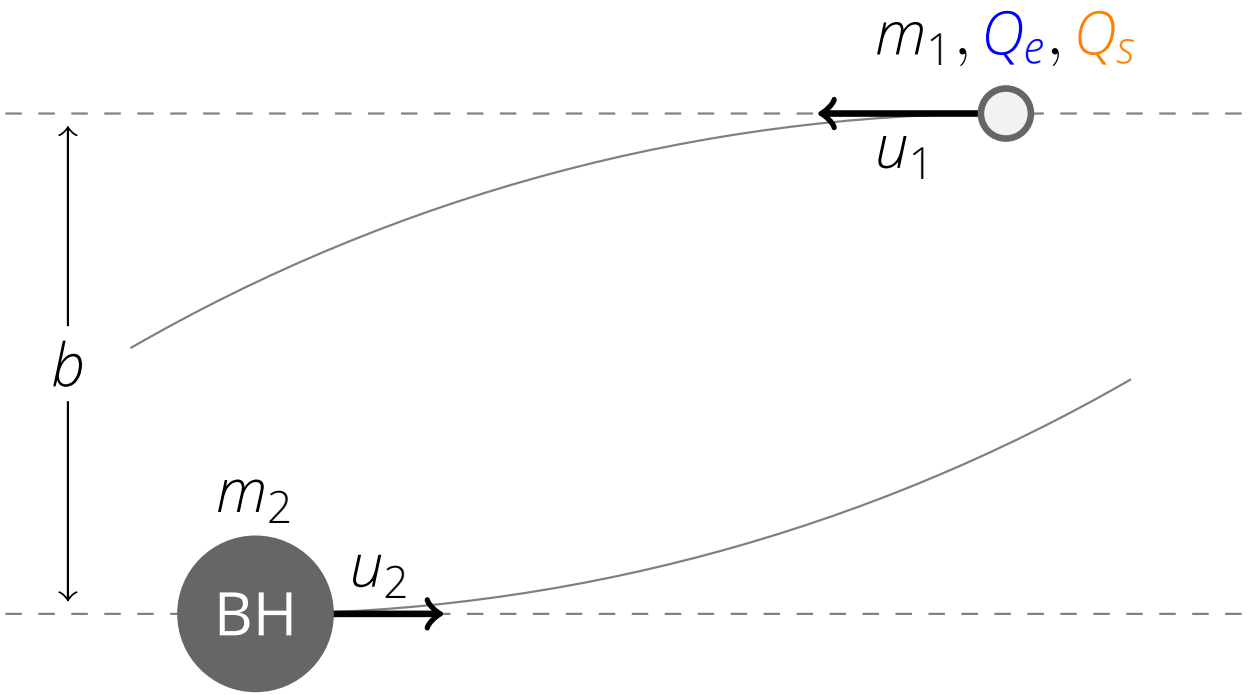
Absorptive Effects and Classical Black Hole Scattering

Callum R. T. Jones

Based on **[2310.00069]** with Michael Ruf

Classical Black Hole Scattering



PM regime:

$r_S \ll b$

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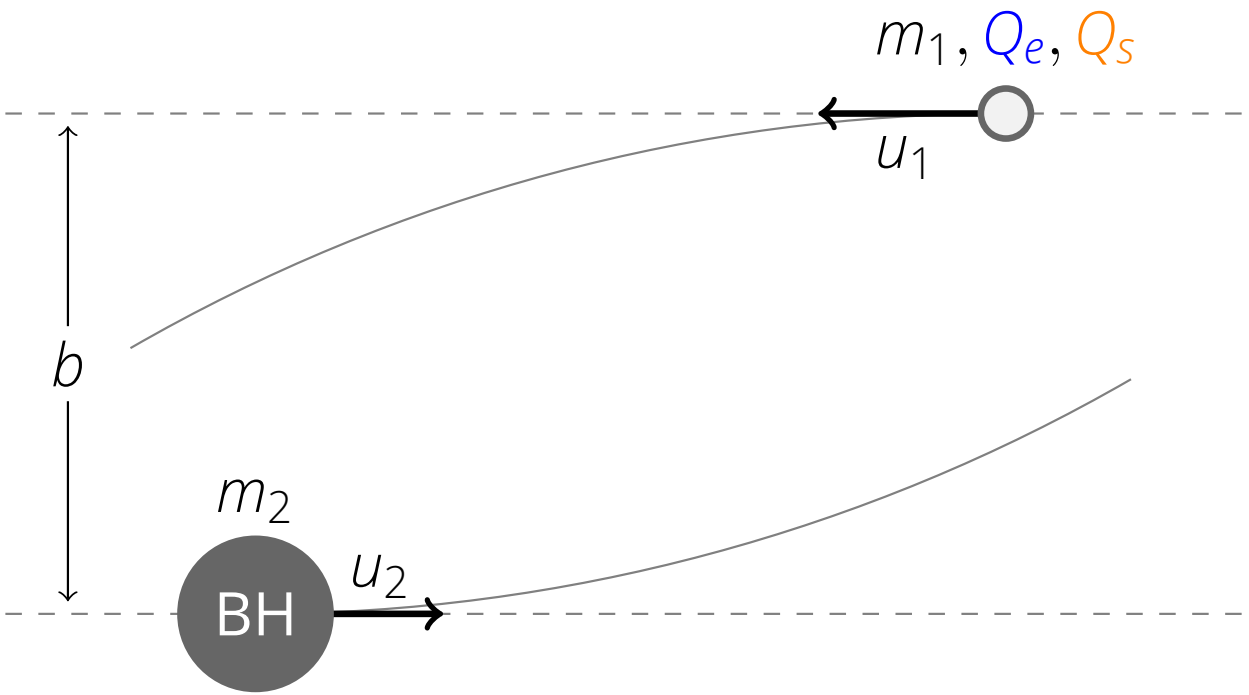

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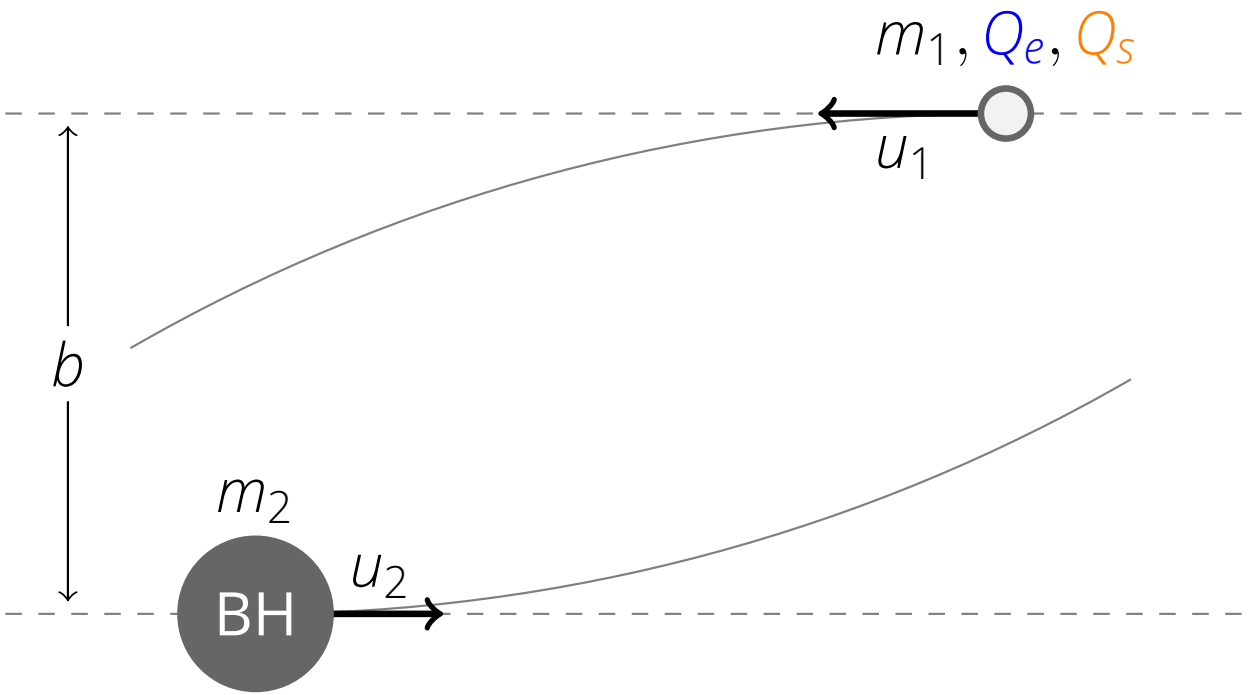

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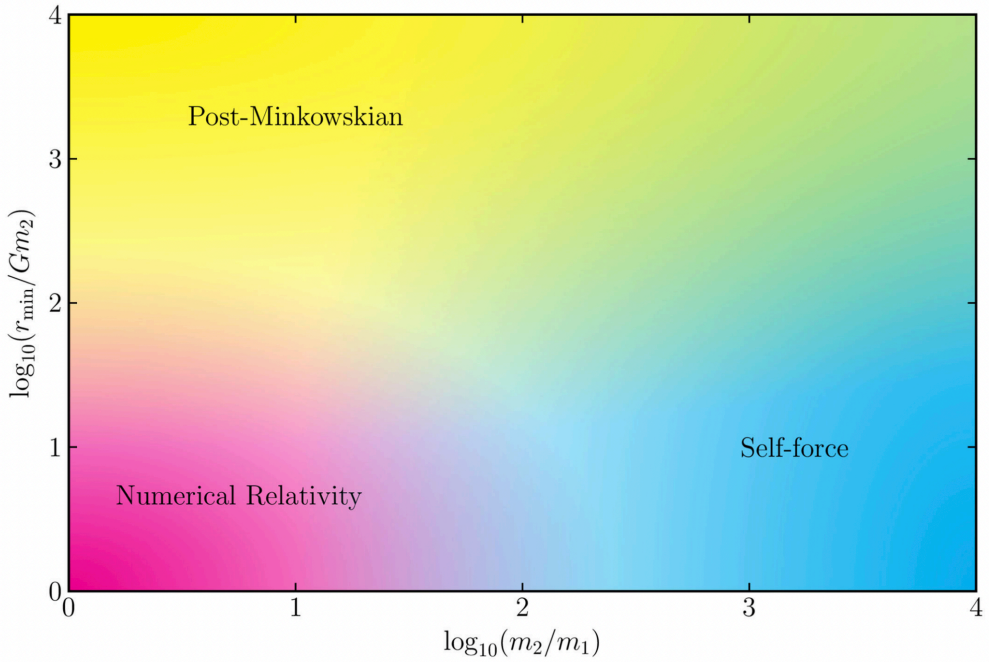
$$\Delta m_2 = \sqrt{y^2-1}\left[\frac{G_N^2 m_2^2 Q_S^2}{32 m_1^2 b^3} + \frac{3G_N^4 m_2^4 Q_e^2}{32 b^5}(5y^2-1) + \frac{5\pi G_N^7 m_1^2 m_2^6}{16 b^7}(21y^4-14y^2+1)\right]$$

$y \equiv u_1 \cdot u_2.$

Motivation

Why should I care about a small effect like horizon absorption?



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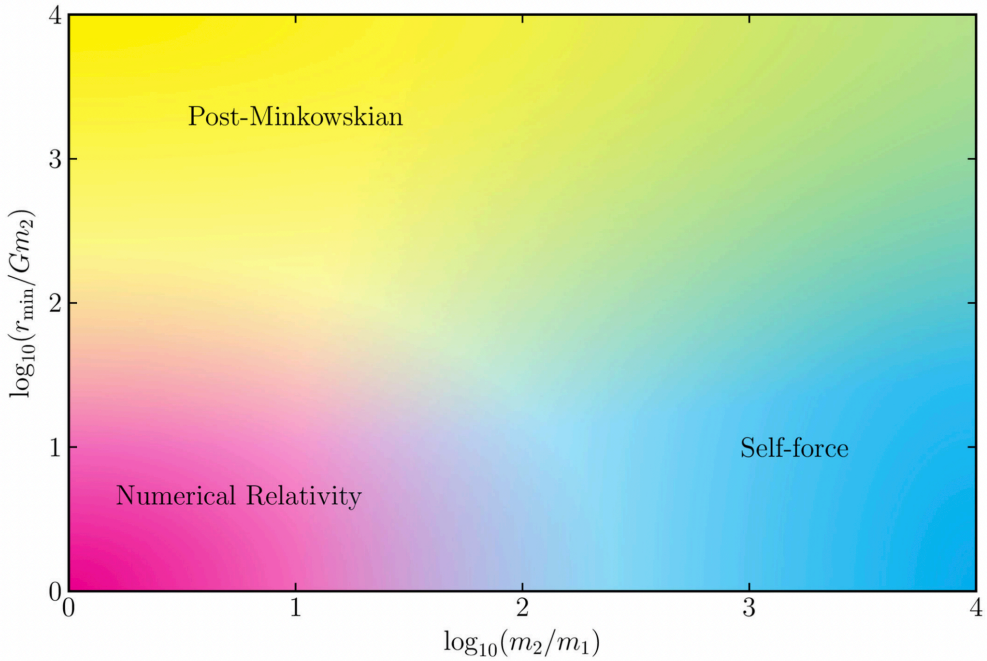

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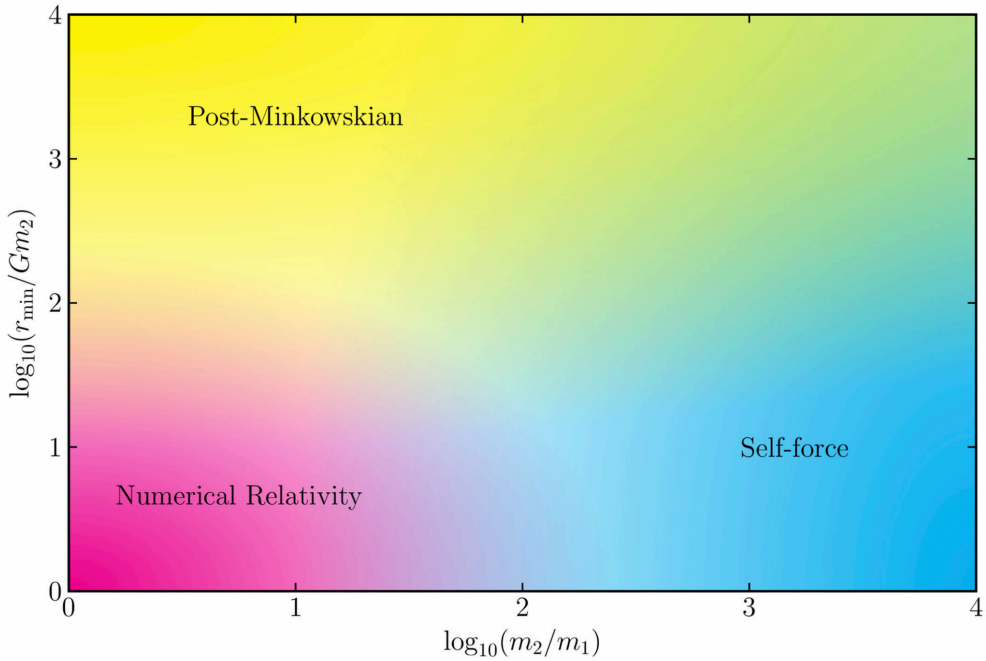

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Recent work on absorption from Amplitudes:
[Aoude, Ochirov 2023; Chen, Hsieh, Huang, Kim 2023]

Outline

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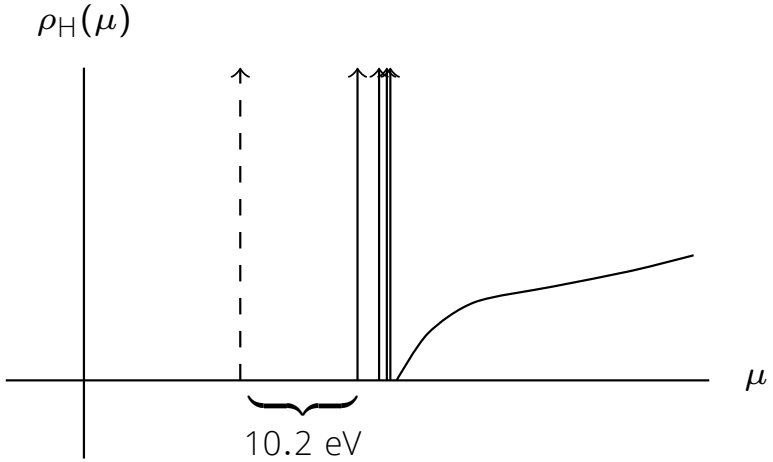
4. Present comparison with numerical self-force

Gapless Excited States

Hydrogen Atom:

$$M_n = M_1 + R_\infty \left(1 - \frac{1}{n^2}\right), \qquad n = 1, 2, 3\ldots$$



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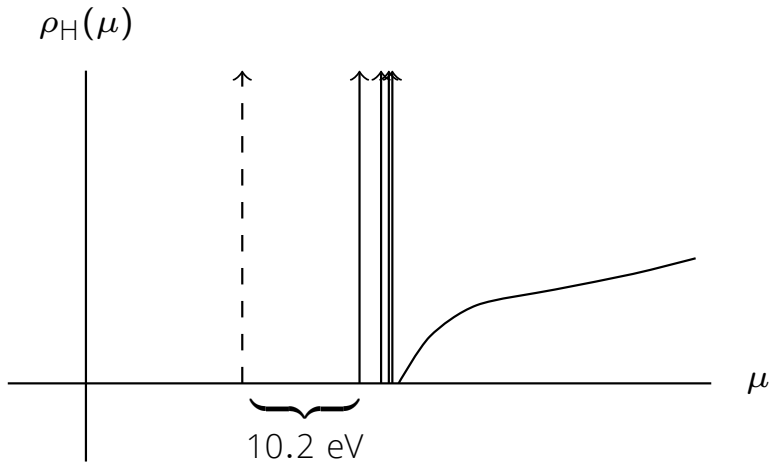
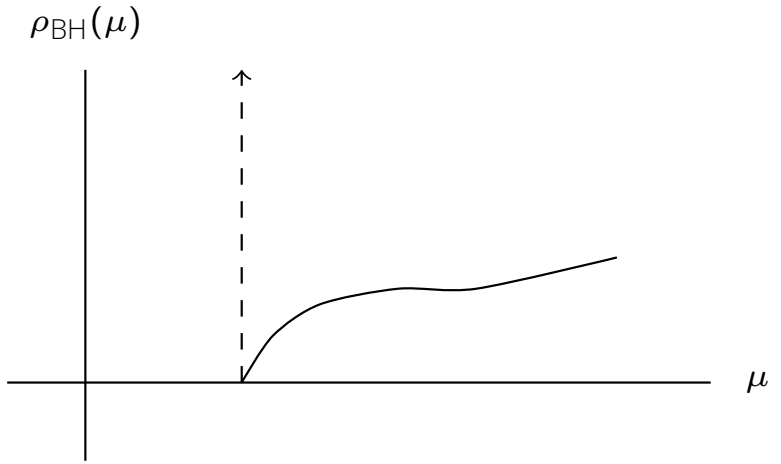


Schwarzschild Black Hole:

$$ds^2 = -\left(1 - \frac{2G_N M}{r}\right) dt^2 + \left(1 - \frac{2G_N M}{r}\right)^{-1} dr^2 + r^2 d\Omega$$



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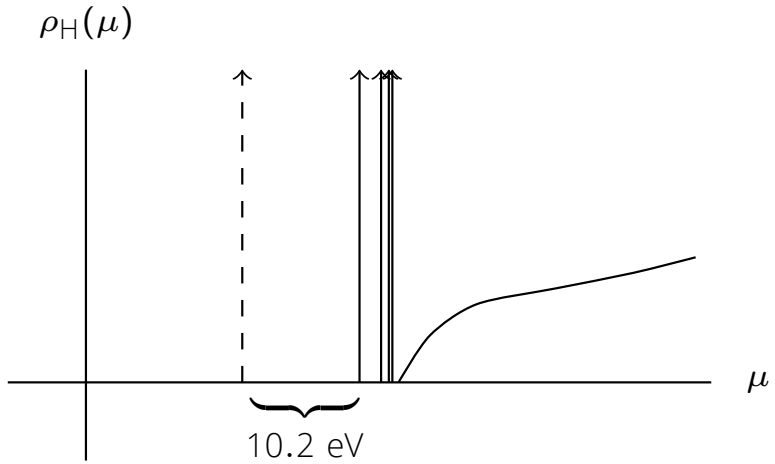

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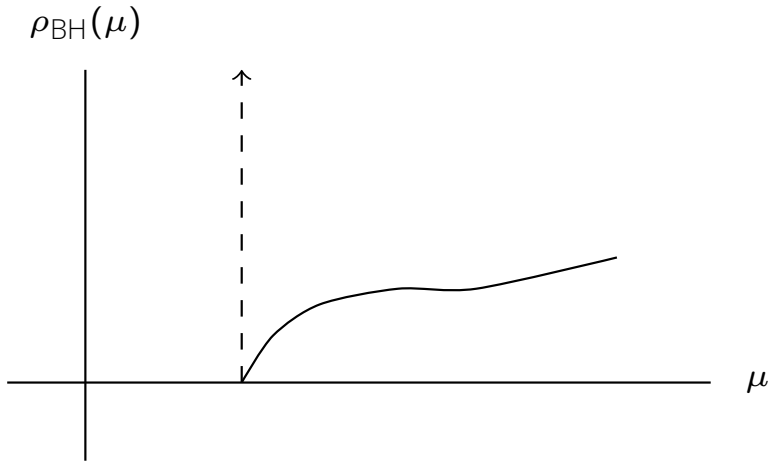

Absorption: physics of *gapless* internal degrees-of-freedom. Can go on-shell during scattering at *arbitrarily large impact parameter*, cannot be integrated out of the EFT.

Effective Theory of Compact Objects

$$\mathcal{H} = \mathcal{H}_{\text{visible}} \otimes \mathcal{H}_{\text{invisible}}$$

Goldstone modes: $\phi_{\mu_1 \ldots \mu_s}$

Soft radiation: $\psi,\ A_\mu,\ h_{\mu\nu}$

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Model independent approach to absorption [Goldberger, Rothstein 2005]

$$S = S_{\text{vis}}[\phi, \psi, A_\mu, h_{\mu\nu}] + S_{\text{inv}}[X] + S_{\text{portal}}[\phi, \psi, A_\mu, h_{\mu\nu}, X]$$

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Portal couplings constrained by **Lorentz invariance**, **locality** and **gauge invariance**.

Invisible States

$$\langle \psi(x_1)\phi(x_2)\phi(x_3)\psi(x_4)\rangle = \int [\mathcal{D}\phi][\mathcal{D}\psi][\mathcal{D}X]\psi(x_1)\phi(x_2)\phi(x_3)\psi(x_4)e^{iS_{\text{vis}}+iS_{\text{inv}}+iS_{\text{portal}}}$$

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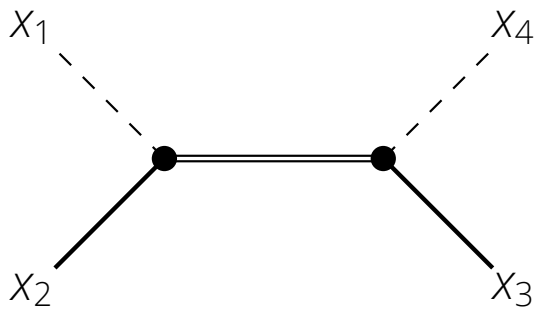

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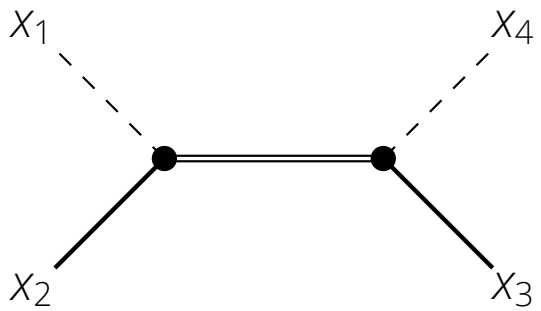

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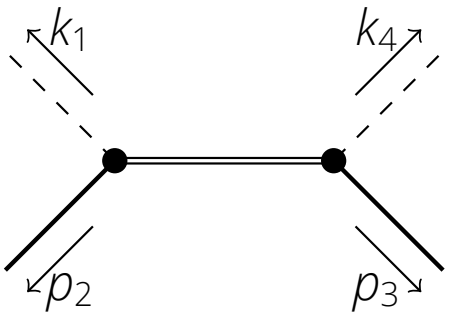
$$\langle \mathcal{O}_0(y_1)\,\mathcal{O}_0(y_2)\rangle_X \equiv \int [\mathcal{D}X]\,\mathcal{O}_0(y_1)\,\mathcal{O}_0(y_2)\,e^{iS_{\text{inv}}}$$

$$= \int \mathrm{d}^4k\, e^{ik\cdot(y_1-y_2)} \int_{m^2}^{\infty} \mathrm{d}\mu^2 \frac{i\rho_0(\mu^2)}{k^2-\mu^2+i0}$$

Leading-order contribution of X-states encoded in **spectral density** $\rho_0(\mu^2)$.

Compton Scattering

Natural on-shell object is the **absorptive Compton amplitude**:



$$= \quad -\kappa^2 m \int_0^\infty \mathrm{d}s \, s^{\alpha} \, \frac{\tilde{\rho}_0(s)}{k_1 \cdot p_2 - ms + i0},$$

$$\tilde{\rho}(s) \equiv \quad \rho(\mu^2)$$

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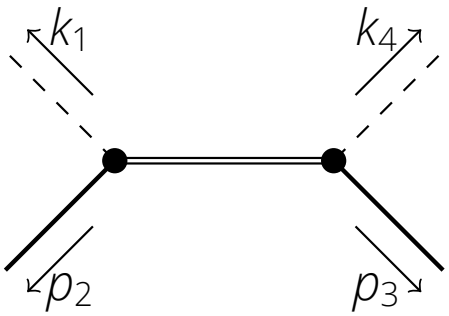

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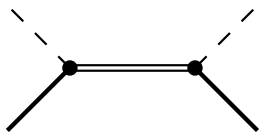
Gapless modes (soft region):

$$s \sim k_i \ll p_i \sim m$$



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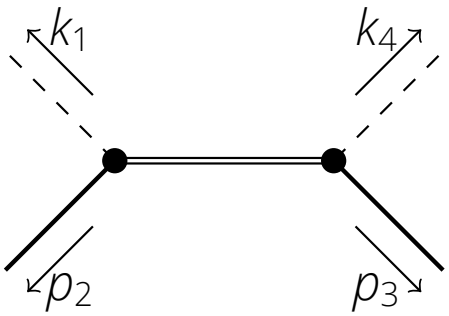

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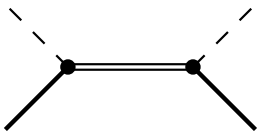

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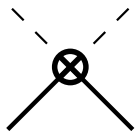

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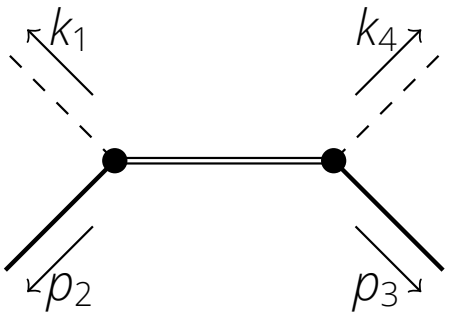

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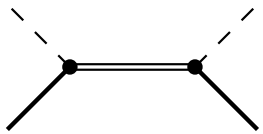

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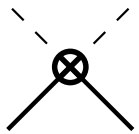

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Absorption encoded in asymptotic ($s \to 0^+$) expansion of the spectral density.

Everything else contributes to finite size Wilson coefficients (**Love numbers**).

Matching Absorption Cross Section

Calculate spectral density by matching **absorption cross section** in BHPT

$$\sigma_{\text{abs}}(\omega) \sim \begin{cases} 16\pi G_{\text{N}}^2 m^2 & \text{for scalars,} \\ \frac{64\pi}{3} G_{\text{N}}^4 m^4 \omega^2 & \text{for photons,} \\ \frac{256\pi}{45} G_{\text{N}}^6 m^6 \omega^4 & \text{for gravitons.} \end{cases} \qquad \omega \to 0^+$$

[Starobinsky, Churilov 1974; Page 1976]

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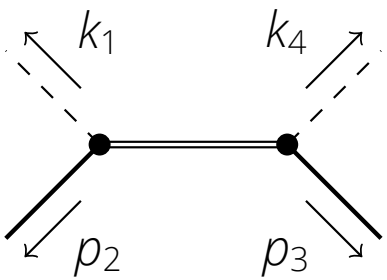

$$-k_1 = k_4 = (\omega, 0, 0, \omega)$$
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Optical theorem:

$$\text{Im}\mathcal{M}_{\text{forward}}(\omega) = 2m\omega\, \sigma_{\text{total}}(\omega)$$

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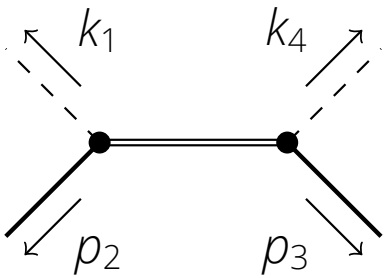

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$$\text{Im}\left(-\kappa^2 \int_0^\infty \text{d}s\, s^\alpha \frac{\tilde{\rho}_0(s)}{\omega - s + i0}\right) = \pi\kappa^2 \tilde{\rho}_0(\omega) \quad \Rightarrow \quad \tilde{\rho}_0(s) \sim \frac{G_N m^3}{\pi} s, \quad s \to 0^+.$$

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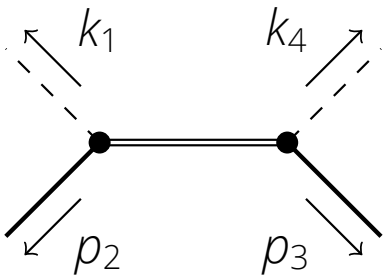
[Starobinsky, Churilov 1974; Page 1976]



$$-k_1 = k_4 = (\omega, 0, 0, \omega)$$
$$-p_2 = p_3 = (m, 0, 0, 0)$$

Optical theorem:

$$\text{Im}\mathcal{M}_{\text{forward}}(\omega) = 2m\omega\, \sigma_{\text{total}}(\omega)$$

$$\text{Im}\left(-\kappa^2 \int_0^\infty \text{d}s\, s^\alpha \frac{\tilde{\rho}_0(s)}{\omega - s + i0}\right) = \pi\kappa^2 \tilde{\rho}_0(\omega) \quad \Rightarrow \quad \tilde{\rho}_0(s) \sim \frac{G_N m^3}{\pi} s, \quad s \to 0^+.$$

$$\mathcal{M}^{(\psi)} = -32\pi G_N^2 m^2 \left[\underbrace{\frac{k_1 \cdot p_2}{\alpha}}_{\text{UV divergence}} + (k_1 \cdot p_2) \underbrace{\log(-k_1 \cdot p_2 - i0)}_{\text{branch cut in "tree" amplitude}} \right]$$

Photon Matching

$$S_{\text{portal}} \supset \int \mathrm{d}^4x\sqrt{-g}\left[\kappa\phi F_{\mu\nu}\mathcal{O}_1^{\mu\nu}\right]$$

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Match absorption cross-section: $\quad\Longrightarrow\quad \tilde{\rho}_2(s) \sim \frac{G_N^5 m^7}{180\pi}, \quad s\to 0^+.$

Classical Observables from Amplitudes

Recycle low-energy spectral density to calculate **new observables**.

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Classical scattering observables:

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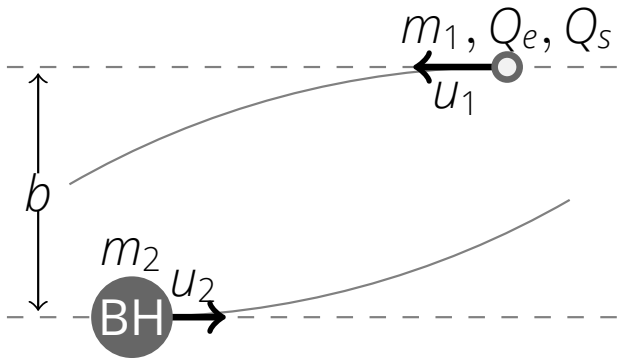

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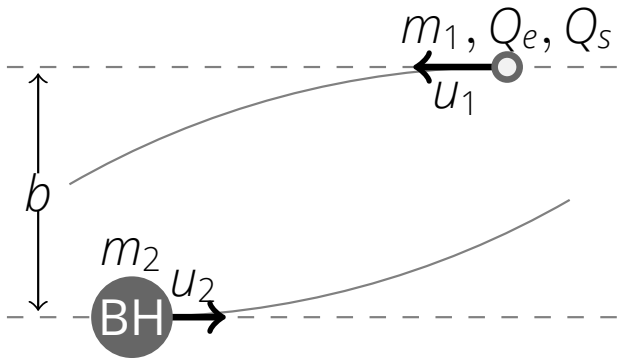

KMOC: on-shell approach to calculating *asymptotic* in-in observables
[Kosower, Maybee, O'Connell 2018]

$$\langle \mathbb{O}(t) \rangle \xrightarrow{t\to\infty} \langle \text{in}|S^\dagger \mathbb{O} S|\text{in}\rangle = \sum_{\text{out}_i} \langle \text{in}|S^\dagger|\text{out}_1\rangle\langle \text{out}_1|\mathbb{O}|\text{out}_2\rangle\langle \text{out}_2|S|\text{in}\rangle \xrightarrow{\hbar\to 0} \mathcal{O}(t\to\infty)$$

$$|\text{in}\rangle = \int \hat{\mathrm{d}}^D p_1 \hat{\mathrm{d}}^D p_2 \hat{\delta}^{(+)}\left(p_1^2 - m_1^2\right) \hat{\delta}^{(+)}\left(p_2^2 - m_2^2\right) \psi_1(p_1)\psi_2(p_2) e^{-ip_1\cdot b_1} e^{-ip_2\cdot b_2} |p_1, p_2\rangle$$

wavepackets ψ_i peaked around classical trajectories $x_i^\mu = b_i^\mu + u_i^\mu t$.

Absorptive Impulse

$$\Delta p_2^\mu \xleftarrow{\hbar \to 0} \underbrace{i\langle \text{in}|[\mathbb{P}_2^\mu, T]|\text{in}\rangle}_{\text{“virtual”}} + \underbrace{\langle \text{in}|T^\dagger[\mathbb{P}_2^\mu, T]|\text{in}\rangle}_{\text{“real”}}, \qquad S \equiv 1 + iT.$$

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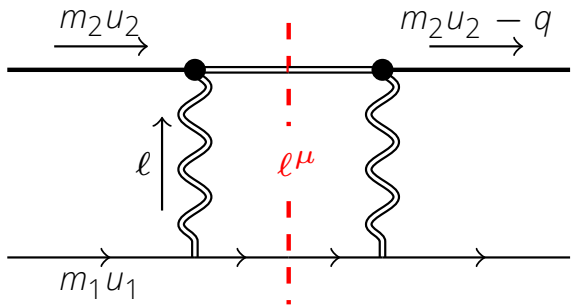

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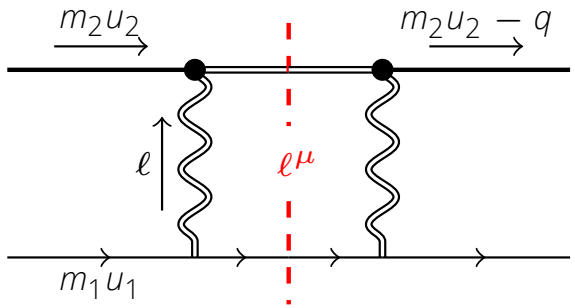

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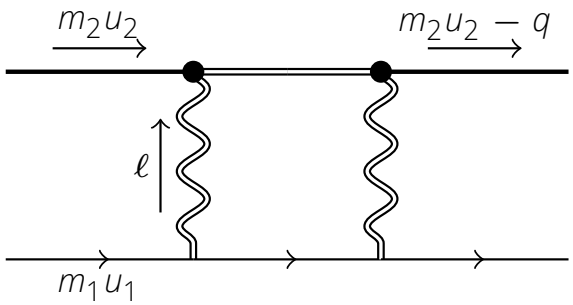

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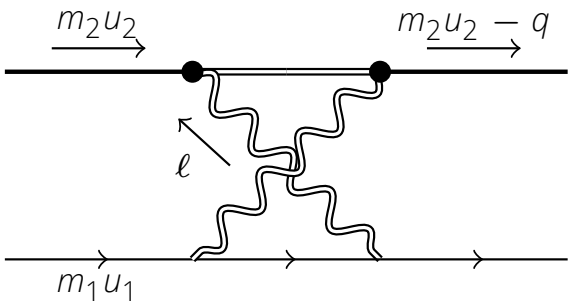

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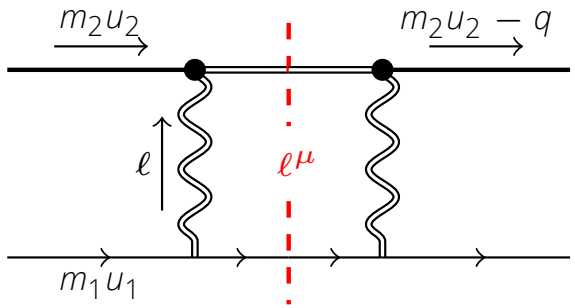

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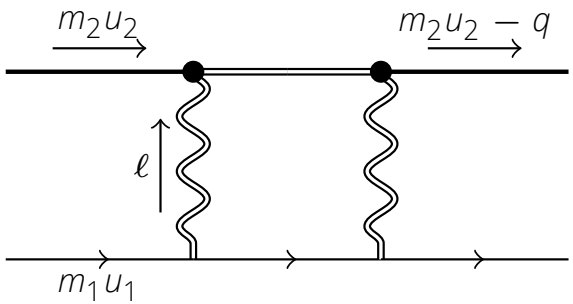

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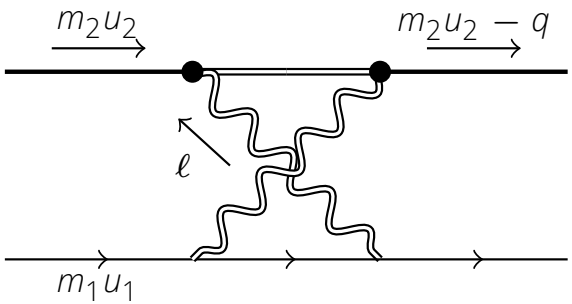

Integrals expanded to LO in **soft region**: $s \sim l^\mu \sim q^\mu \ll m_i \sim u_i^\mu$.

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$$(\Delta p_2^\mu)_{\text{abs}} = \underbrace{(\Delta m_1)}_{=0} \times \check{u}_1^\mu + (\Delta m_2) \times \check{u}_2^\mu - \frac{J}{b^2} \underbrace{(\Delta \chi)}_{=0} \times b^\mu, \qquad u_i \cdot \check{u}_j = \delta_{ij}$$

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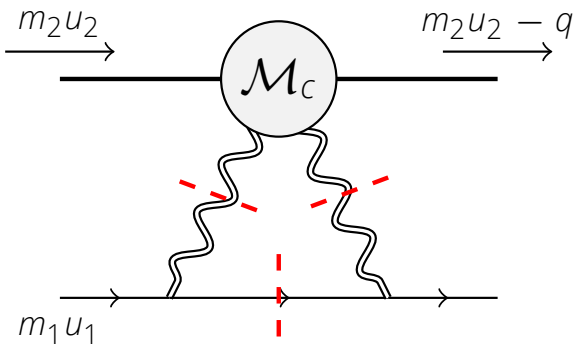

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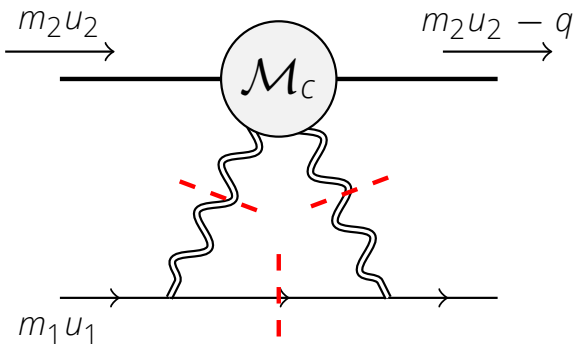


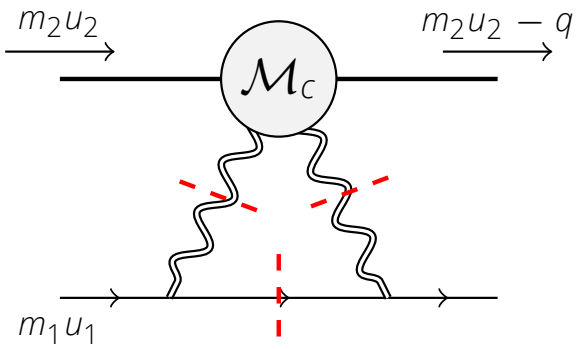
LO absorptive impulse is completely determined by the *mass shift*

$$\Delta m_2 = \frac{1}{m_1} \int \hat{\mathrm{d}}^D q \; \hat{\delta}(u_1 \cdot q) \, \hat{\delta}(u_2 \cdot q) \, e^{-\imath q \cdot b} \int_0^\infty \mathrm{d}s \; s \, \tilde{\rho}(s) \, \mathrm{Im} \mathcal{M}_4 \left(s, q^2\right)$$

Absorptive Impulse

$$(\Delta p_2^\mu)_{\text{abs}} = \underbrace{(\Delta m_1)}_{=0} \times \check{u}_1^\mu + (\Delta m_2) \times \check{u}_2^\mu - \frac{J}{b^2} \underbrace{(\Delta \chi)}_{=0} \times b^\mu, \qquad u_i \cdot \check{u}_j = \delta_{ij}$$

- Mass of body-1 cannot change by assumption
- Virtual contribution integrates to zero, need only triangle cut for real contribution
- Absorptive contribution to scattering angle delayed by additional PM order



LO absorptive impulse is completely determined by the *mass shift*

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Manifestly $\Delta m_2 > 0 \;\Rightarrow\; \Delta\,(\text{horizon area}) > 0$ [Hawking 1972]

Schwarzschild Mass Shift

Scalar absorption:

$$(\Delta m_2)^{(\psi)} = \underbrace{\frac{G_N^2 Q_s^2 m_2^2}{32 m_1^2 b^3}}_{\text{3PM}} \sqrt{y^2 - 1}, \qquad y \equiv u_1 \cdot u_2$$

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Complete agreement with [Goldberger, Rothstein 2020] ✓

Dissipation Numbers

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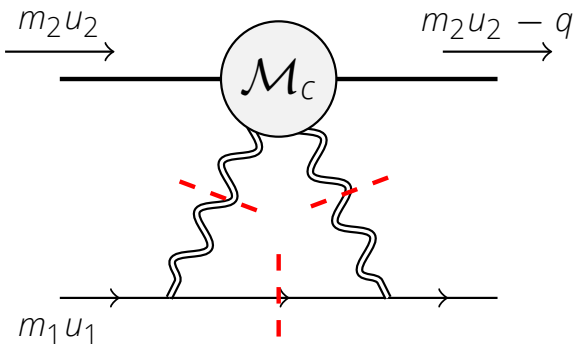

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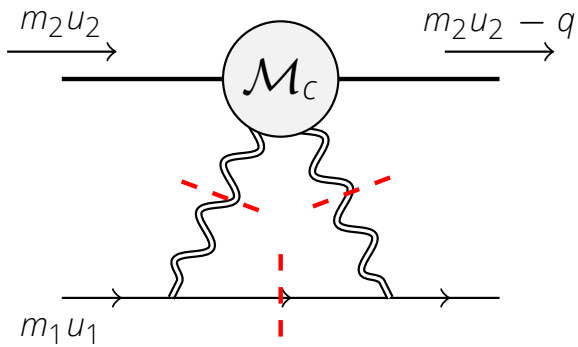
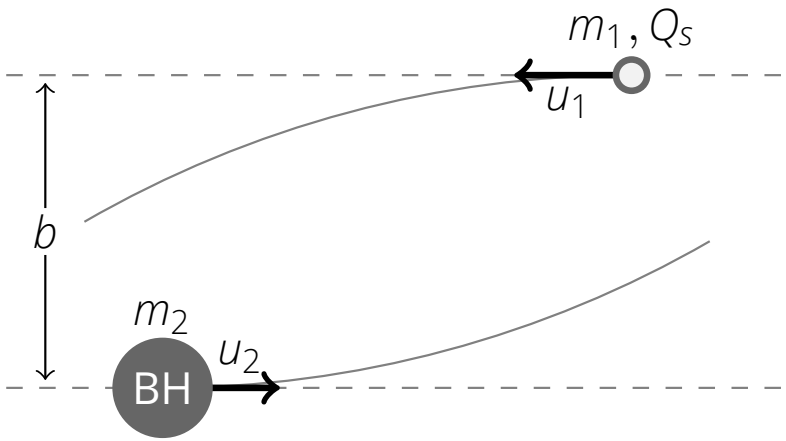


$$(\Delta m_2)^{(\psi)} = \frac{\pi G_N Q_s^2 c^{(\psi)}}{32 m_1^2 m_2 b^3}\sqrt{y^2-1}$$

$$(\Delta m_2)^{(\gamma)} = \frac{9\pi G_N Q_e^2}{32 m_2 b^5}\left[c^{(\gamma)}_{+-}\left(5y^2-1\right) - 4c^{(\gamma)}_{++}\right]\sqrt{y^2-1}\,,$$

$$(\Delta m_2)^{(h)} = \frac{225\pi^2 G_N^2 m_1^2}{16 m_2 b^7}\left[c^{(h)}_{+-}\left(21y^4-14y^2+1\right) + 8c^{(h)}_{++}\right]\sqrt{y^2-1}$$

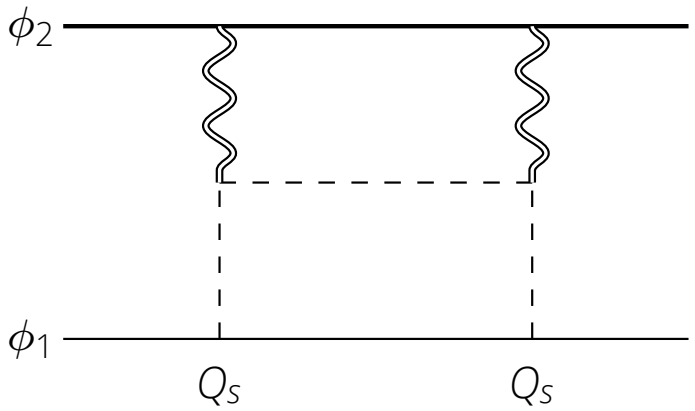
Comparison with Numerical Self-Force



Scalar self-force expansion:

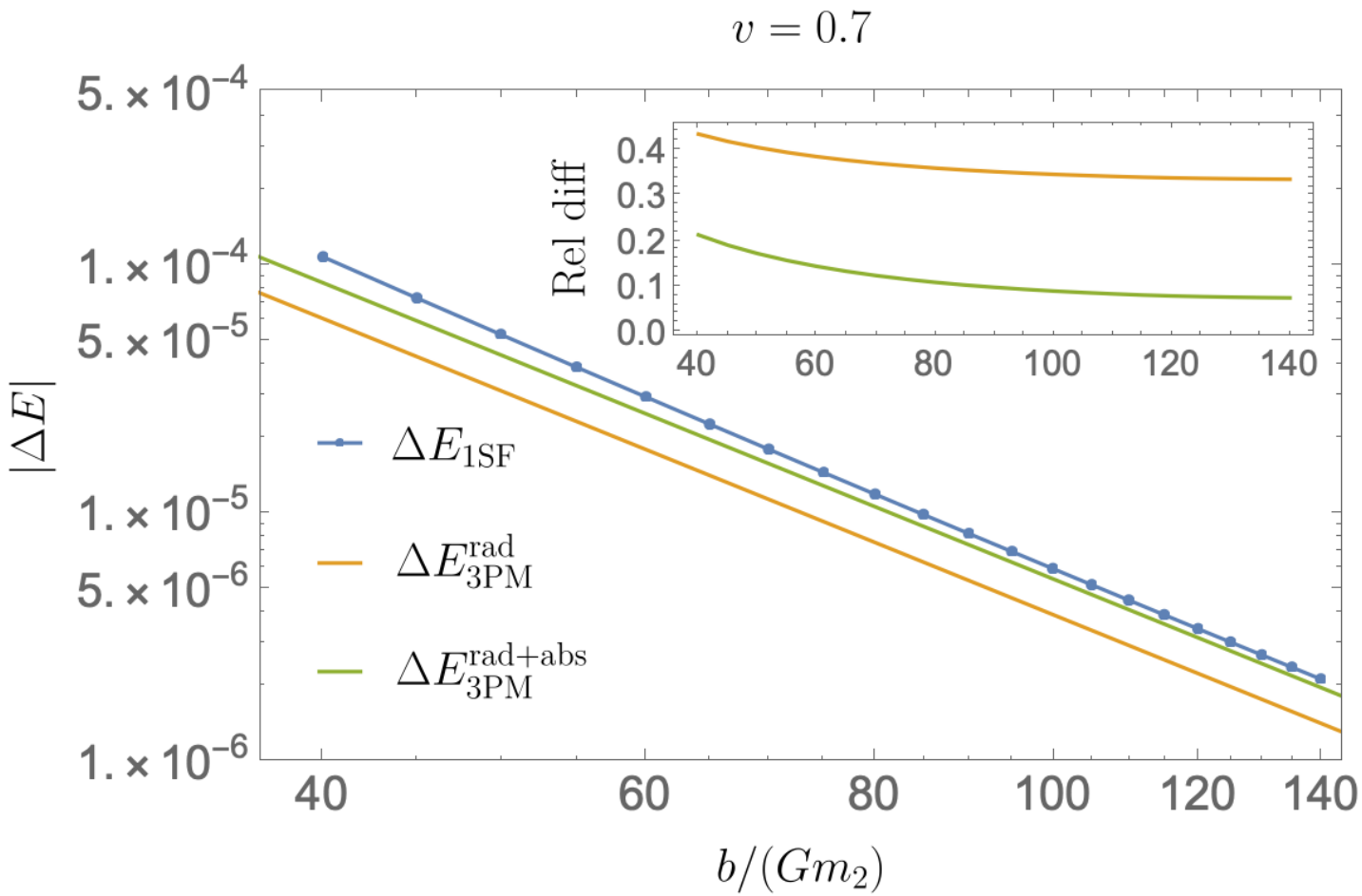
$$\frac{Q_s^2}{G_N m_1 m_2} \ll 1$$

Comparison between numerical self-force and PM calculations:
[Barack, Bern, Herrmann, Long, Parra-Martinez, Roiban, Ruf, Shen, Solon, Teng, Zeng, 2023]



Can we see horizon absorption by comparing $(\Delta E)_{3\text{PM}}$ and $(\Delta E)_{1\text{SF}}$?

Comparison with Numerical Self-Force



[Credit: Leor Barack and Oliver Long]

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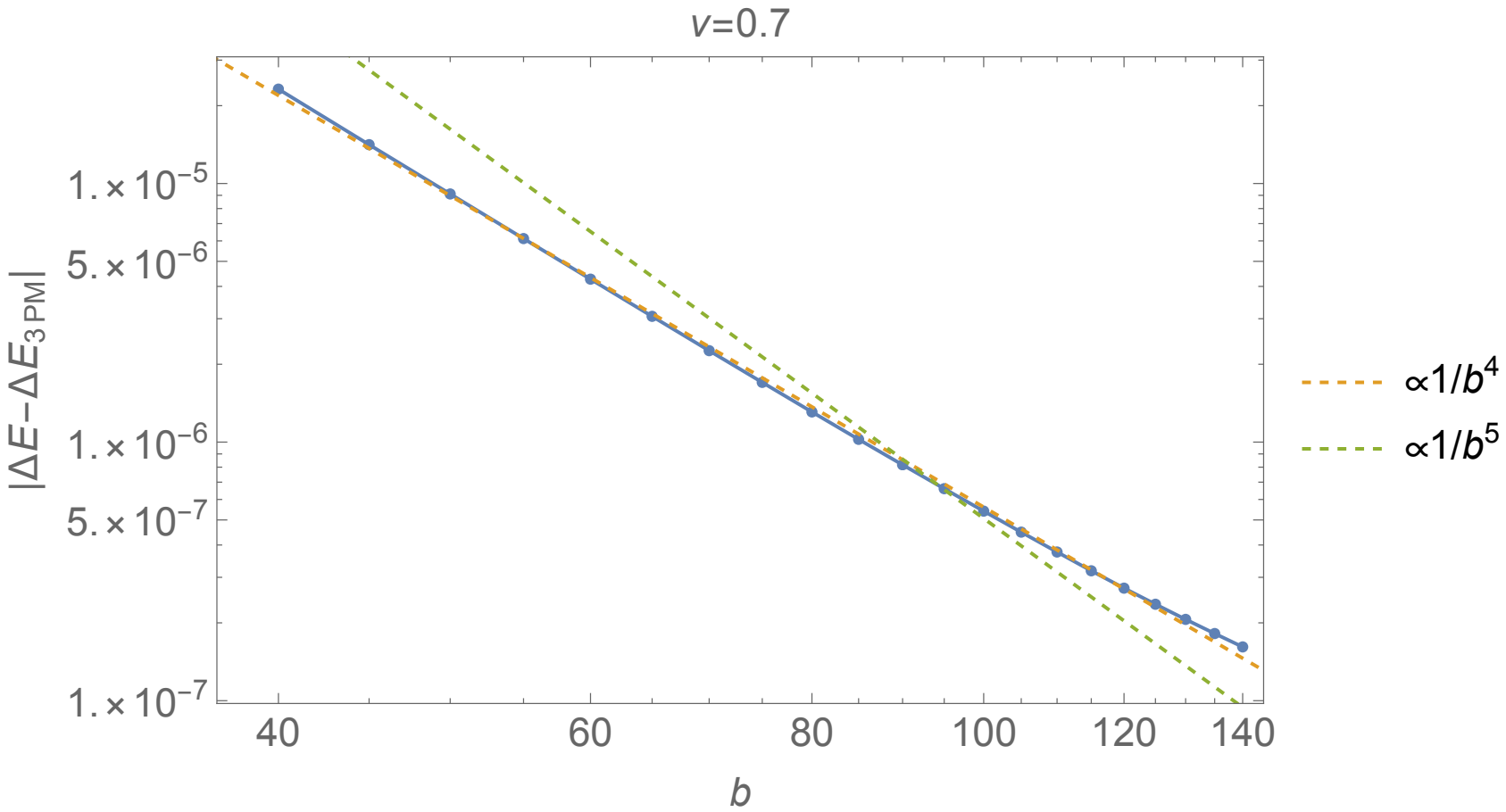
Thank You!

UCLA

Backup Slide



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