show

Nordita (Stockholm) - *Amplitudes, Strong-Field Gravity and Resummation*

Nicole Grillo - 8 April 2026

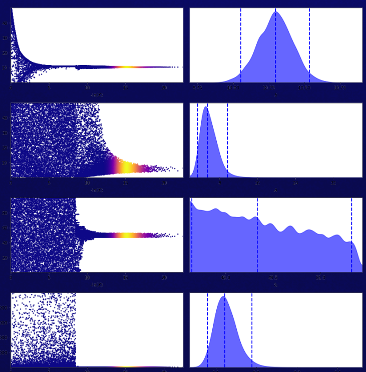


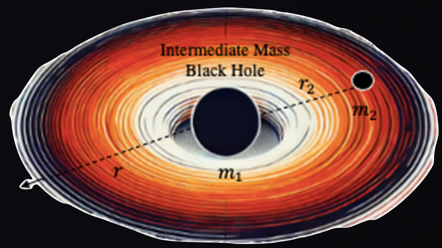
Who am I?

Background: Master's at University of Milan-Bicocca, currently 1st year PhD student

Main interests: GW-phenomenology, from astrophysical environments to tests of GR (*work in progress*!)

```python
    def frequency(self, r):
        return np.sqrt(G * self.M_tot / r**3) / np.pi

    def radius(self, f):
        return (G * self.M_tot / (f**2 * np.pi**2))**(1/3)

    def df_dr(self, r):
        return 1 / np.pi * (-3/2) * np.sqrt(G * self.M_tot / r**5)

    def vacuum_phase(self, r):
        freqs = self.frequency(r)
        r_isco = 6 * G * self.m1 / c**2
        f_isco = self.frequency(r_isco)
        return 1/16 * (c**3 / (np.pi * G * self.chirp_mass))**(5/3) * -freqs**(-5/3) #+ f_isco**(-5/3))

    def dvacuum_phase_df(self, r):
        freqs = self.frequency(r)
        return 1/16 * (c**3 / (np.pi * G * self.chirp_mass))**(5/3) * (5/3) * (freqs**(-5/3-1))

    def dot_r_gw(self, r):
        return - 64 * self.M_tot * G**3 * self.m1 * self.m2 / (5 * c**5 * r**3)
```





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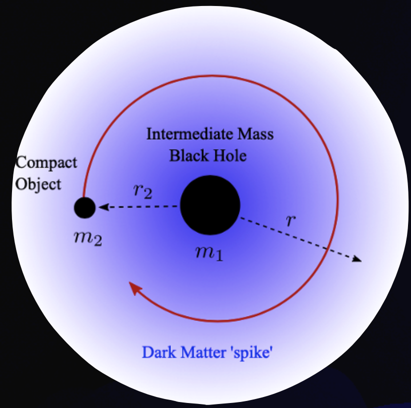
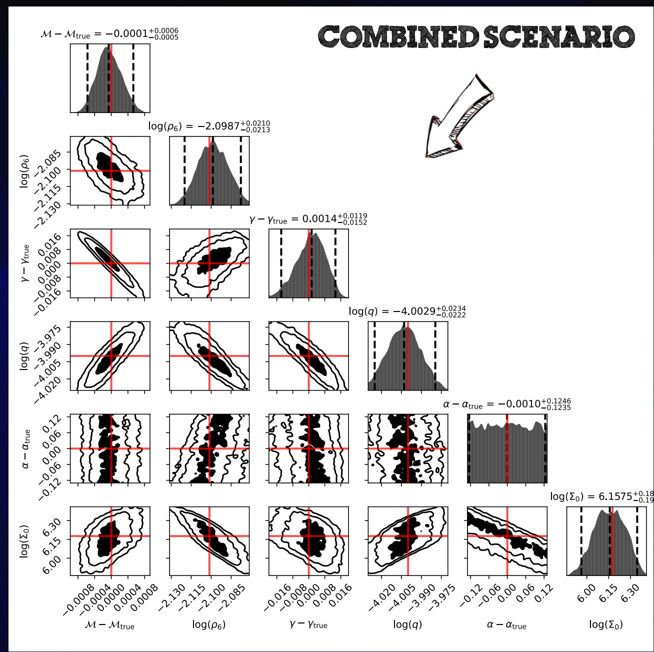
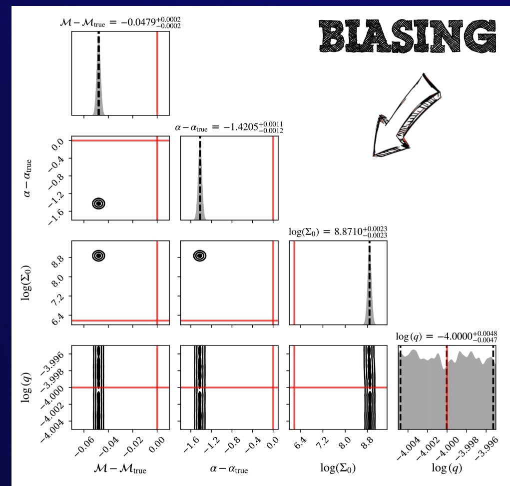


Environmental effects

Why are they are relevant for future analyses?

- Dark matter halos and accretion disks
- Imprints on GW signals to probe unknown physical objects
- Waveform inclusion for better accuracy

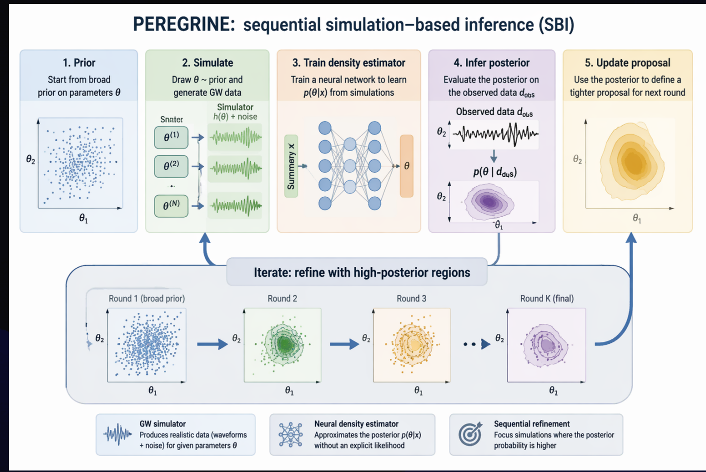


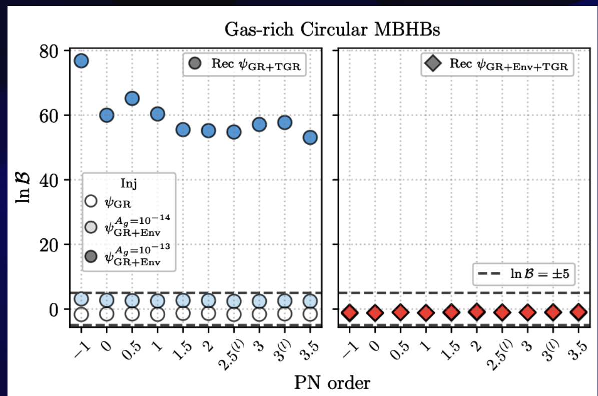


Current/future research interests

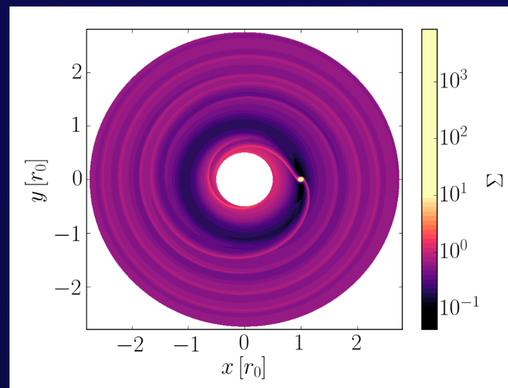
- Application of AI/ML techniques to simulated gravitational-wave data, focusing on parameter estimation
- Investigation of degeneracies between environmental effects and deviations from GR
- Improved modelling of astrophysical environments in gravitational-wave sources

Credits: "*Peregrine: Sequential simulation-based inference for gravitational wave signals*" - Bhardwaj et. al (2024)





Credits: "*Systematics in tests of general relativity using LISA massive black hole binaries*" - Garg et. al (2024)



Credits: "Probing gas disc physics with LISA: simulations of an intermediate mass ratio inspiral in an accretion disc" - Derdzinski et. al (2019)

Nordita school - April 2026

Analytic structure of gravity amplitudes in the Regge Limit

Lorenzo Pietrini[1,2]

[1]Physics Department, Roma “La Sapienza”
[2]LNF

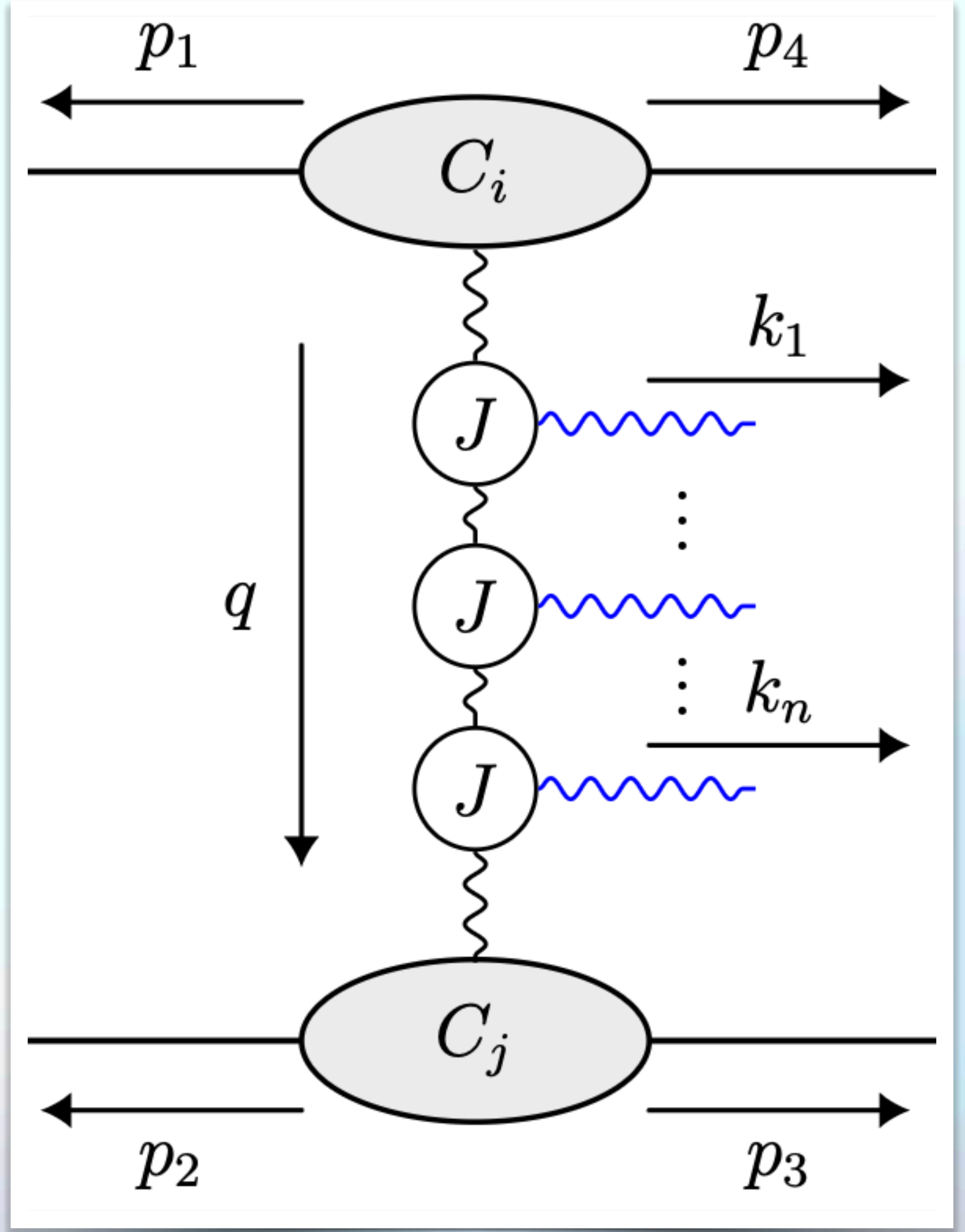
Key Features

- ***Regge Limit & Multi-Regge Kinematics;***
- ***Gauge-Gravity correspondence;***
- ***Exact tree level formulas at fixed helicities in the spinor helicity formalism:***

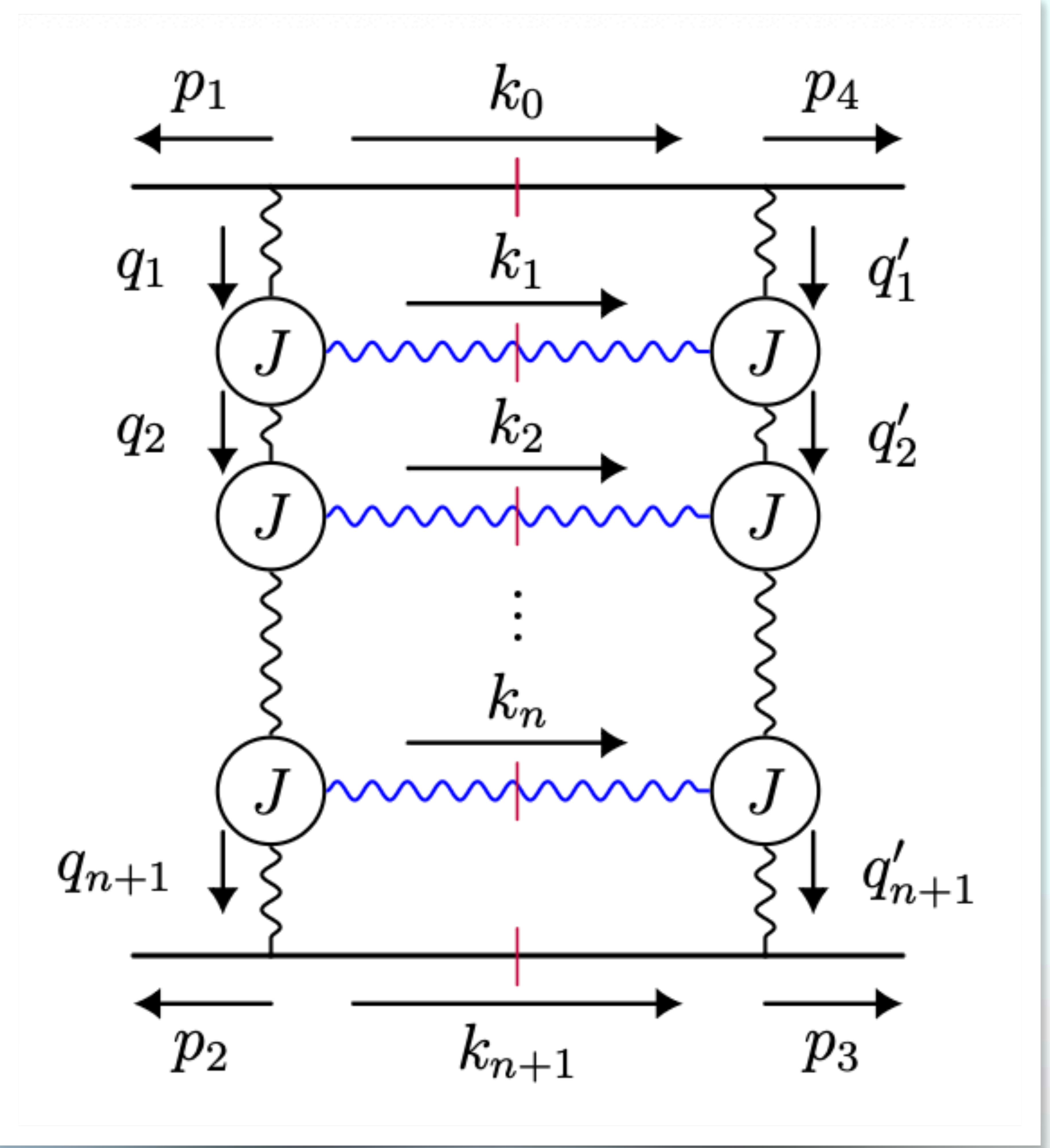
$$\mathscr{M}_4^{\textbf{tree}}(1_h^-,2_h^-,3_h^+,4_h^+) = k^2\frac{\langle 12\rangle^7[12]}{\langle 13\rangle\langle 14\rangle\langle 23\rangle\langle 24\rangle\langle 34\rangle^2}$$

- ***Factorisation in the Regge Limit into universal building blocks:***

$$\mathscr{M}_{2\to n+2}^{\textbf{tree}} \sim 2s\,\frac{C_i}{t_1}\left(\prod_i J^{(0)}(q_i,q_{i+1})\frac{1}{t_{i+1}}\right)C_j$$



BFKL Kernel



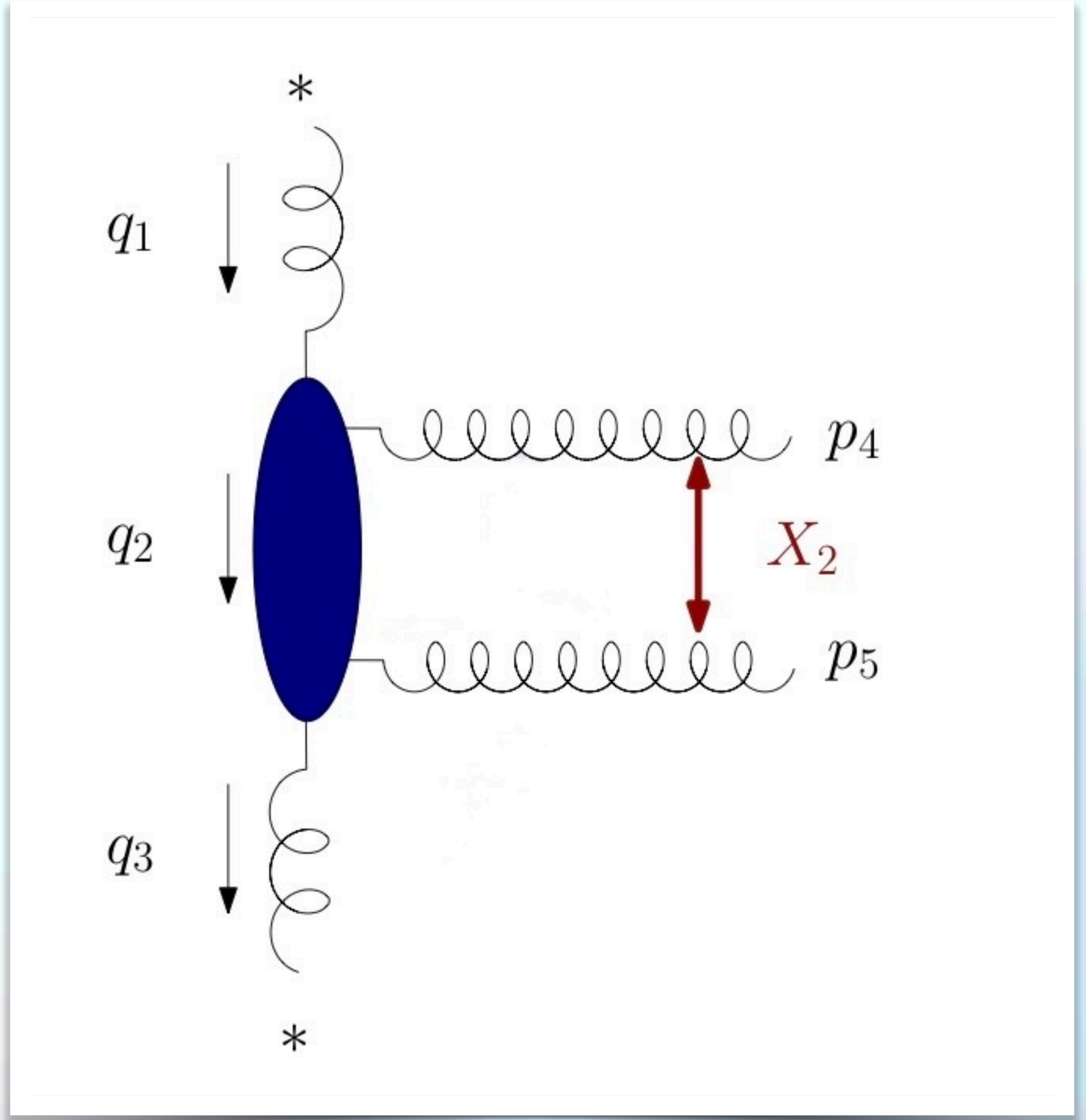
- $\dfrac{\partial \mathscr{A}(t,y)}{\partial y} = \mathbb{K} \otimes \mathscr{A}(t,y)$, $\otimes$ ***is the convolution with respect to the transverse momentum;***

- ***Computation of the squared two-gluon/graviton CEV in the four-point (H2) sector;***

- ***Analysing NMRK corrections beyond strict MRK limit.***

Outlook

- ***Complete Characterisation of the NMRK regime in gravity amplitudes;***
- ***Derivation of a consistent representation for the 2-graviton CEV;***
- ***Systematic analysis of soft and collinear limits of gravitons in multi-point amplitudes.***



Thank you for the attention 🙃

Gravitational Multipoles in higher dimensions from scattering amplitudes

Francesco Campanella[1,2]

[1]La Sapienza, University of Rome

[2]Infn Roma1

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Multipolar structures in arbitrary dimensions

From General Relativity, the spin-induced multipole moments in arbitrary dimensions $D = d + 1$ are given by the mass $\mathcal{M}$, the current $\mathcal{J}$ and the stress $\mathcal{G}$ multipoles [Bianchi-Gambino-Pani-Riccioni, 2025]:

$$\mathcal{M}^{(2\ell)}_{A_{2\ell}} = \frac{(d+4\ell-4)!!}{(d-2)!!}(-1)^\ell F_{2\ell,1}(\mathcal{S}\cdot\mathcal{S})_{A_{2\ell}}|_{STF} \ ,$$

$$\mathcal{J}^{(2\ell+1)}_{i,A_{2\ell+1}} = \frac{(d+4\ell-2)!!}{(d-2)!!}(-1)^\ell F_{2\ell+1,3}\mathcal{S}_{ia_1}(\mathcal{S}\cdot\mathcal{S})_{A_{2l}}|_{ASTF} \ ,$$

$$\mathcal{G}^{(2\ell)}_{ij,A_{2\ell}} = (d-1)\frac{(d+4\ell-4)!!}{(d-2)!!}(-1)^\ell F_{2\ell,2}\mathcal{S}_{ia_1}\mathcal{S}_{ja_2}(\mathcal{S}\cdot S)_{A_{2\ell-2}}|_{RSTF}$$

STF, *ASTF* and *RSTF* denote symmetric trace-free, antisymmetric trace-free and Riemann symmetric trace-free tensors, respectively.
In $d = 3$, the Riemann-like structure vanishes and there are only two kind of multipole moments.

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Spin Universality in 4 dimensions from scattering amplitudes

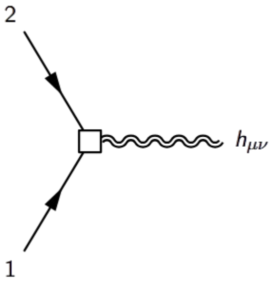

Figure: Three point vertex with emission of a graviton

- Study of three-point function involving a massive spinning field and gravity;
- In four dimensions, the coupling between two massive spin-s fields and gravity generates all multipole moments up to order $2s$;
- The **minimal coupling is universal** and corresponds to the multipolar structure of the Kerr solution [Chung-Huang-Kim-Lee, 2019].

Table of Contents

Our case: Gravitational Multipoles in higher dimensions from scattering amplitudes

In higher dimensions, the situation becomes more complex due to the presence of three independent types of multipole moments:

- **Minimal coupling universality is lost**;
- **Minimal coupling does not reproduce Myers-Perry structure**;
- Fields coupled to gravity cannot generate all the mass and the stress multipole moments (**e.g. the vector cannot produce the stress quadrupole**).

Thanks for your attention!

Transient Resonance Beyond Leading Order

Guangzi Xu
Supervisor: Maarten van de Meent
Center of Gravity, NBI

Funded by the European Union
European Research Council
Established by the European Commission
THE CENTER OF GRAVITY
GWSKY

What is Resonance?

- Consider an EMRI system with mass ratio $\epsilon \ll 1$

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$$\frac{dp^\mu}{d\tau} + \Gamma^\mu_{\rho\sigma} p^\rho p^\sigma = \epsilon a^\mu(x)$$

$$p^\sigma = \frac{dx^\sigma}{d\tau}$$

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$$\frac{dp^\mu}{d\tau} + \Gamma^\mu_{\rho\sigma} p^\rho p^\sigma = \epsilon a^\mu(x) \qquad \qquad \frac{dJ_\alpha}{dt} = \epsilon G_\alpha(\vec{J}, q_r, q_\theta)$$

$$\xrightarrow{\text{canonical tranform}}$$

$$p^\sigma = \frac{dx^\sigma}{d\tau} \qquad \qquad \frac{dq_\alpha}{dt} = \Omega_\alpha(\vec{J}) + \epsilon g_\alpha(\vec{J}, q_r, q_\theta)$$

- (almost) periodic on short timescale

$\longrightarrow$ Fourier decomposition $G_\alpha(\vec{J}, \vec{q}) = G^{(0)}_\alpha(\vec{J}) + \sum_{\vec{k} \neq 0} G^{(k)}_\alpha(\vec{J})\, e^{i\vec{k}\cdot\vec{q}}$

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- To extract adiabatic effects: $\langle G_\alpha(\vec{J}, \vec{q}) \rangle = \int dq_r\, dq_\theta\, G_\alpha(\vec{J}, \vec{q})$

- Transient resonance occurs when $k_r \Omega_r + k_\theta \Omega_\theta = 0$ for some nonzero integers k_r, k_θ.

Why Resonance?

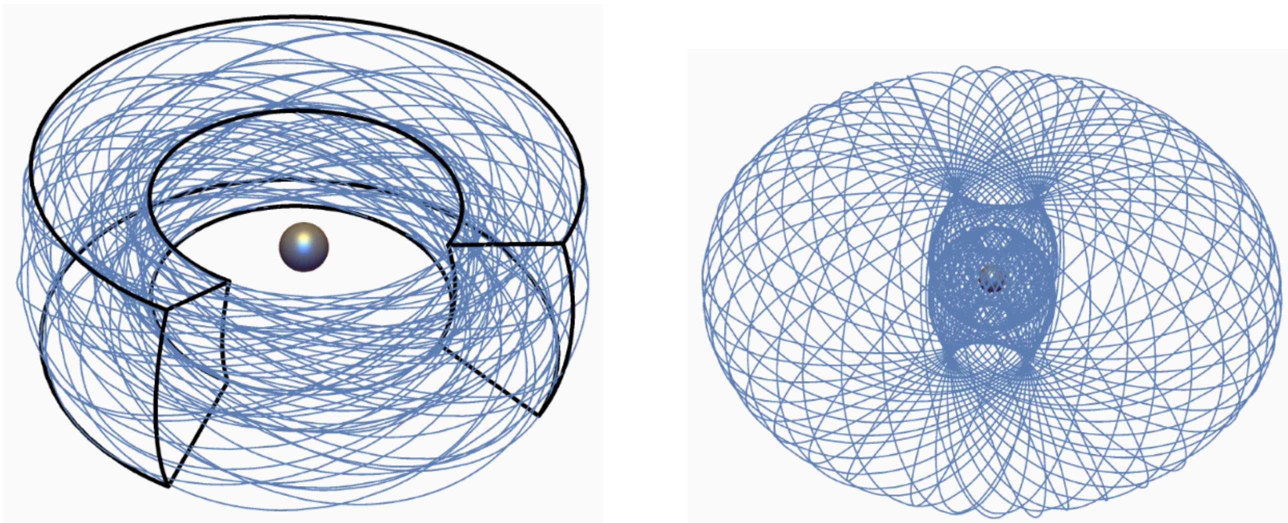

Fig 1. Non-resonance orbit on the left and resonance orbit on the right, from Barack and Pound [1].

[1] Barack, L., & Pound, A. (2018). *Rep. Prog. Phys., 82(1), 016904.* arXiv:1805.10385

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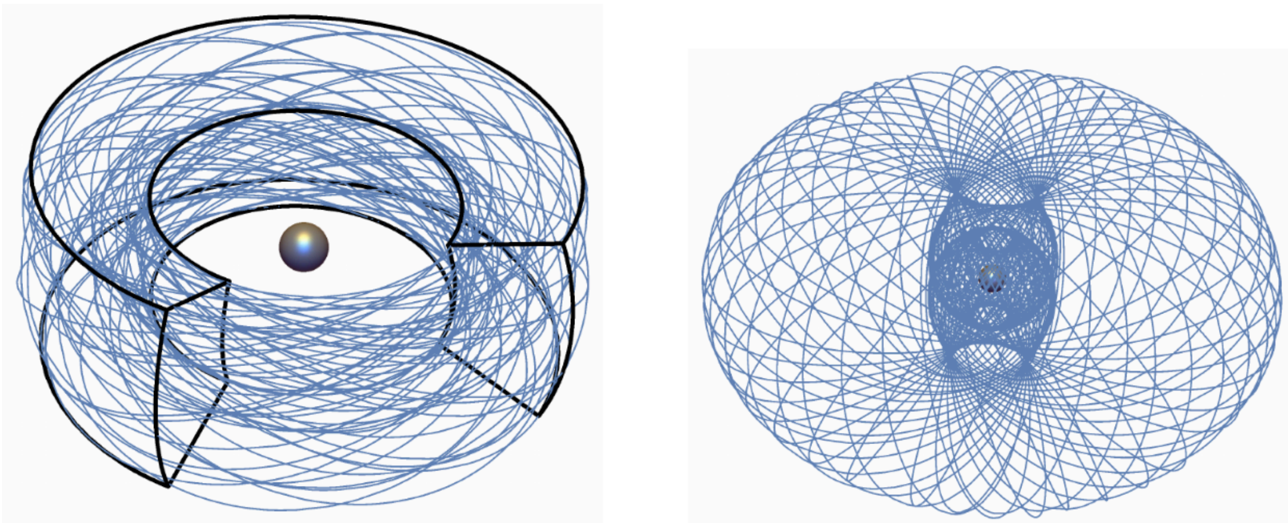

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Near Resonance,

=0 at resonance

$$e^{i\vec{k}\cdot\vec{q}} = exp\,(i\vec{k}\cdot\overrightarrow{q_0} + \cancel{i\vec{k}\cdot\overrightarrow{\Omega}\,t} + i\vec{k}\cdot\dot{\overrightarrow{\Omega}}\,\frac{t^2}{2} + \dots)$$

constant

duration of resonance

$$\tau_{res} \sim \sqrt{\frac{1}{\vec{k}\cdot\dot{\overrightarrow{\Omega}}}} \sim \frac{1}{\sqrt{\epsilon}} \gg 1$$

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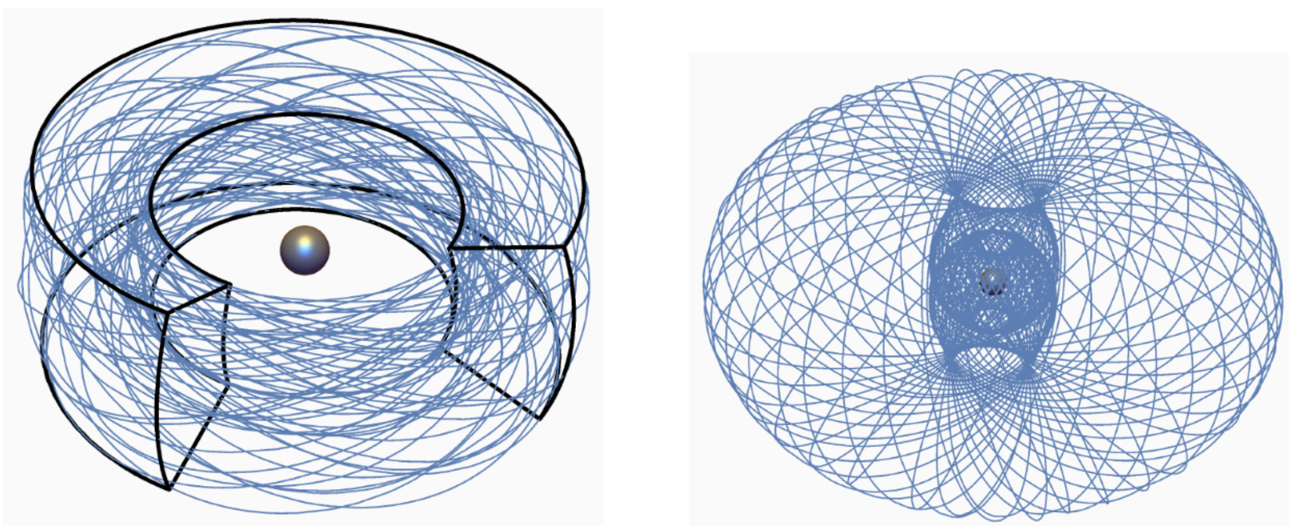

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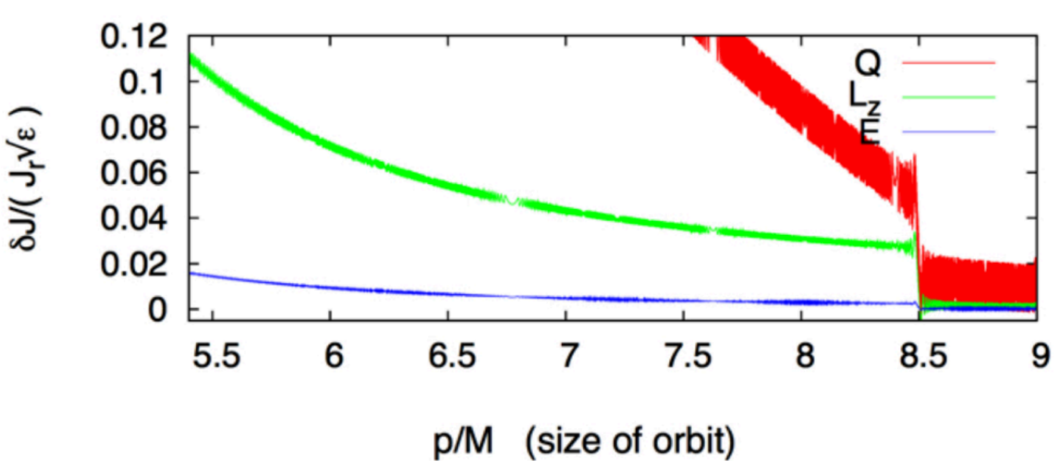

Fig 2. Jumps in orbital parameters at resonance, from Flanagan and Hinderer [2].

The accumulated phase through the inspiral:

$$\Psi = \frac{1}{\epsilon}\Psi^{(0)} + \quad 0 \quad + \Psi^{(1)} + \mathcal{O}(\epsilon) \quad \text{non-resonant}$$

$$+ \frac{1}{\sqrt{\epsilon}}\Psi^{(1/2)}_{res} + \Psi^{(1)}_{res} + \mathcal{O}(\epsilon^{1/2}) \quad \text{resonant}$$

[1] Barack, L., & Pound, A. (2018). *Rep. Prog. Phys., 82(1), 016904.* arXiv:1805.10385

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Thanks.

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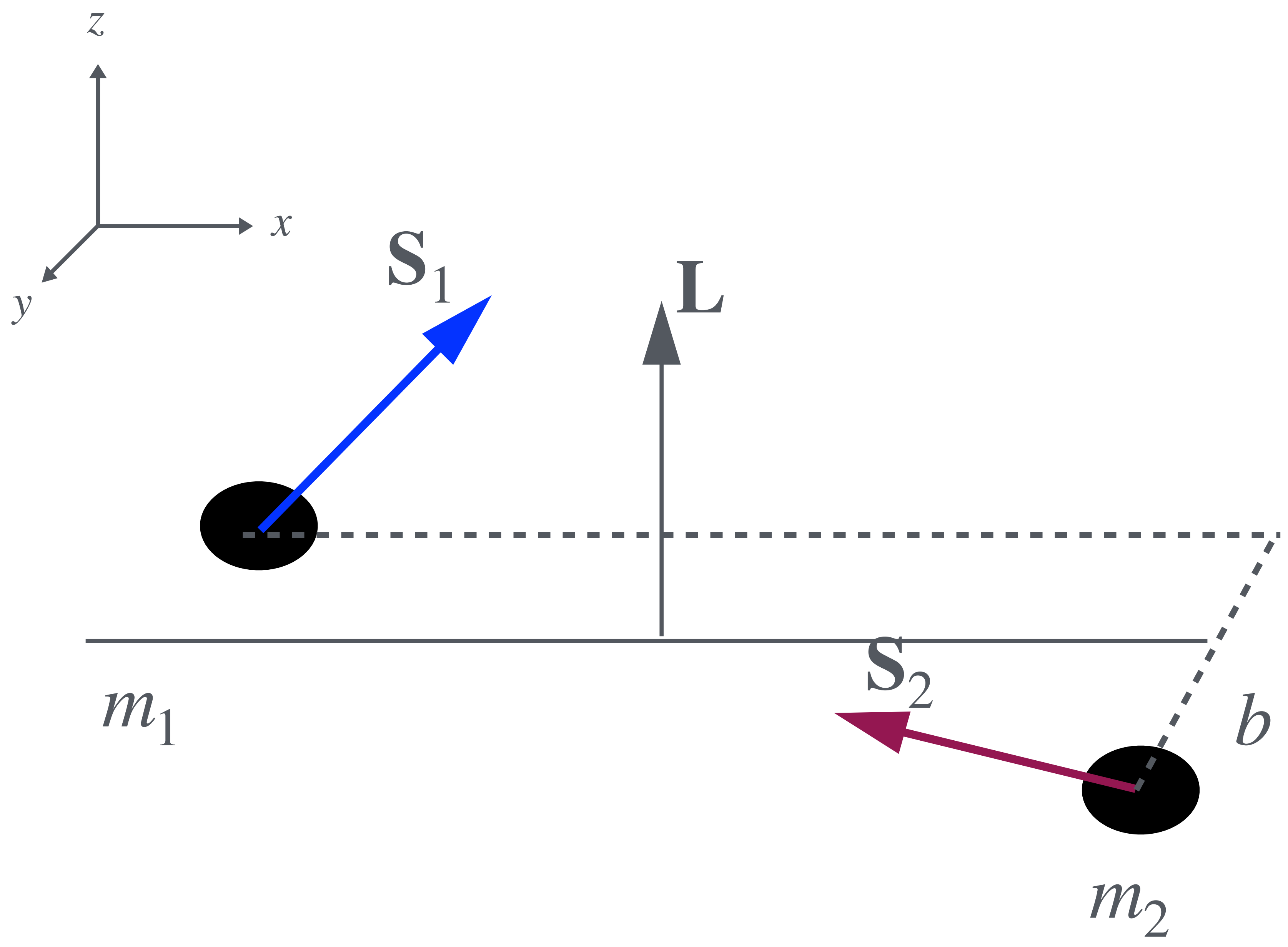
Strong Field Scattering of Black Holes with Generic Spin Orientations

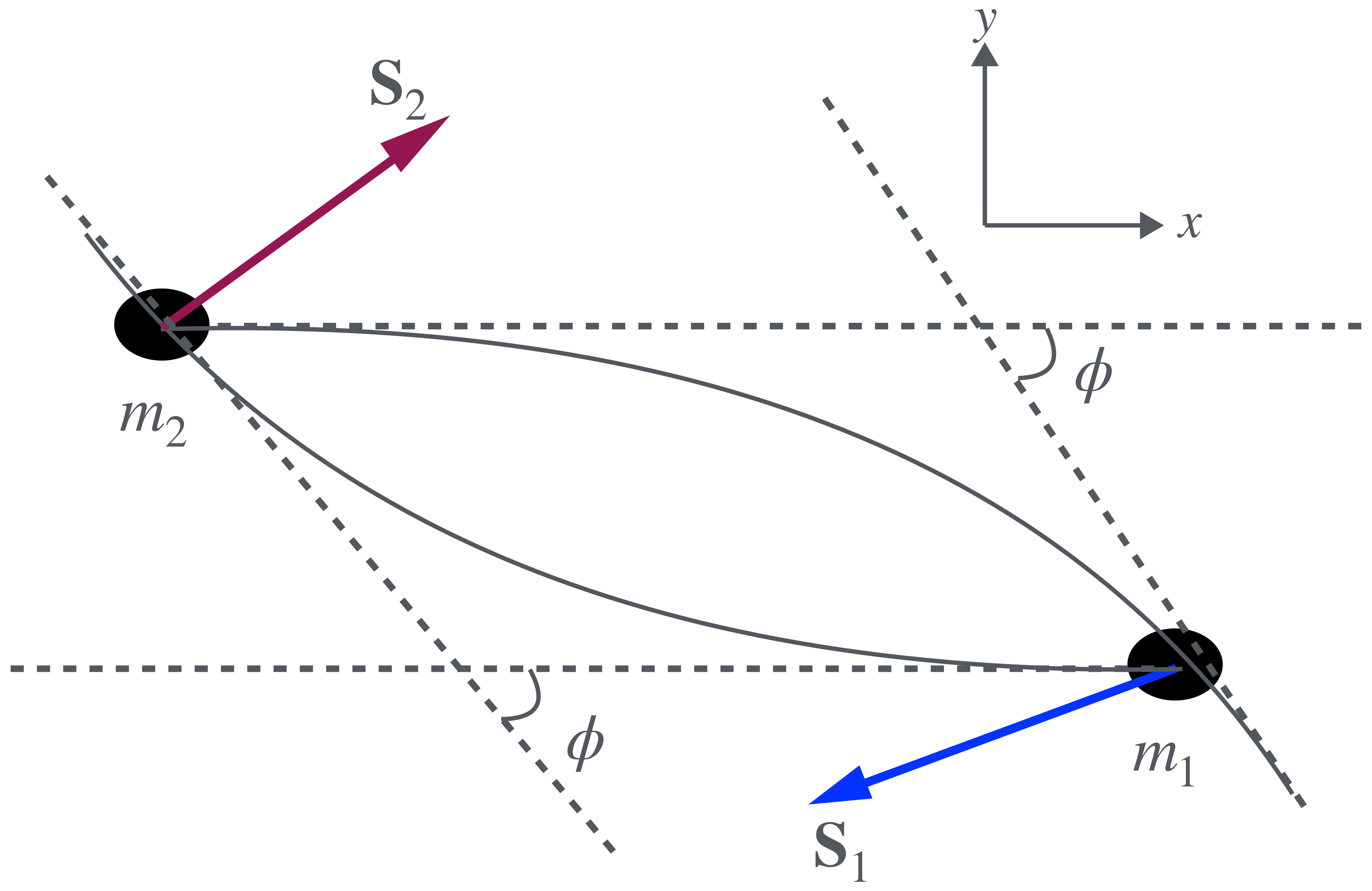
Adam Clark,
University of Birmingham

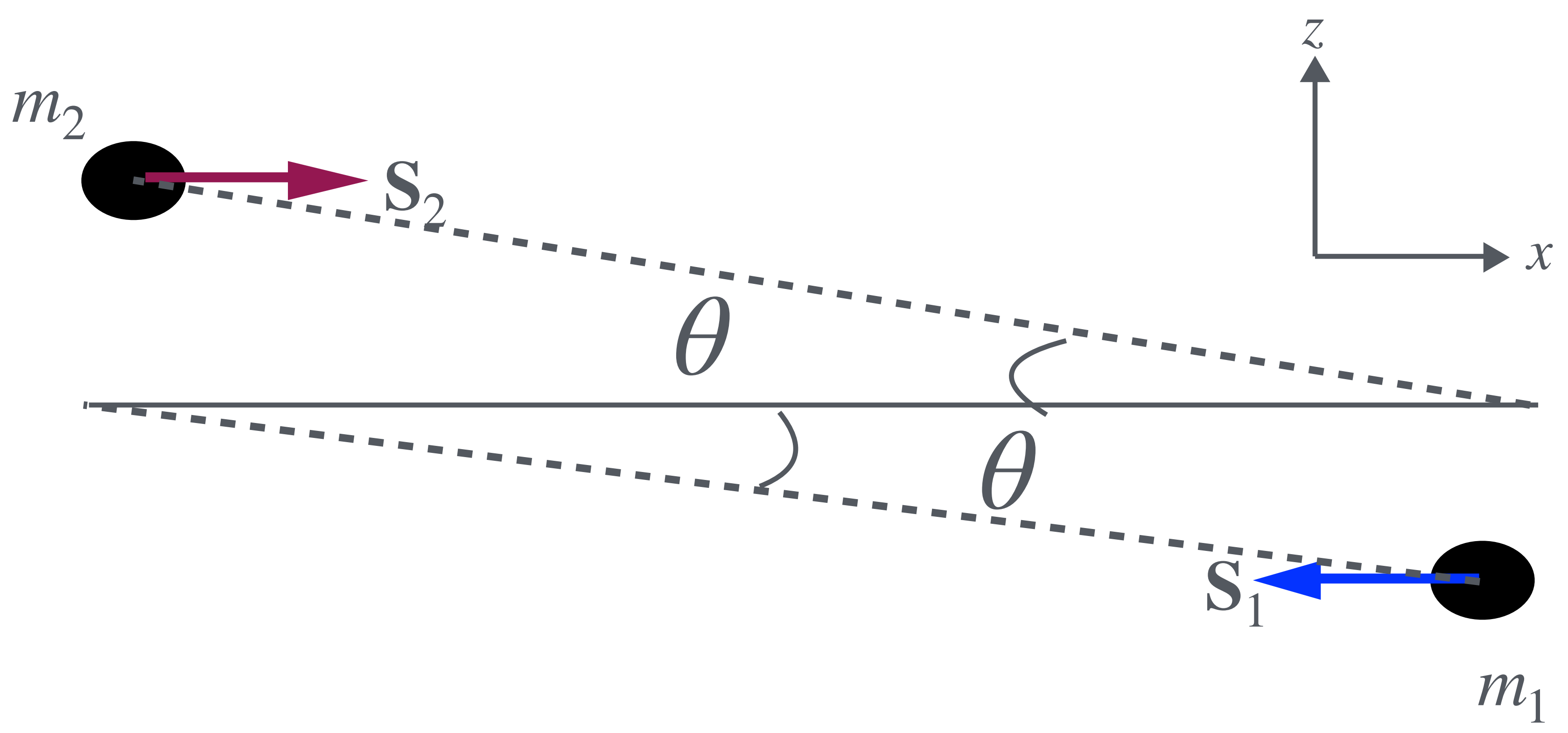
Based on:
AC, Schmidt, Pratten (2026)
In Prep.

Lightning Introduction

Spin Precession







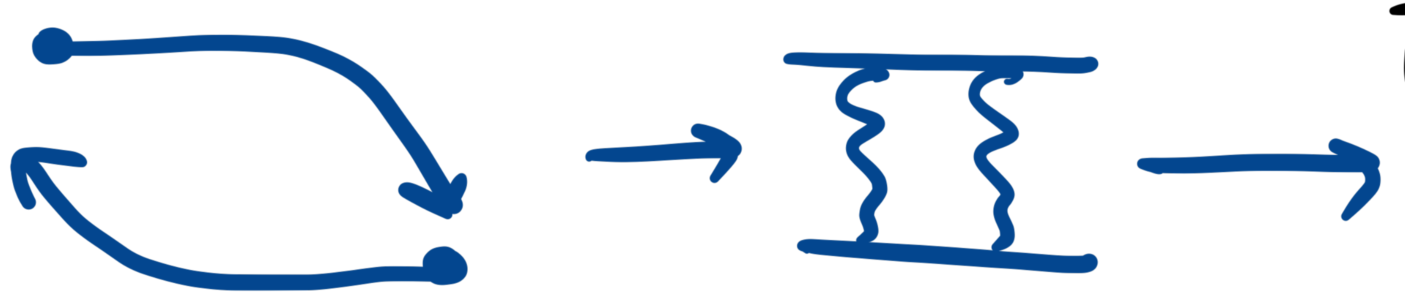
$$\dot{\mathbf{L}} = -\dot{\mathbf{S}}$$

$$\dot{\mathbf{S}} \sim \frac{1}{r^3}(\mathbf{L} \times \mathbf{S})$$

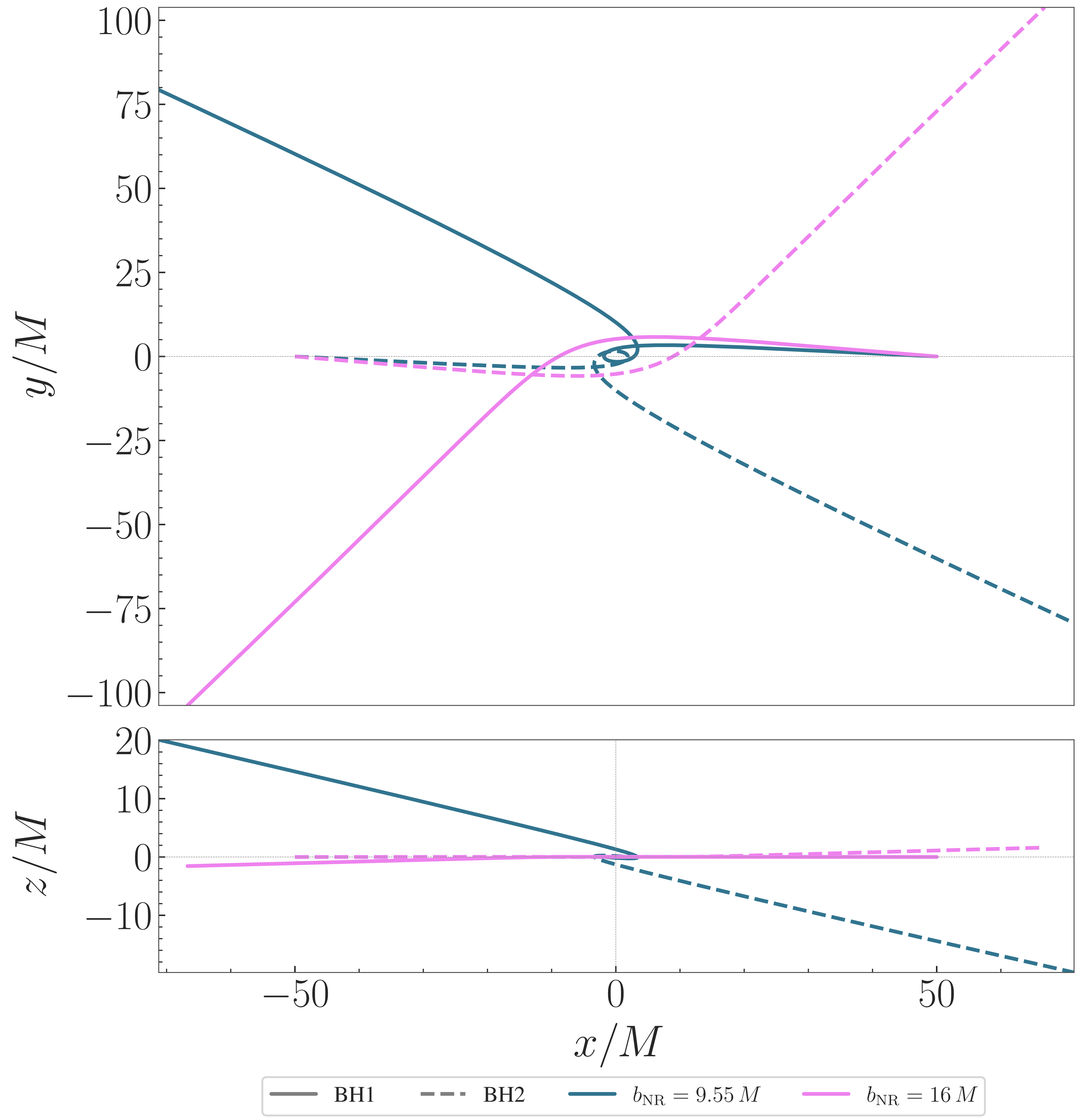
Lightning Introduction

Precessing Scattering

- We produced a suite of Numerical Relativity simulations of scattering with misaligned spins
- In the strong field, we see substantial out-of-plane motion, due to spin-orbit precession effects
- As well as this, we have computed **observables** from **post-Minkowskian theory**



$\longrightarrow \boxed{\Delta p^r \rightarrow (\varphi, \theta)}$



What about the Spin Kick?

- From a simple geometric argument, we relate the scattering angles with the *Euler angles*

$$\cos\beta = \hat{L}_z^\infty \qquad \tan\alpha = \frac{\hat{L}_y^\infty}{\hat{L}_x^\infty}$$

- Comparing the Euler angles between NR and PM lets us compare the precession sector directly!

$$\tan\theta = \tan\beta\cos(\phi - \alpha)$$

Impulse $\rightarrow$ Scattering Angles

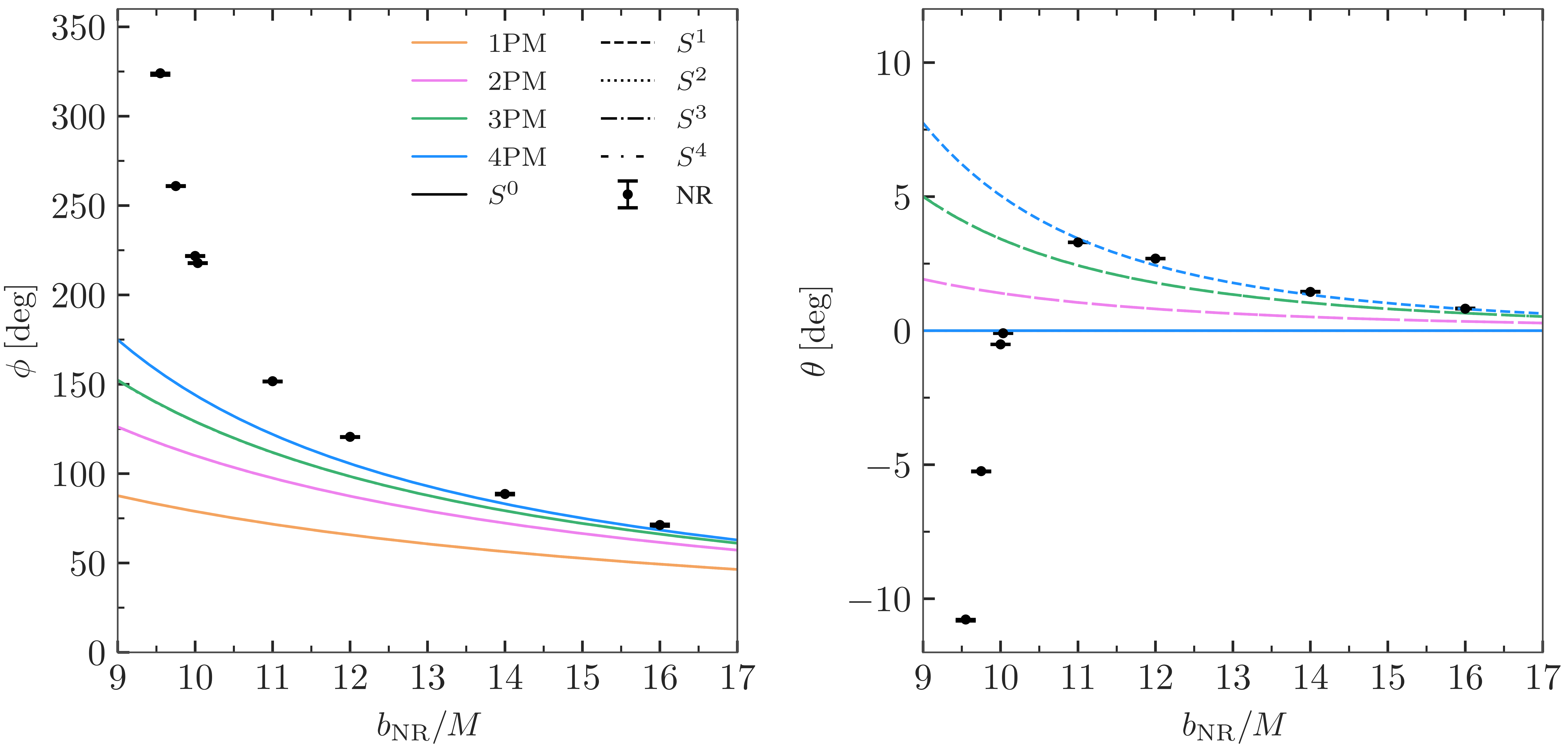
Spin Kick $\rightarrow$ Precession Angles

$$\Delta L^\mu = -\left(\Delta S_1^\mu + \Delta S_2^\mu\right)$$

$$\sin\frac{\beta}{2} = \frac{||\Delta L||}{2p_\infty}$$

Key Results

Impact Parameter Variation



Black Hole Scattering in Einstein-scalar-Gauss-Bonnet: Numerical Relativity Meets Analytics

UNIVERSITY OF BIRMINGHAM

Shaun Swain, Tamanna Jain, Llibert Aresté Saló*

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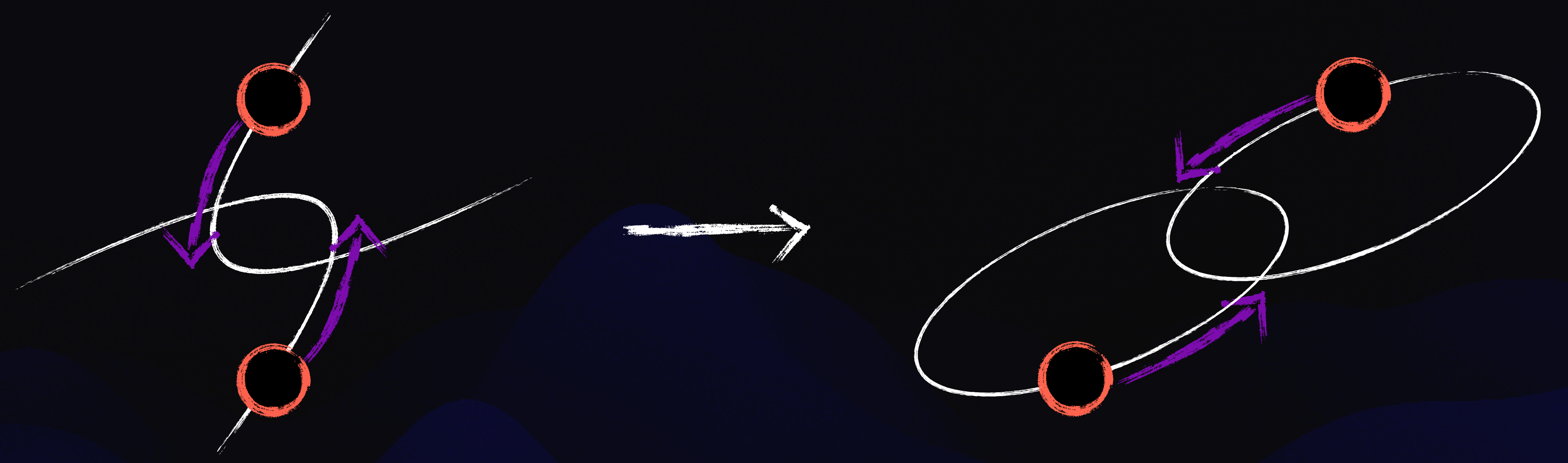
Previous work: [Damour+ 14, Damour+ 22, Rettegno+ 23, Swain+ 24, ...]



→ Can we utilise BBH scattering to inform GR waveform models for bound orbits?

→ Validate analytical predictions of scattering angle with Numerical Relativity (NR).

This work: Can we extend to alternative theories of gravity?

We consider Einstein-scalar-Gauss-Bonnet (EsGB), an EFT extension of GR with a new fundamental scalar field.

$$S = \frac{1}{16\pi}\int \mathrm{d}^4x\,\sqrt{-g}\,\left(R - 2(\nabla\varphi)^2 + 2\lambda\varphi\mathcal{R}^2_{\mathrm{GB}}\right)$$

How accurately can we model the contributions of the scattering angle due to scalar-scalar & scalar-graviton interactions?

*sxs2159@student.bham.ac.uk

Black Hole Scattering in Einstein-scalar-Gauss-Bonnet: Numerical Relativity Meets Analytics

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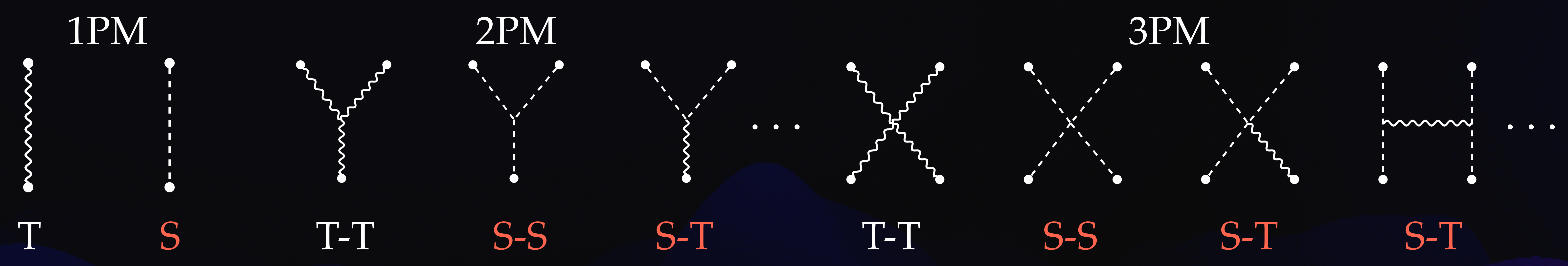
Calculate S-S & S-T contributions to the scattering angle up to 3PM (Conservative) order using EFT approach.



[Kälin+ 2020, Bernard+ 2026]

PM-expanded scattering angle uniquely informs EOB potential.

$$\chi_{n\mathrm{PM}} \rightarrow w_{n\mathrm{PM}} \quad , \quad w^{\mathrm{BH}}_{\mathrm{EsGB}} = w^{\mathrm{BH}}_{\mathrm{GR}} + w^{\mathrm{BH}}_{\mathrm{mod}}$$

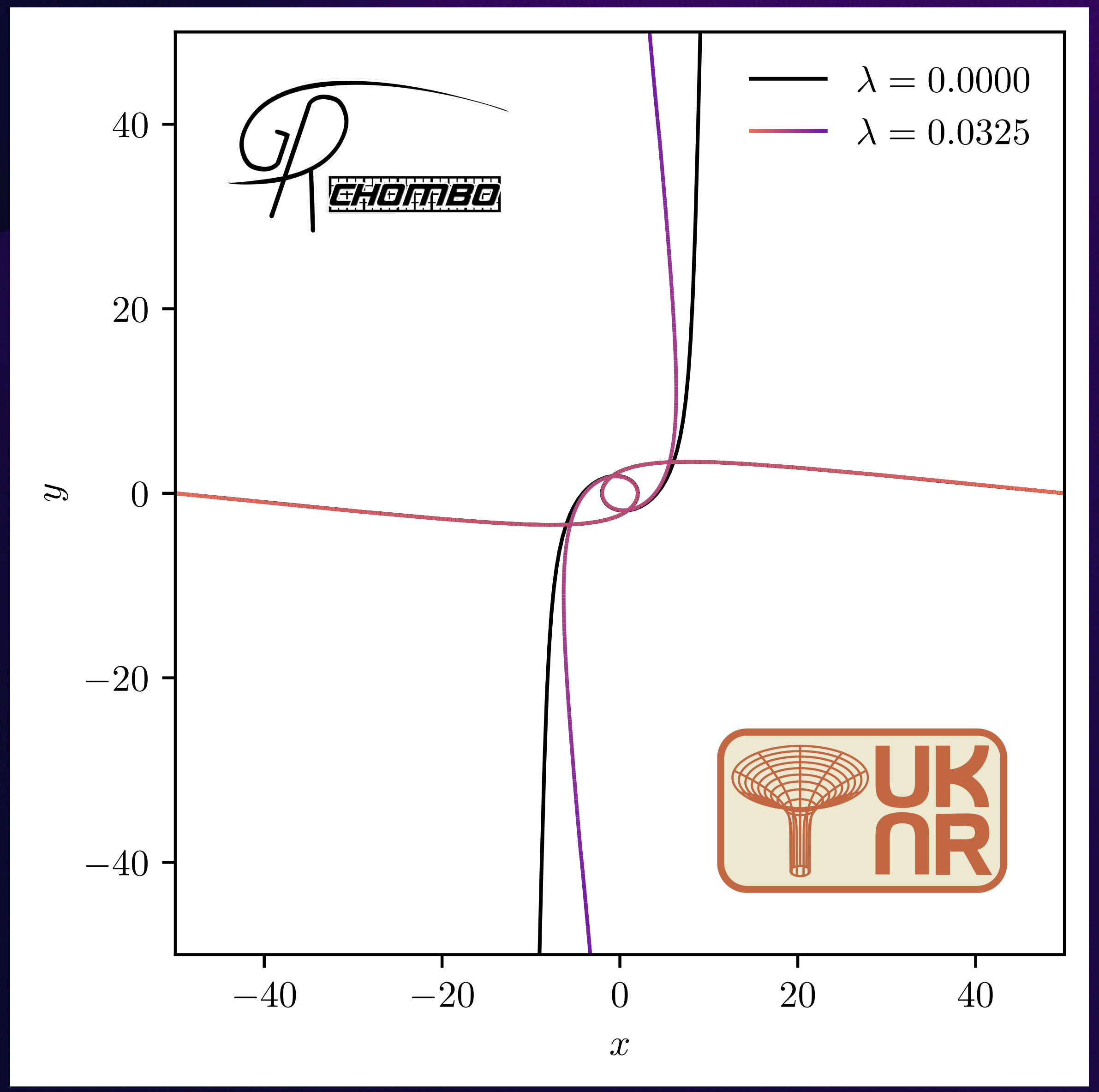
$$w^{\mathrm{BH}}_{\mathrm{GR}} = w^{\mathrm{BH}}_{4\mathrm{PM}} + w^{\mathrm{BH}}_{5,\mathrm{fit}}$$ [Rettegno+ 23]

$$\boxed{w^{\mathrm{BH}}_{\mathrm{mod}} = w^{\mathrm{BH}}_{3\mathrm{PM,mod}}}$$

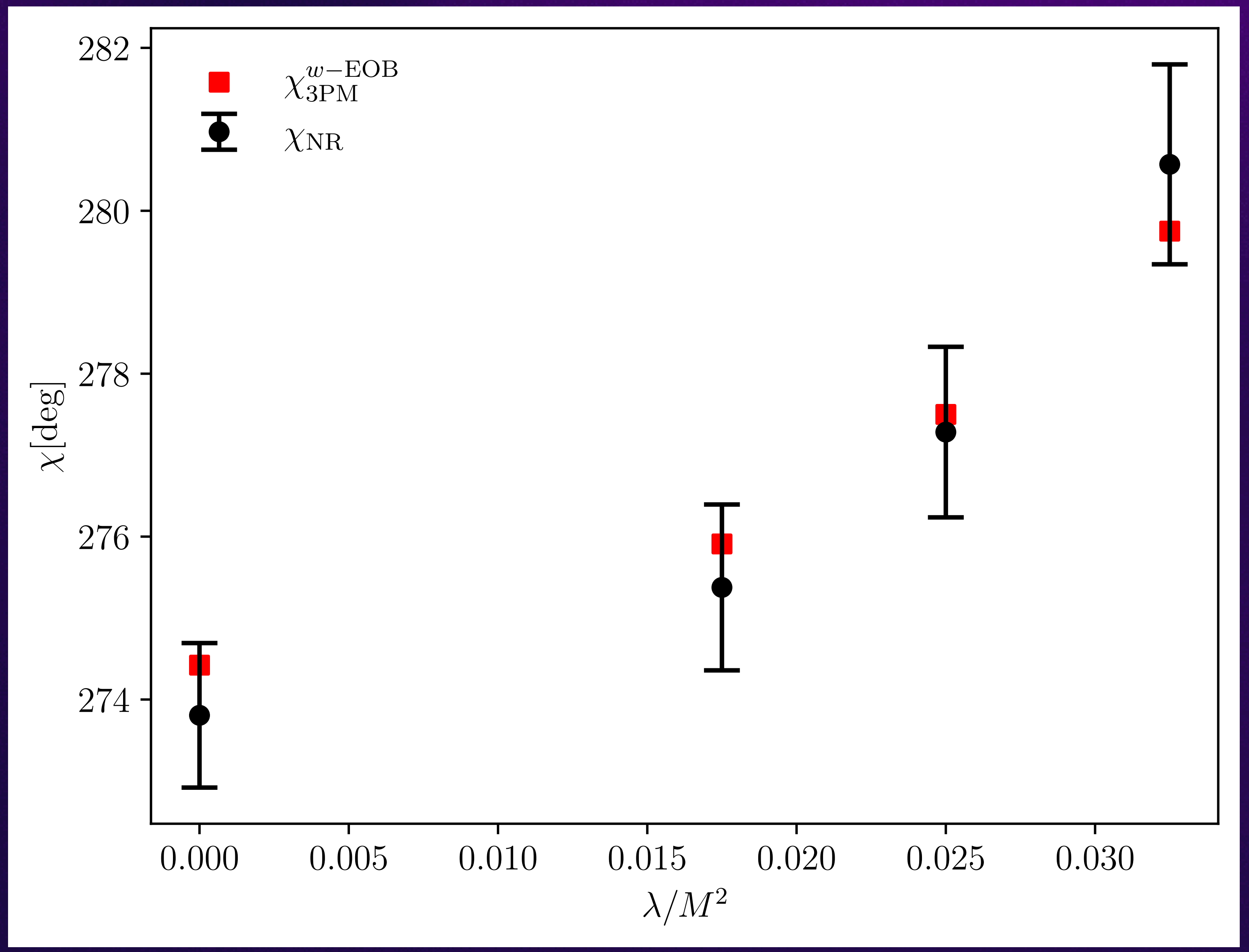
EOB resummation used to improve scattering angle prediction [Damour 17]

$$\pi + \chi^{w-\mathrm{EOB}}_{n\mathrm{PM}}(\gamma, j) = 2j \int_0^{\bar{u}_{\max}(\gamma,j)} \frac{d\bar{u}}{\sqrt{p_\infty^2 + w^{\mathrm{BH}}_{\mathrm{EsGB}}(\bar{u},\gamma) - j^2\bar{u}^2}}$$

NR Simulations performed with GRFolres, an extension of GRChombo to 4∂ST theories.



Excellent agreement between EOB analytics and NR data



*sxs2159@student.bham.ac.uk

Emanuele Rosi

PhD in Rome, La Sapienza University and INFN

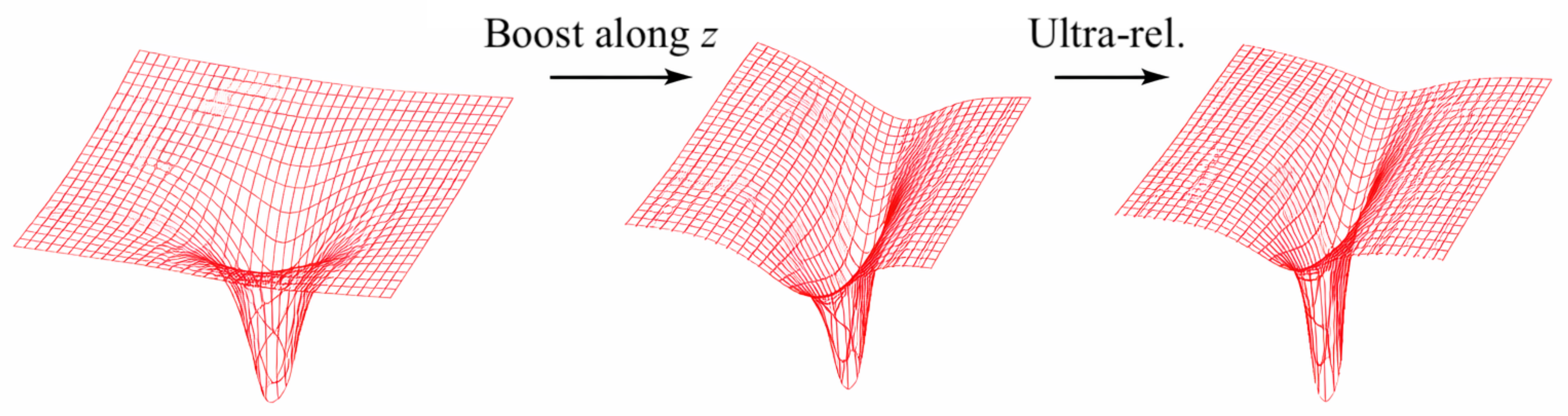
Supervisors: Vittorio Del Duca & Riccardo Gonzo

[**2511.11457**] F.Alessio, V. Del Duca, R. Gonzo, ER, M. Saavedra, I. Z. Rothstein - *"Analytic structure of the high-energy gravitational amplitude: multi-H diagrams and classical 5PM logarithms"*
[**2601.21687**] F.Alessio, V. Del Duca, R. Gonzo, ER- *"Gravitational amplitudes in the Regge limit: waveforms, shock waves and unitarity cuts"*

BH scattering at high energies

- Import tools from colliders: Amplitudes, Feynman integrals, Effective Field Theories

- At the level of scattered isolated metrics: **AS shockwaves** + **mass corrections**



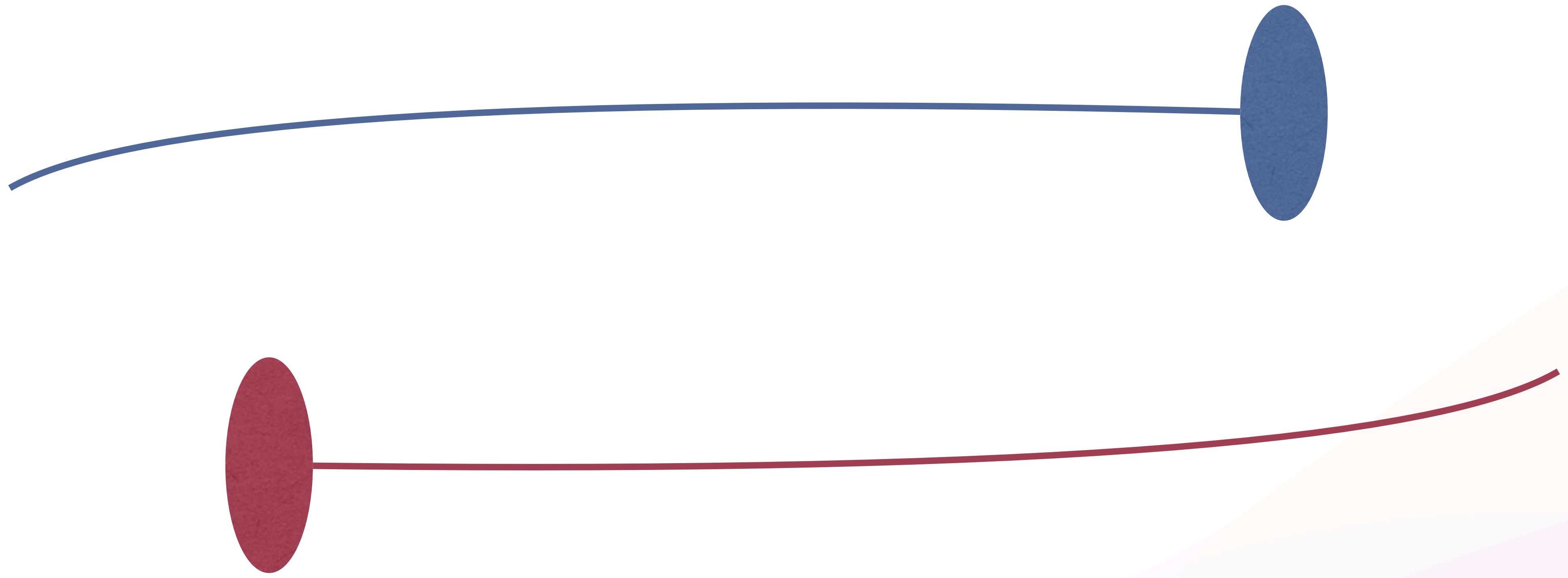
$$ds_a^2 = ds_{\mathrm{sw},a}^2 + \sum_{n\geq 1} C_a^{(n)} \left(m_a/E_a\right)^n$$

- Aim to export this **systematic expansion** of a single solution at the level of conservative and radiative **observables** for a two body scattering system.

- Two frameworks:
  - BHs in the CoM system with relative boost $\gamma \longrightarrow$ **Post-Minkowksian** (Amplitudes, High-Energy EFTs)
  - BHs with asymmetric energies $E_1 \gg E_2 \longrightarrow$ **"Self-Force" inspired** (SF-EFT, Worldlines)

Combining SF, PM and High-Energy

- <u>Framework #1</u>: BHs in the CoM, no energy or mass ordering

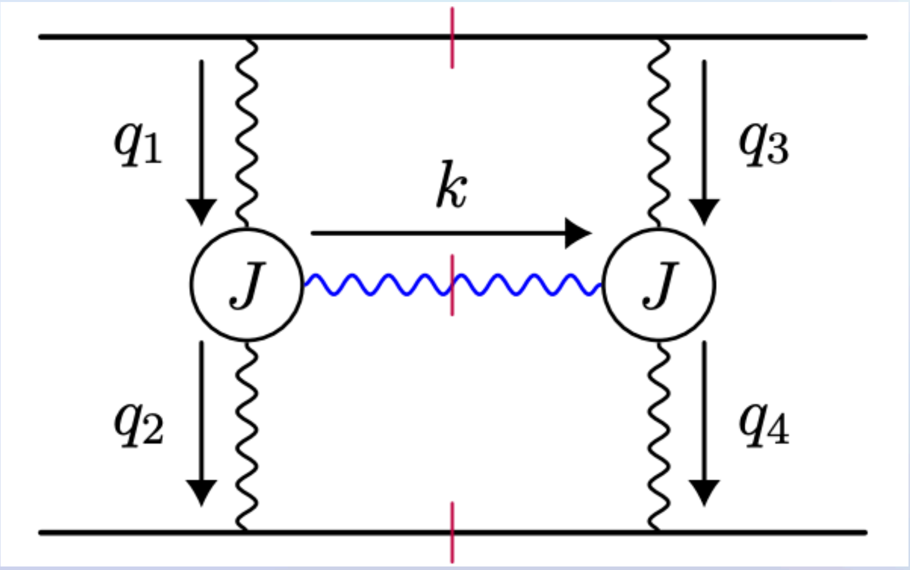


- Issues in facing the PM expansion in the ultra relativistic limit

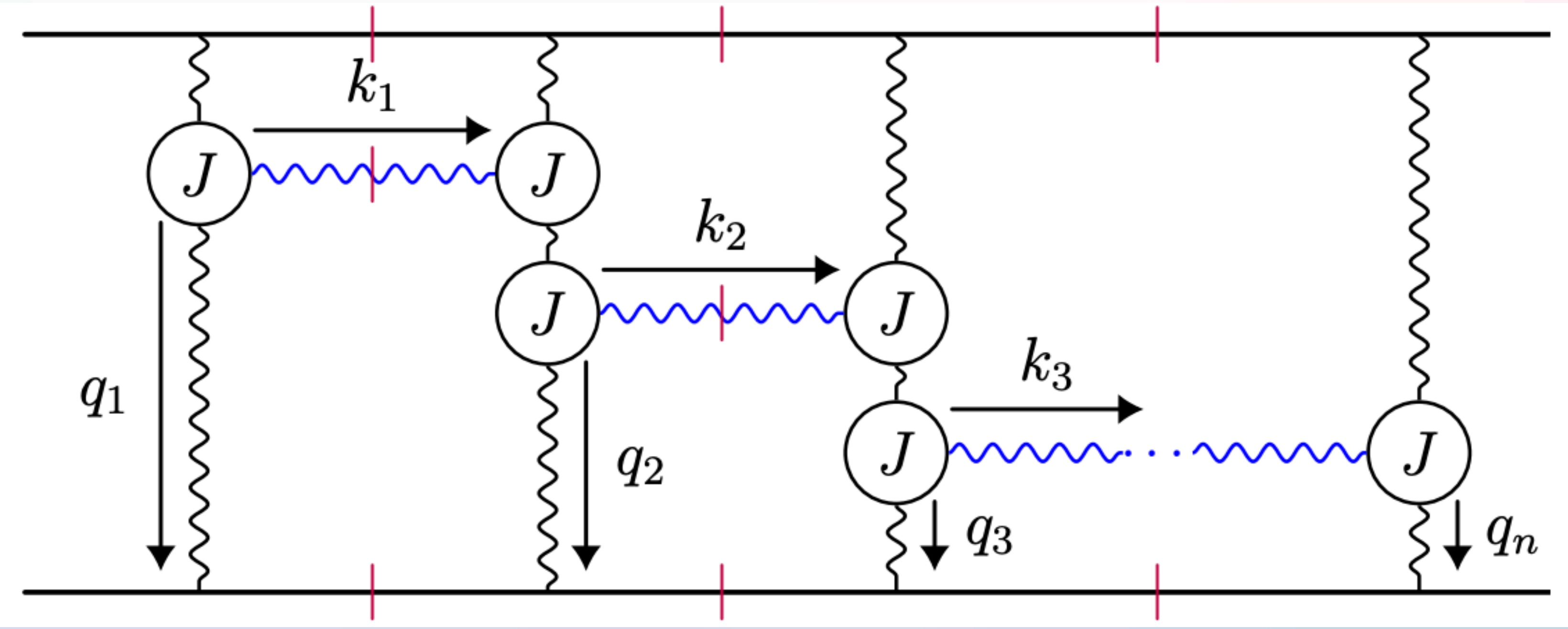
$$\text{PM}: \qquad \frac{Gs}{J} = \frac{G\sqrt{s}}{b} \ll 1\,, \qquad \text{UR}: \quad Gs \gg 1$$

Planckian scattering: PM expansion allowed, but Newton's constant is no more a *good* expansion "parameter" → need for full **resummation in G**. [*e.g.* Eikonal resummation]

We recognise a sequence of "**multi-H diagrams**" contributing to the leading logarithmic classical $2 \to 2$ amplitude.

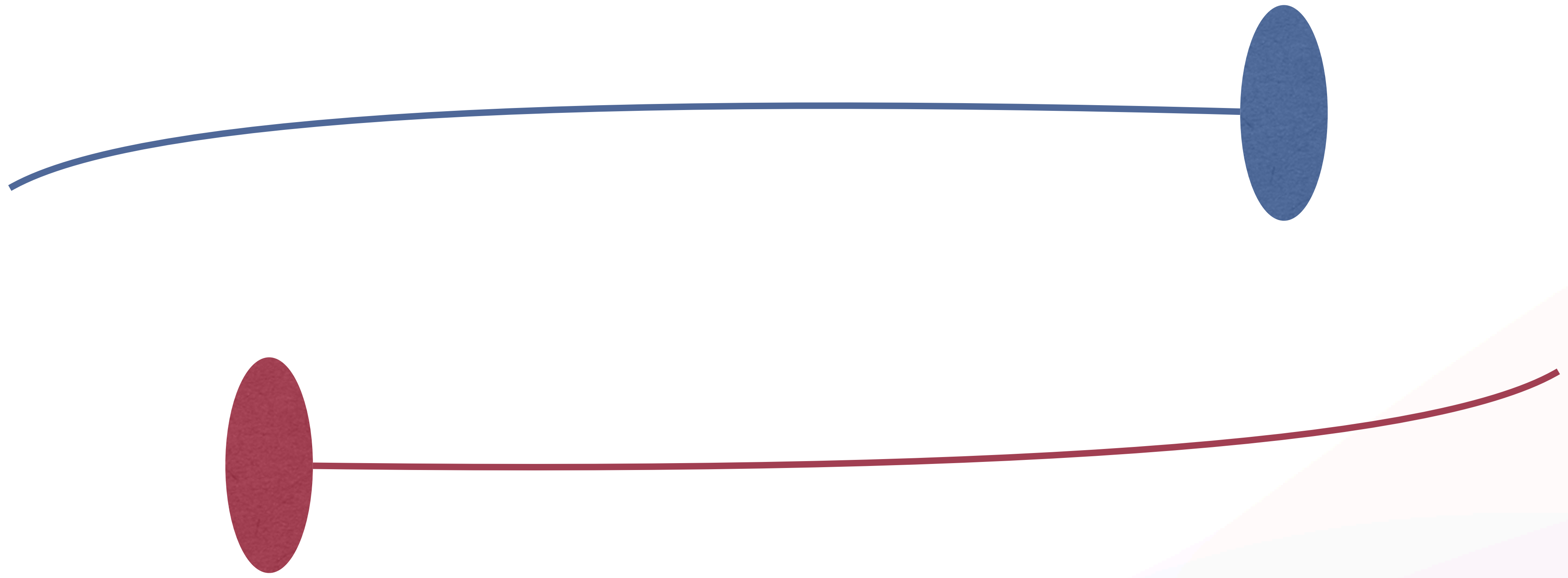


$+\cdots+$



$$= \frac{Gs^2}{t} \sum_n h_n \cdot \left(G^2 st \log|s/t|\right)^n$$

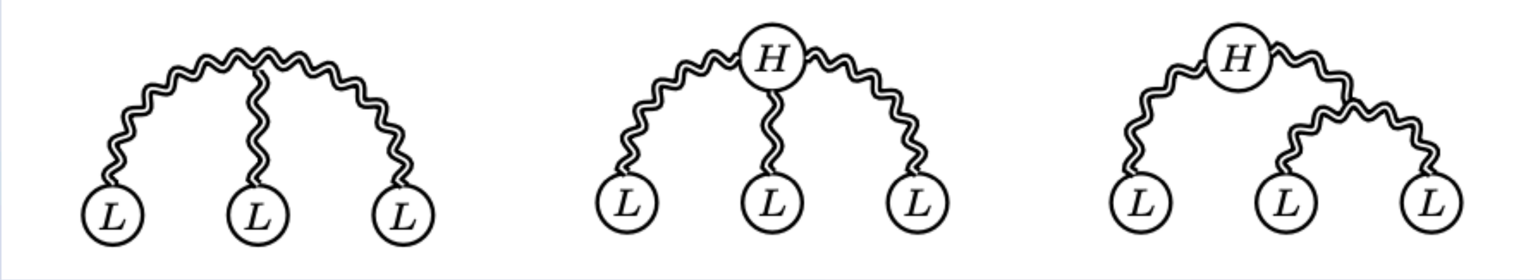
Combining SF, PM and High-Energy



- Framework #1: BHs in the CoM, no energy or mass ordering
- Issues in facing the PM expansion in the ultra relativistic limit

$$\text{PM}: \qquad \frac{Gs}{J} = \frac{G\sqrt{s}}{b} \ll 1\,, \qquad \text{UR}: \quad Gs \gg 1$$

Planckian scattering: PM expansion allowed, but Newton's constant is no more a *good* expansion "parameter"
→ need for full **resummation in G**. [*e.g.* Eikonal resummation]

- Framework #2: $E_1 \gg E_2$ Use SF-EFT [Cheung, Parra-Martinez, Rothstein, Shah, Wilson-Gerow]
  - BH1 generates AS-shockwave background + corrections to background $\epsilon_1 = m_1/p_1 \sim$ **int. vertices**
  - BH2 follows geodesic motion on AS, exact in mass p_2, m_2
  - Compute **SF diagrams**  → corrections $\epsilon_2 = m_2/p_1$

Combining SF, PM and High-Energy

Many tools are available or/and under development:

- Amplitudes, Feynman Integrals, etc
- Simplified by: **high-energy factorisation.**
- Modal **Effective Field Theories** [e.g. Regge theory, SCET, JIMWLK-Balitsky]
- Manage shockwave infinities through **Rapidity evolution equations.**

Projects:

- Resum the tower of **leading logarithmic** $\sim \log^n |s/t|$ amplitudes in conservative sector.
- Push computation at leading UR order [shockwave collision] in **radiative sector**.
  - Understand how logarithmically enhancements emerge in observables [e.g. Energy Radiated at 4PM]
- Develop framework for **systematically expand** in $m_i / |p_i|$.

Thank you!