# Hyperbolic-like Encounters of Binary Black Holes with the numerical relativity code SpEC

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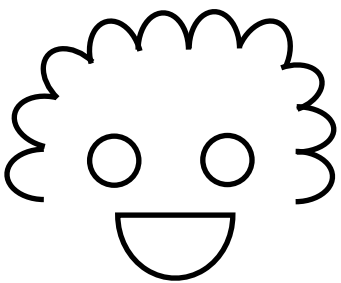
Albert Einstein Institute
Potsdam

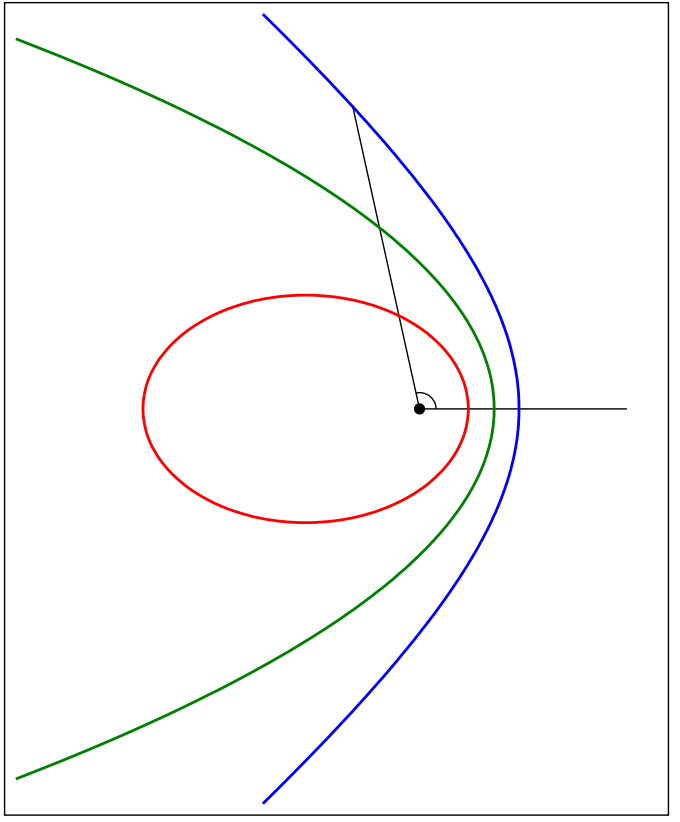


# Hyperbolic-like Encounters

Hyperbolic-like orbit
= initially unbound orbit

$$E_{\mathrm{orb}}(t=0) > 0$$

Orbital parameters change due to gravitational wave emission



https://en.wikipedia.org/wiki/File:Kepler_orbits.svg

# Motivation

Hyperbolic-like encounters are astrophysically rare events

Mostly expected near the center of galaxies

Validation/Calibration of post-Newtonian and effective-one-body predictions [Damour - PRD 081503 (2014), Nagar - PRD 064013 (2021)]

# Setup

Spectral Einstein Code (SpEC)
https://www.black-holes.org/code/SpEC.html [CQG 36, 195006 (2019)]

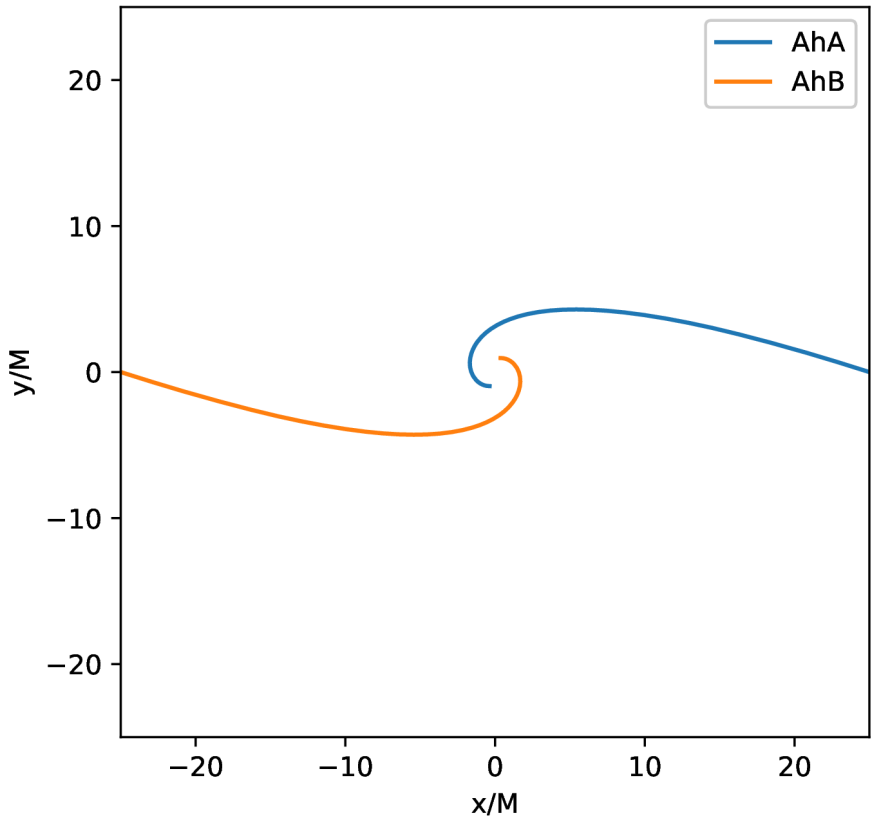
Evolve spacetime with
Generalized Harmonic Gauge (GHG) system

Damped Harmonic Gauge

Equal mass binary: $m_A = m_B = 0.5M$

No spin

$E_{orb} = 0.00052\ M$ $J_{orb} = 0.85\ M^2$



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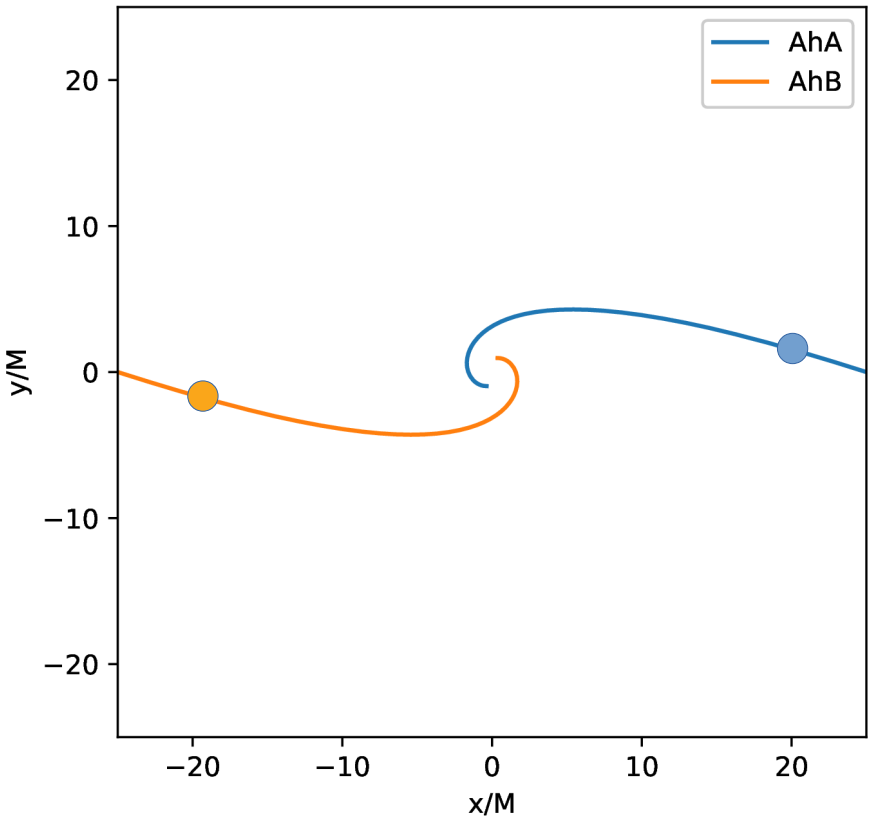

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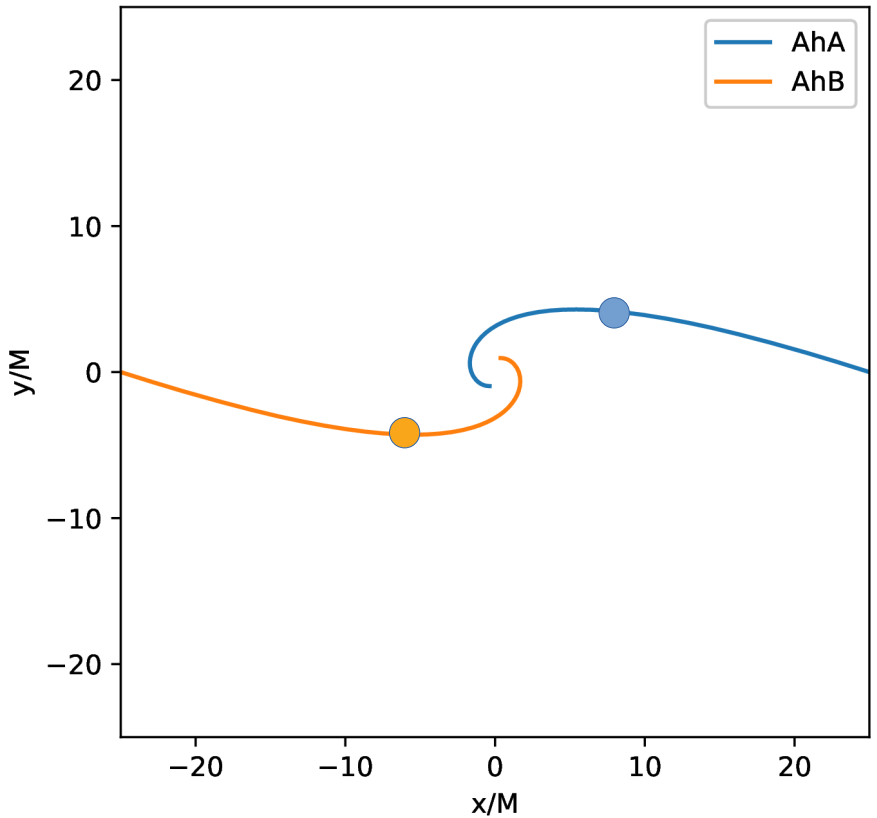

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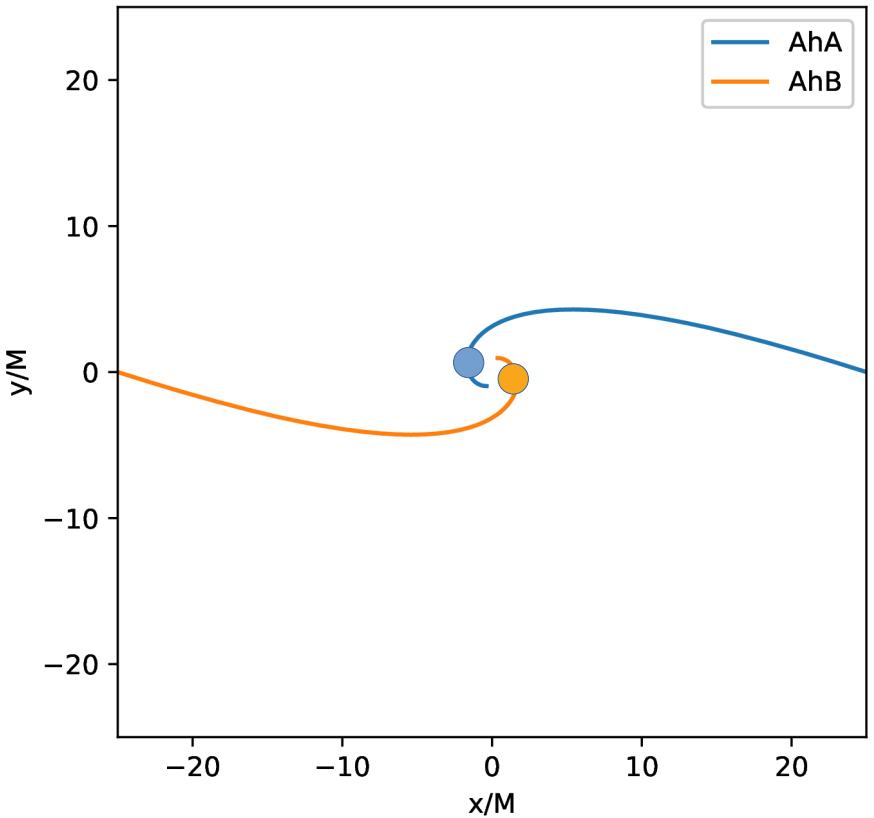

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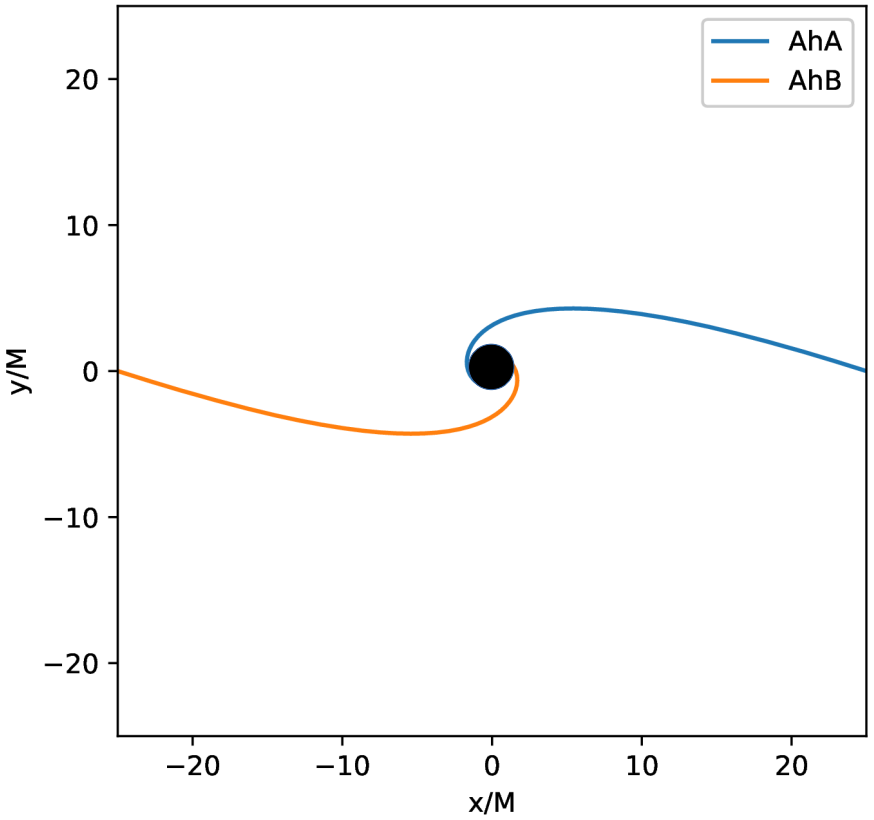
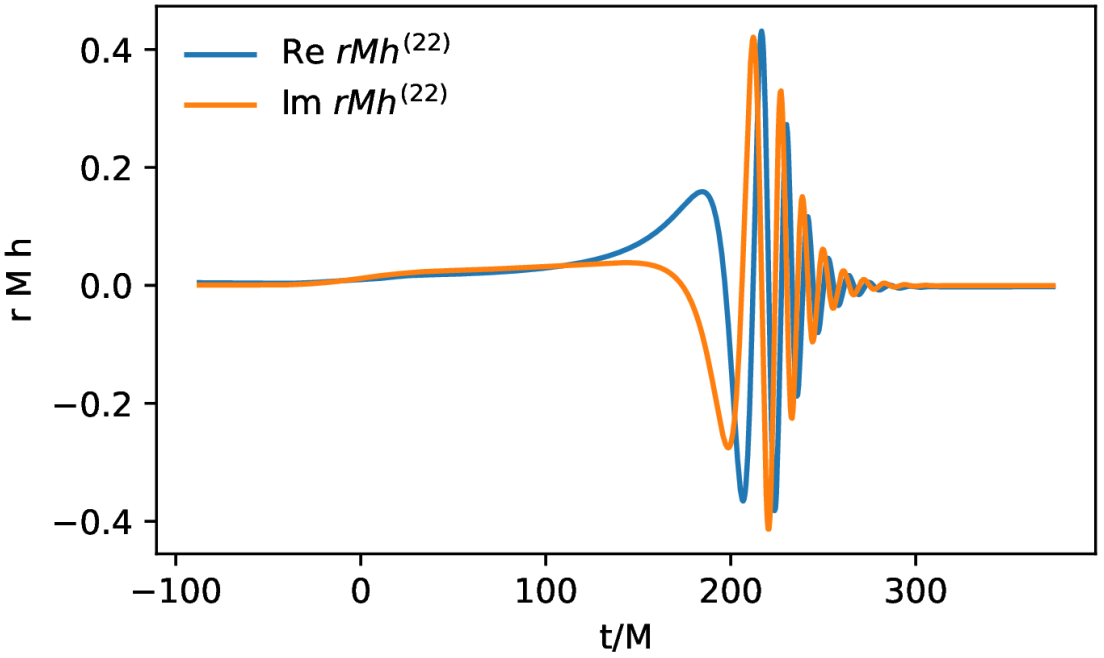
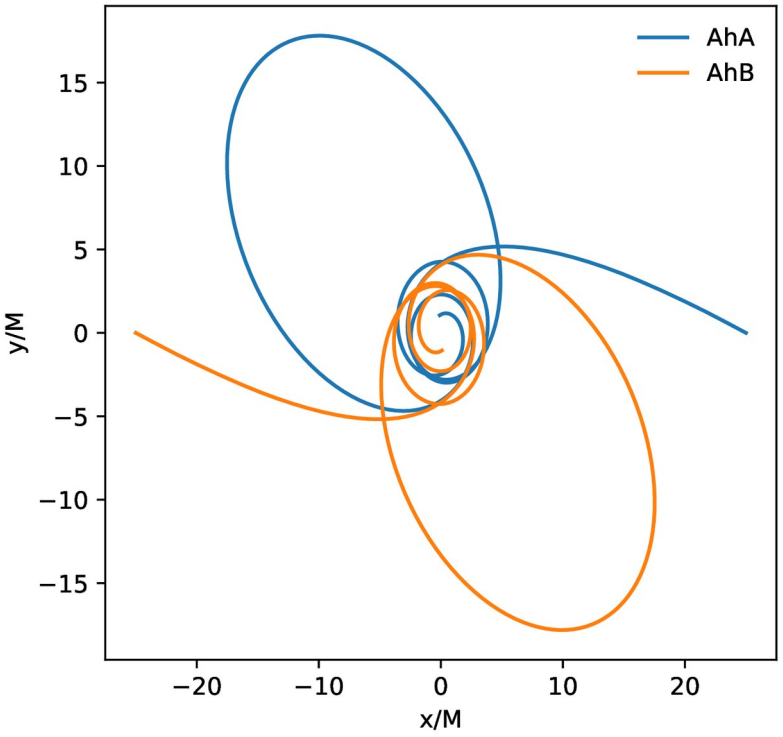
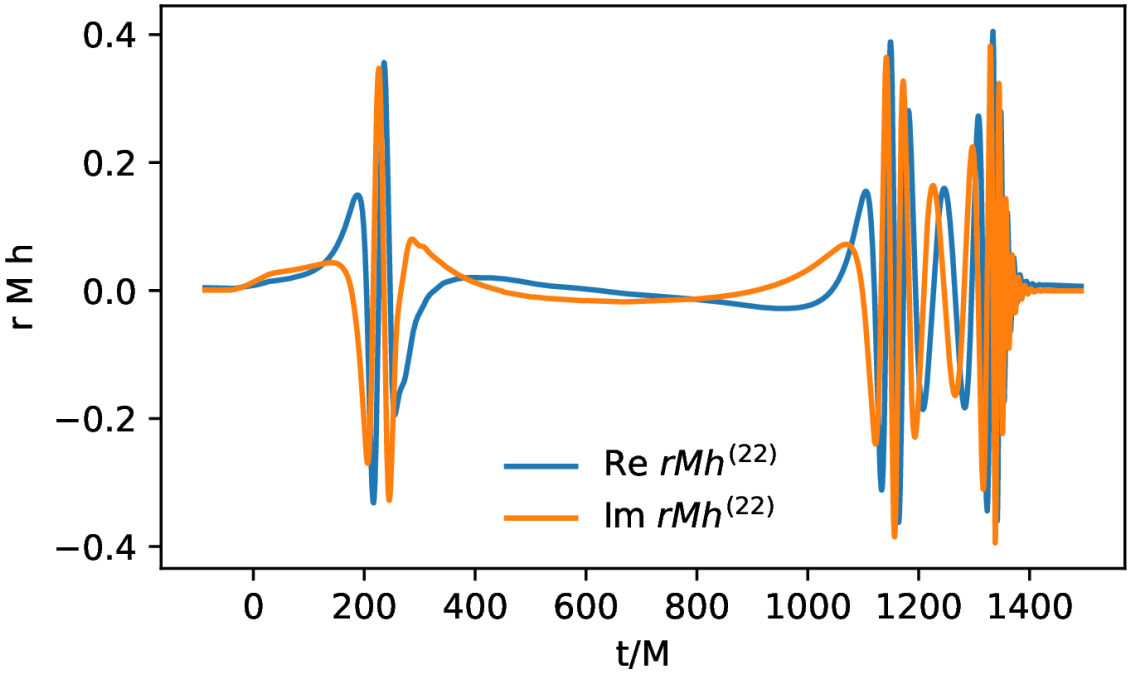


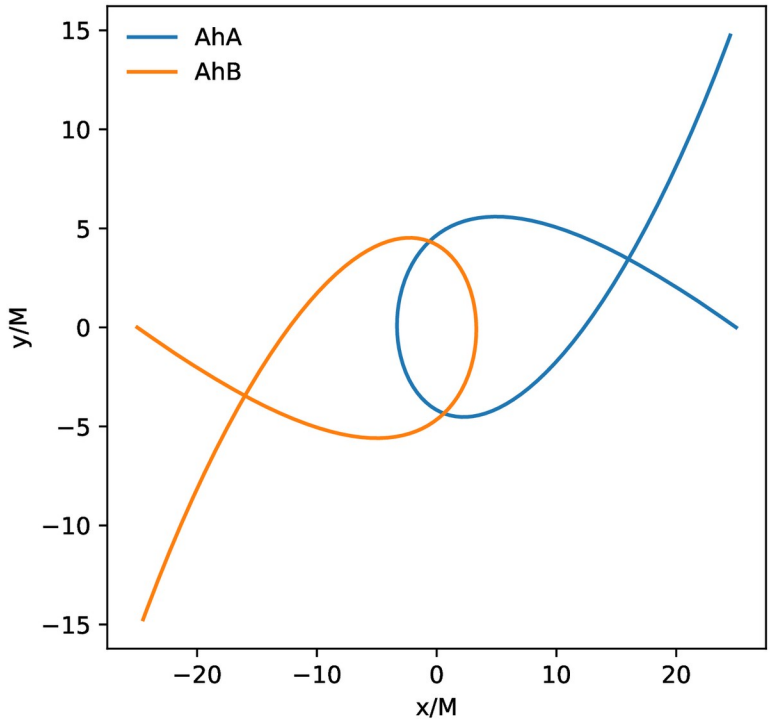



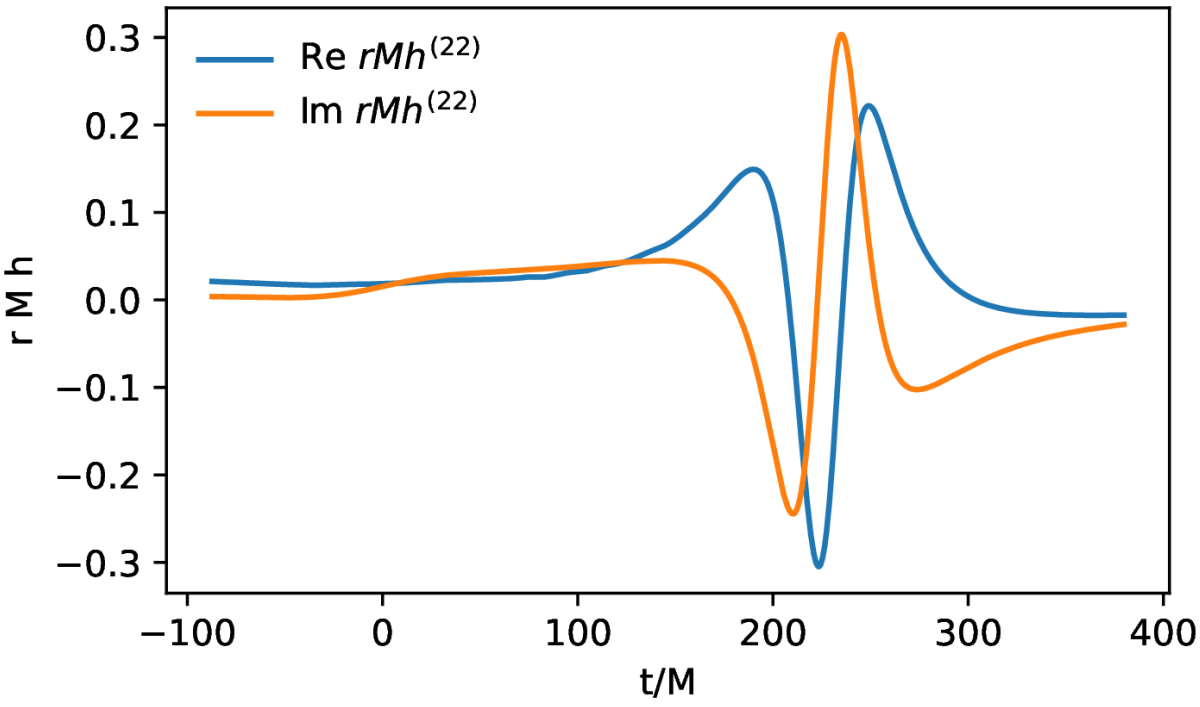
$E_{orb} = 0.00052\ M$ $J_{orb} = 1.007\ M^2$



$E_{orb} = 0.00052\ M \qquad J_{orb} = 1.076\ M^2$



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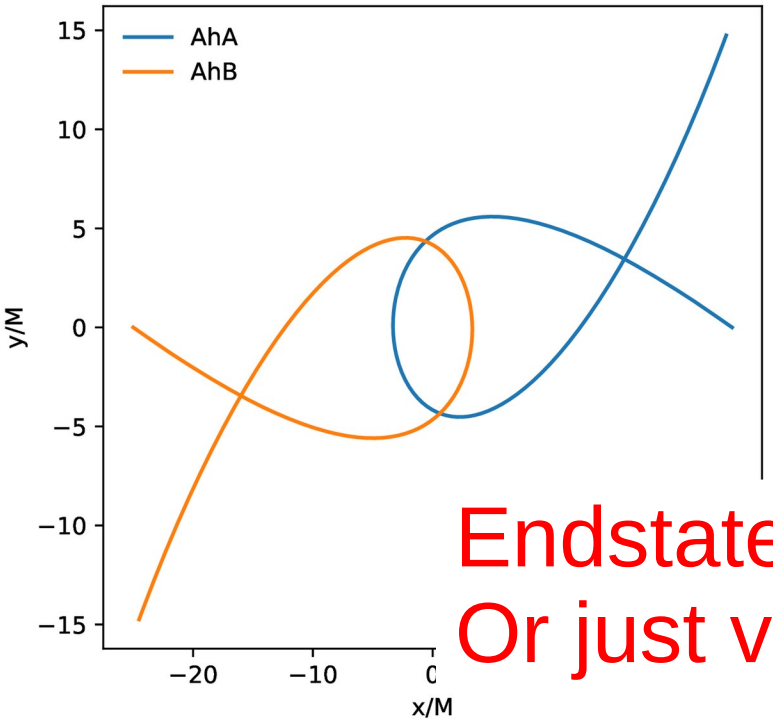
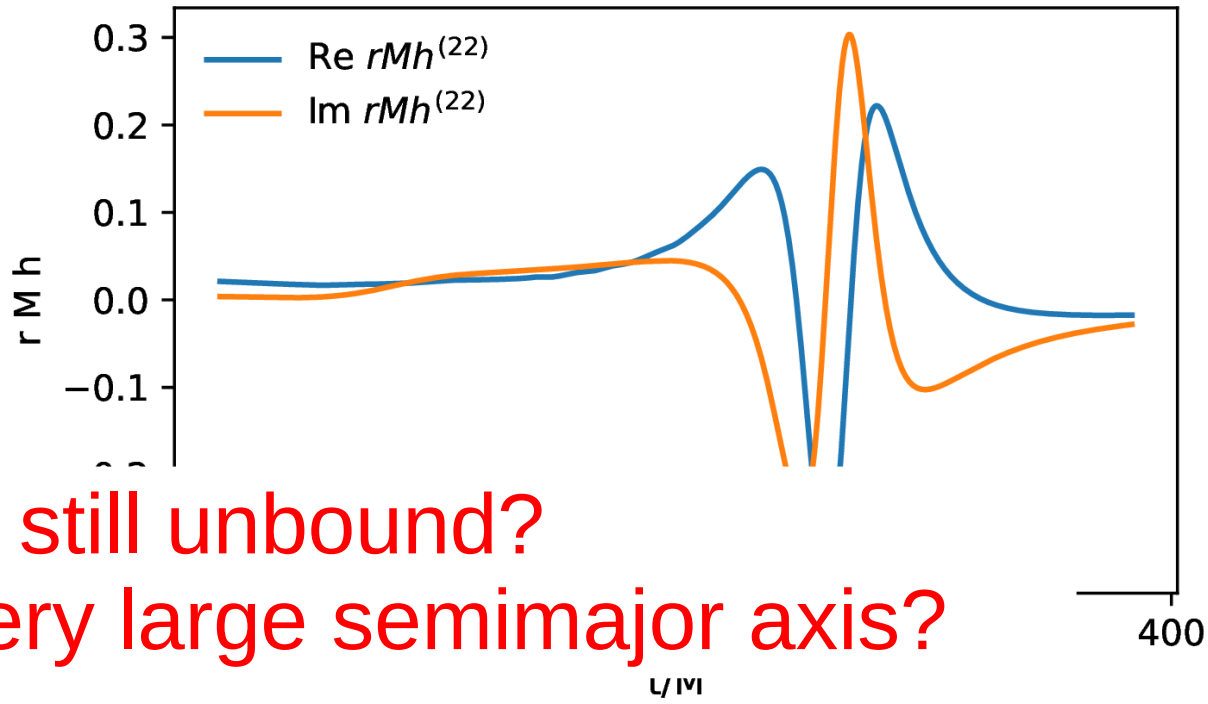



Endstate still unbound?

Or just very large semimajor axis?

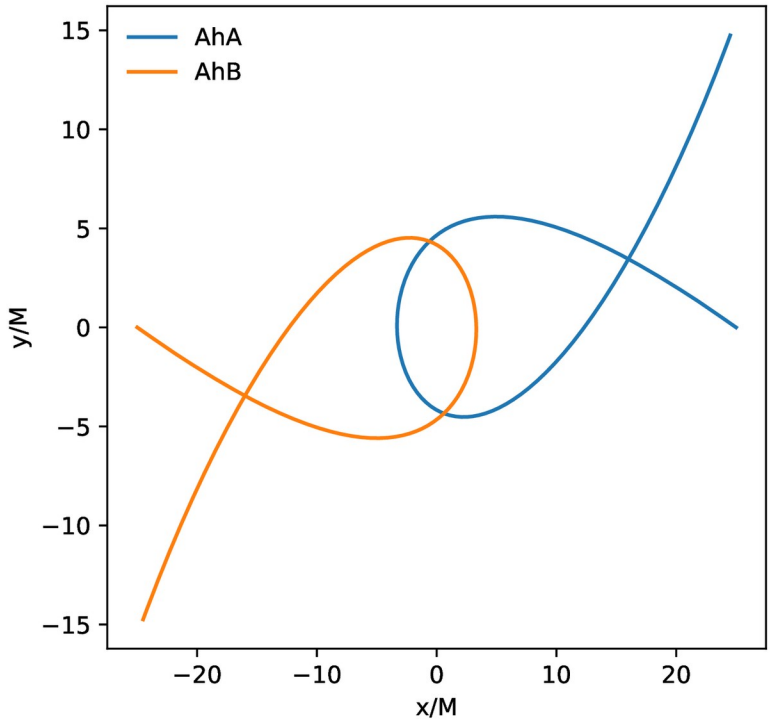
# Computation of Orbital Energy

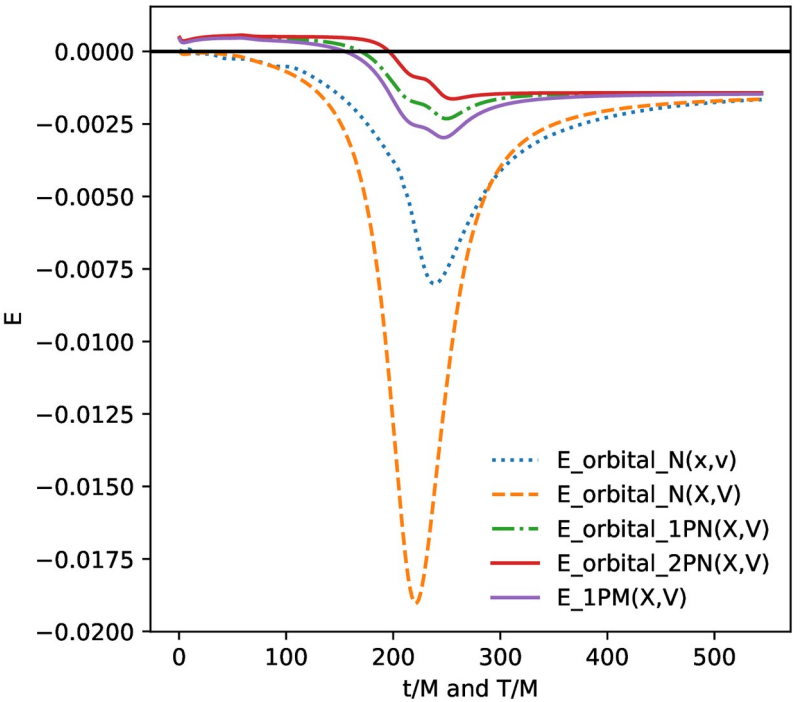
Coevolve harmonic coordinates $X^\mu$
[Prayush Kumar]

Use PN expressions for orbits in harmonic coordinates [Memmesheimer - PRD 104011 (2004)]

$\rightarrow \quad E_{\rm orb}(X^\mu, V^\mu) \qquad J_{\rm orb}(X^\mu, V^\mu)$

$E_{orb} = 0.00052\ M \qquad J_{orb} = 1.076\ M^2$



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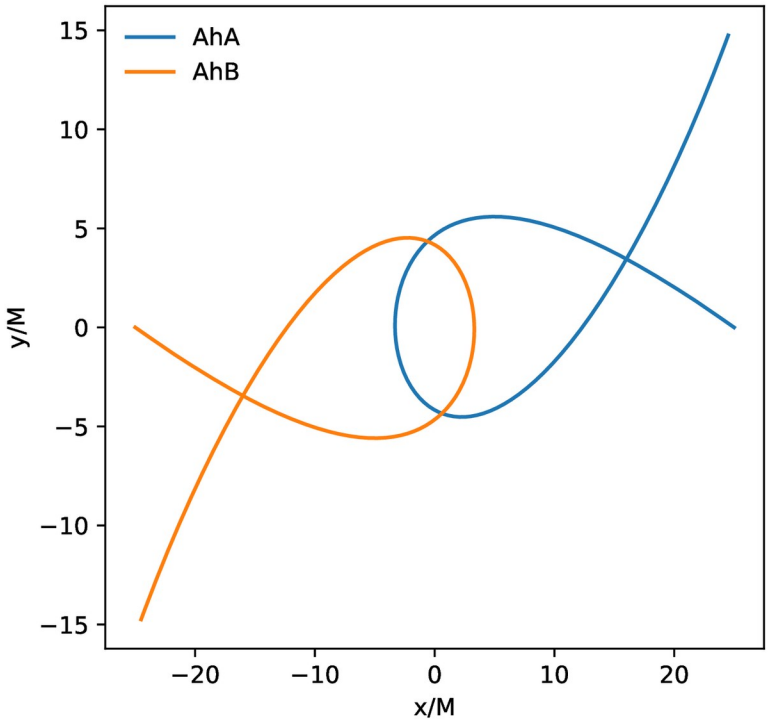
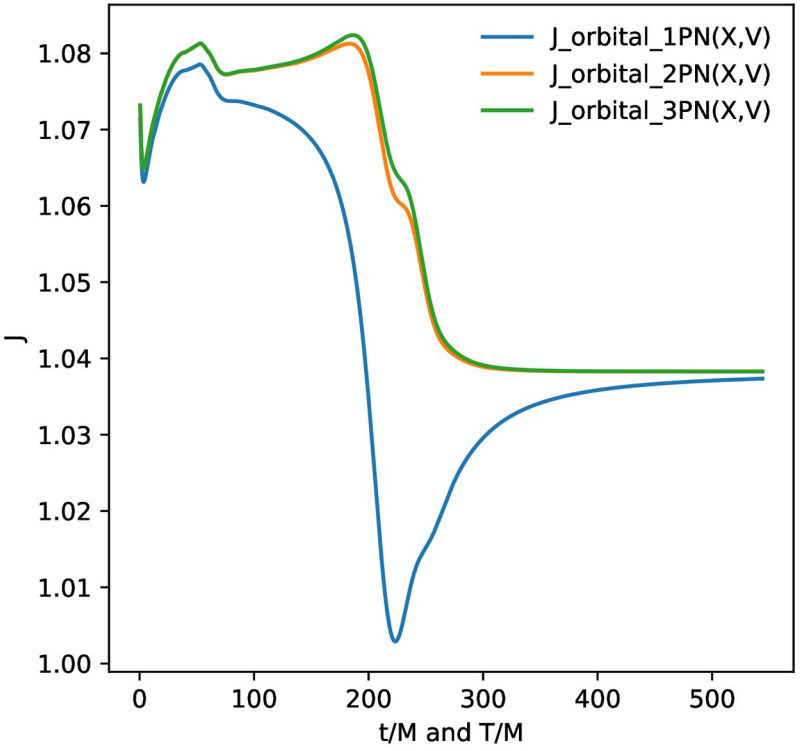
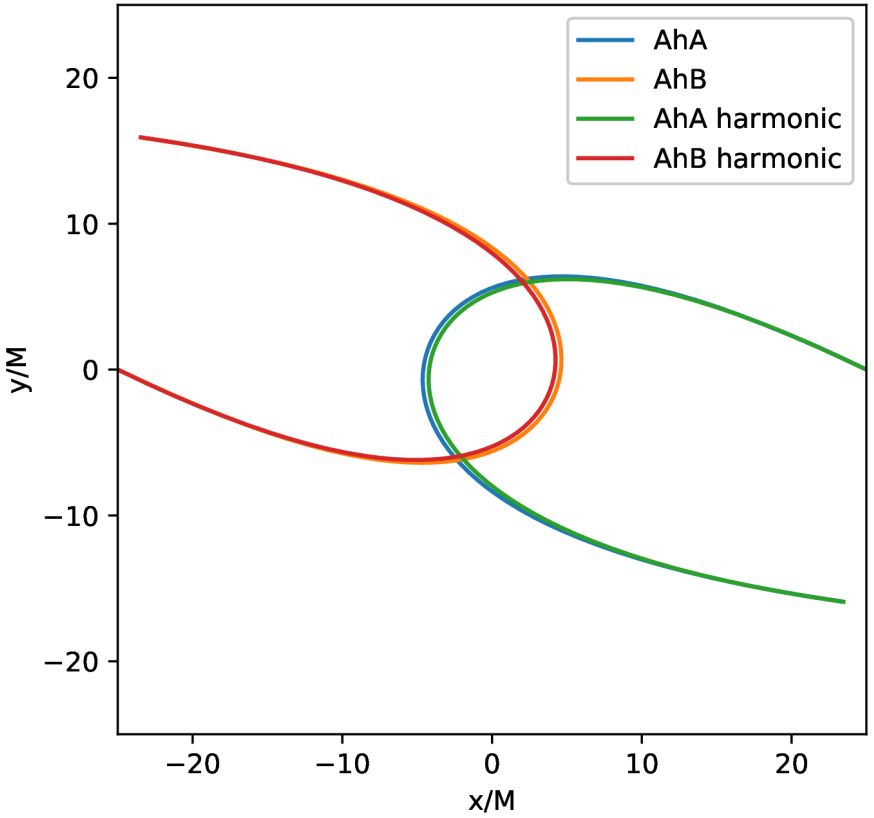
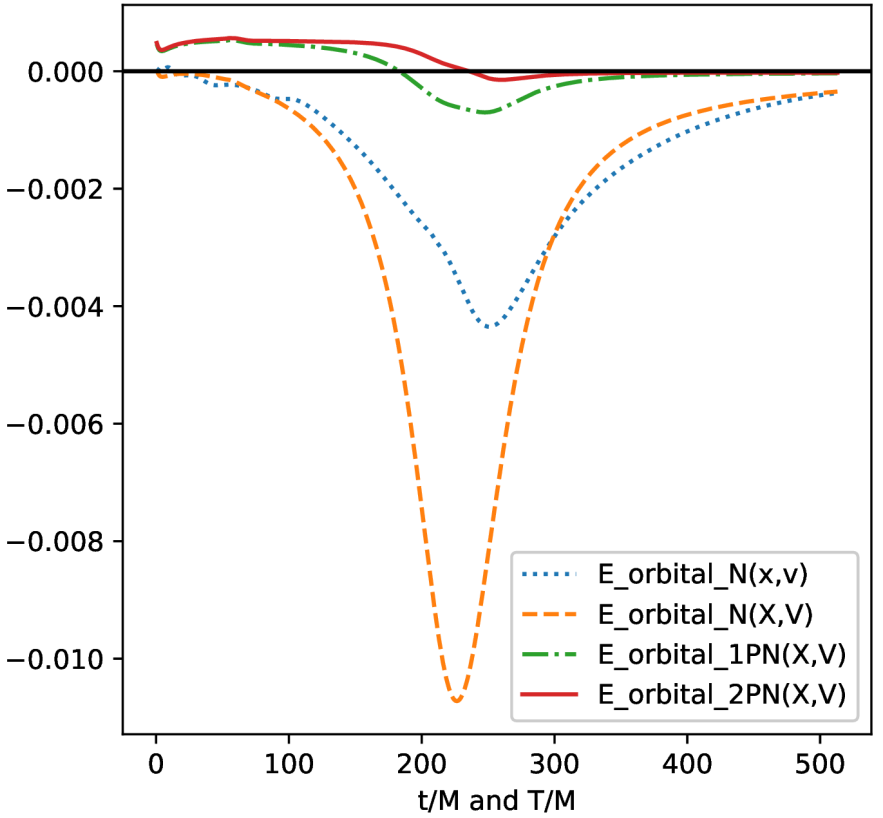


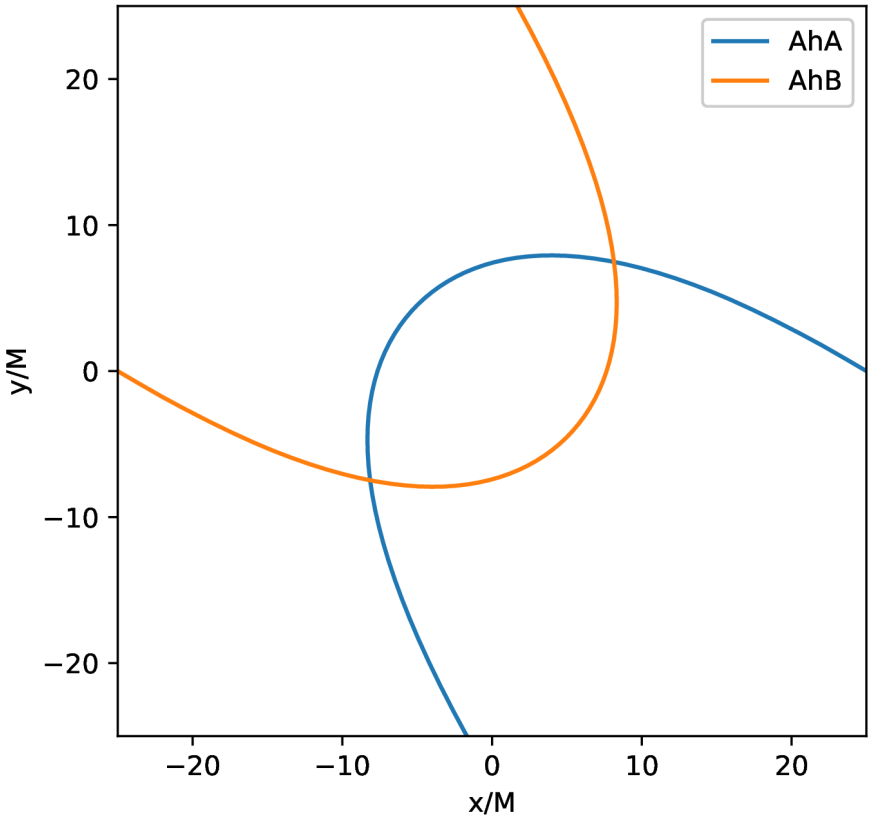



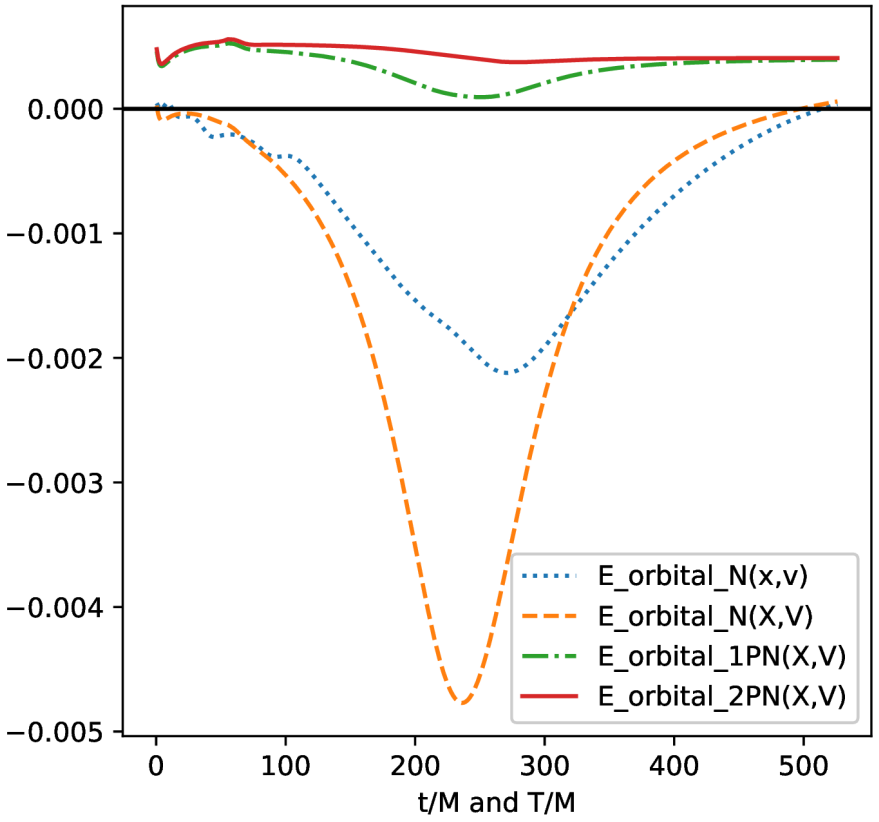
$E_{orb} = 0.00052\ M$ $J_{orb} = 1.204\ M^2$



$E_{orb} = 0.00052\ M \qquad J_{orb} = 1.425\ M^2$



# Scattering Angle: $E_{orb}$ = 0.000157 M

Extrapolate orbit to t=±
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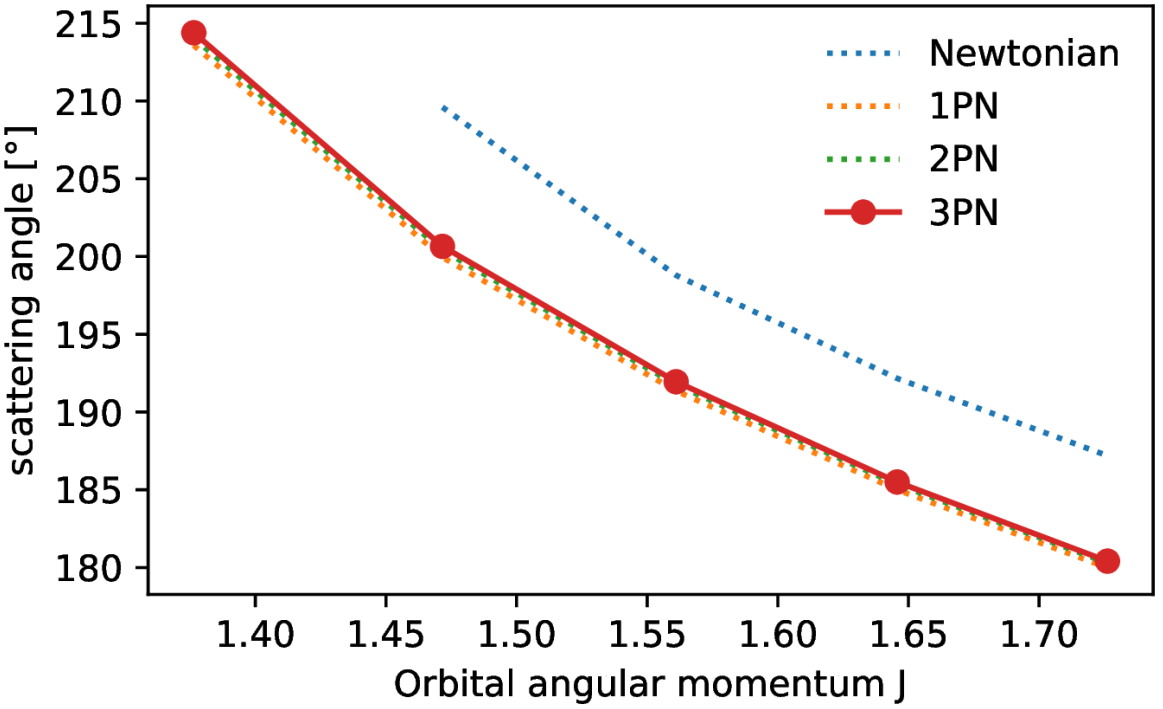
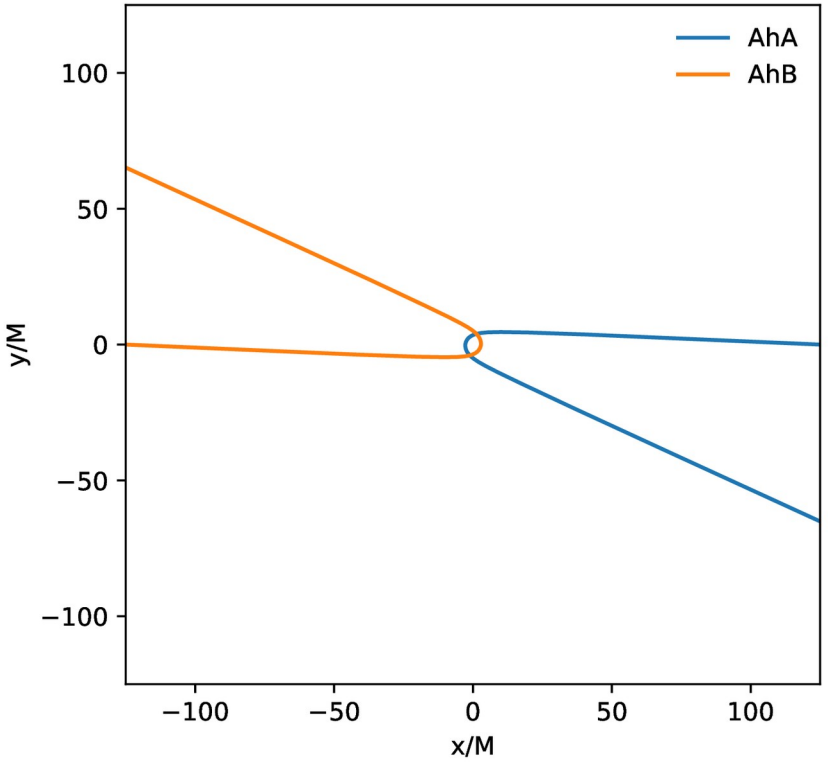
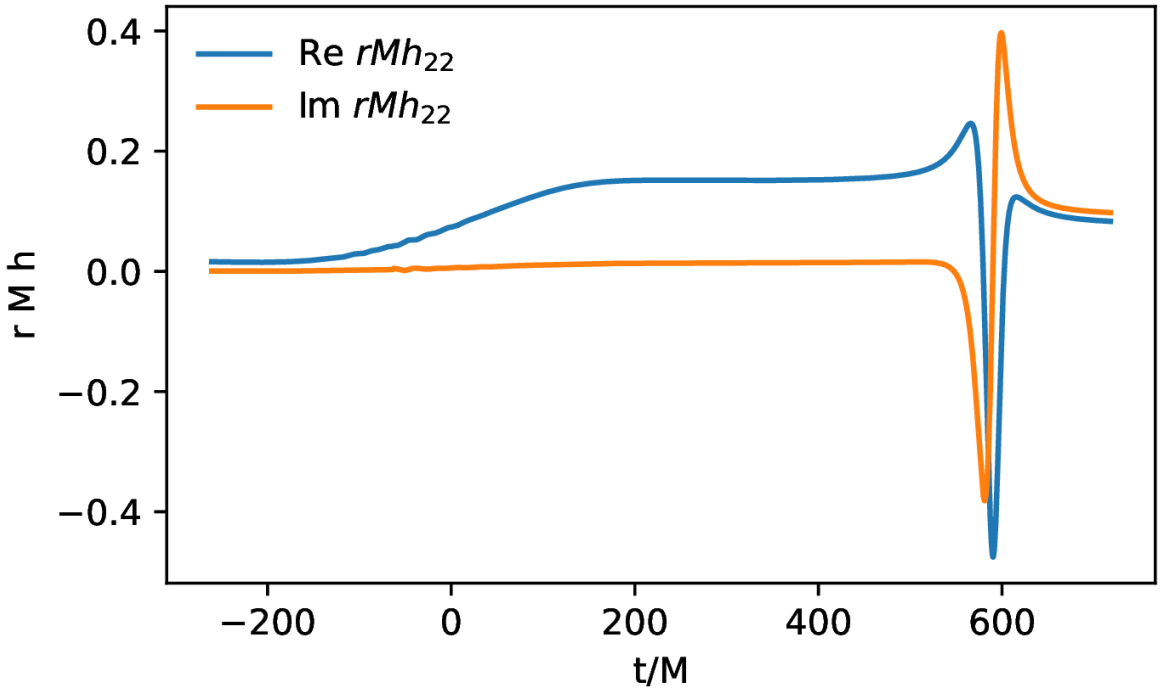


# Towards Higher Energies

$E_{orb} = 0.0226\ M \quad J_{orb} = 1.145\ M^2$



# Scattering Angle: $E_{orb}$ = 0.0226 M

Damour NR
Damour - PRD 89, 081503 (2014)

Damour EOB tuned
Nagar - PRD 103, 064013 (2021)

PN
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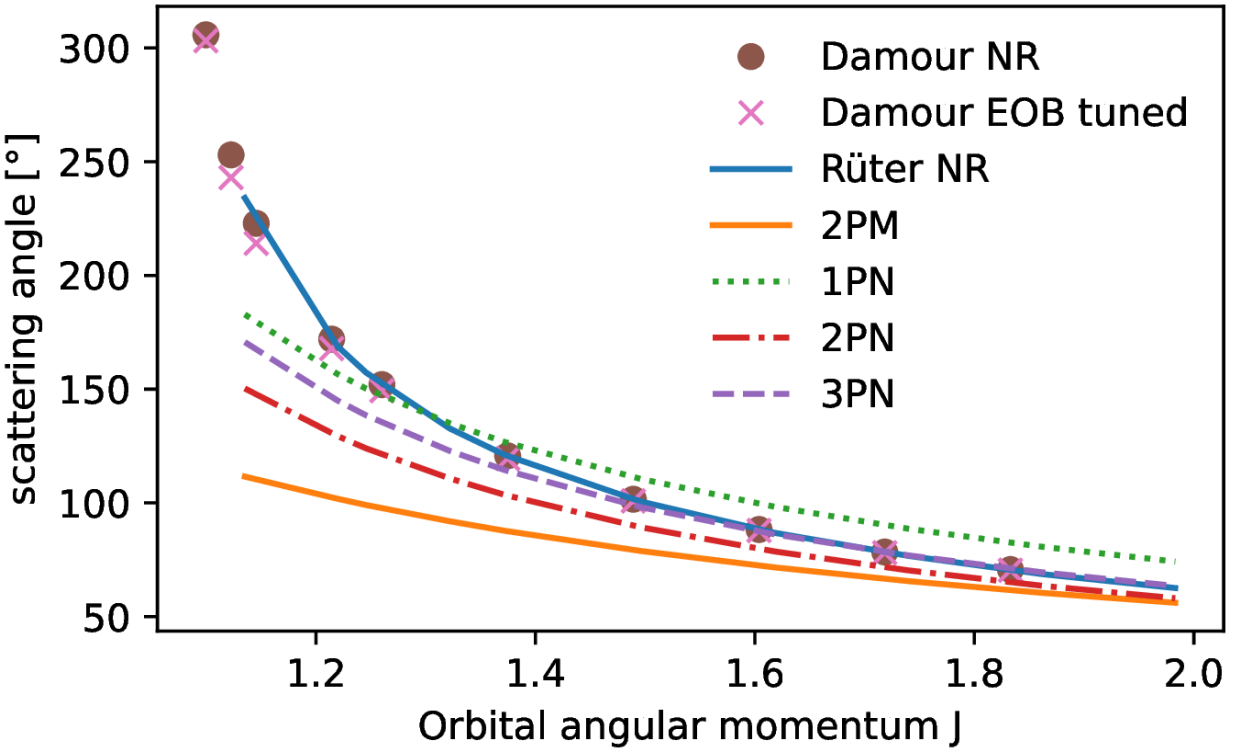


# Challenges when simulating hyperbolic-like encounters

# Challenges

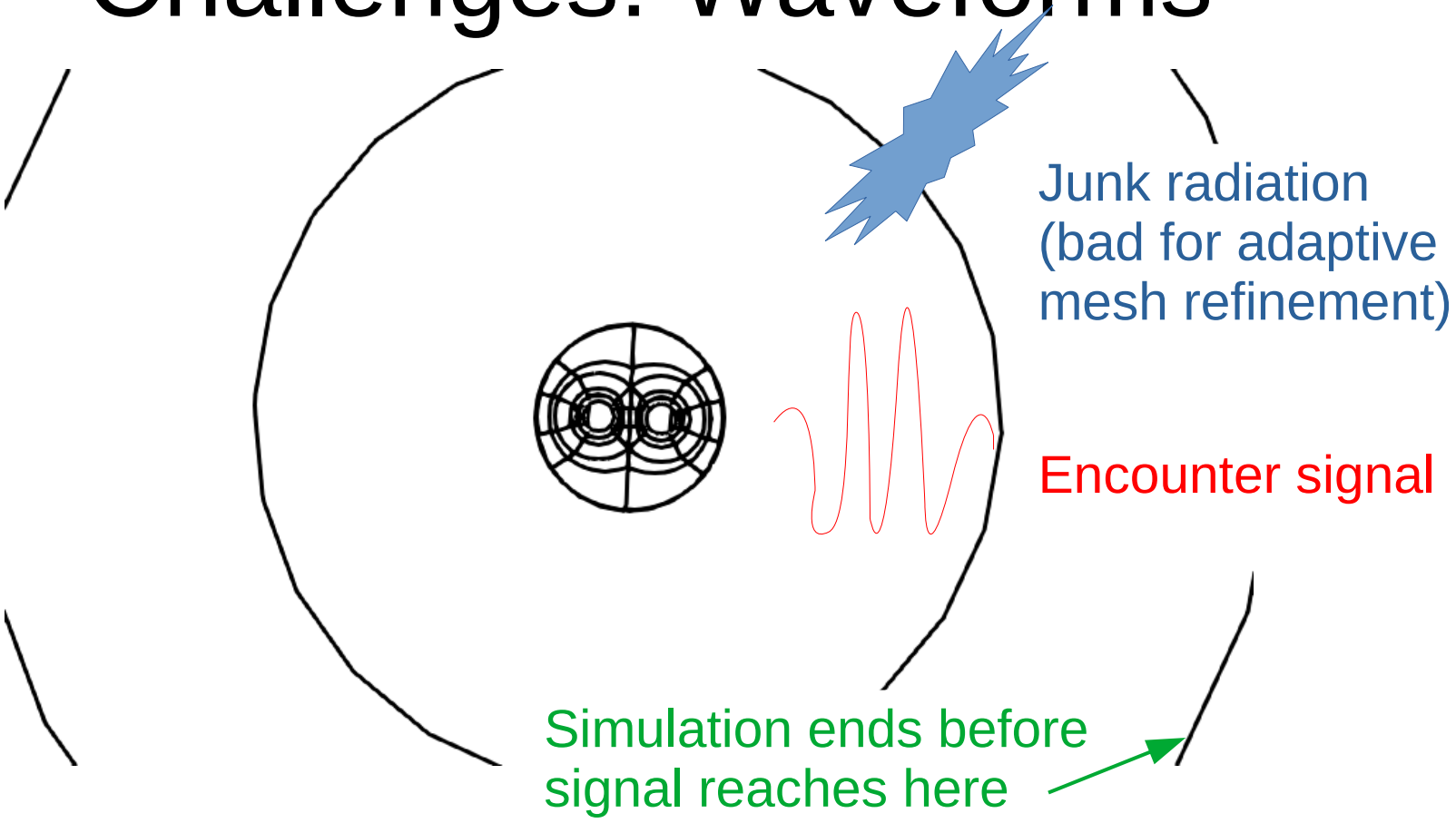
## Coordinates

Use defined coordinates
→ coevolve harmonic coordinats

Choose suitable gauge

Keep the coordinate maps well-defined
→ control system must react very fast

# Challenges: Waveforms



# Challenges: initial data

Junk radiation
→ superposed harmonic Kerr initial data

High velocities
→ initial data problem becomes harder

# Conclusion

Accurate waveforms for hyperbolic encounters and captures

Use coevolved harmonic coordinates to analyze orbital parameters E, J, $\chi$

Future: configurations with spin