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

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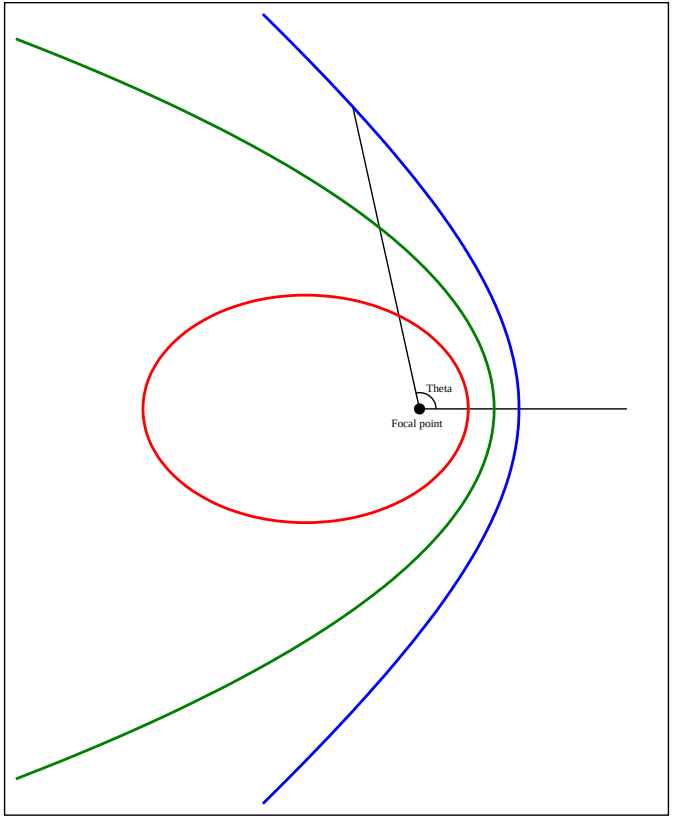
Simulating eXtreme Spacetimes
www.black-holes.org

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

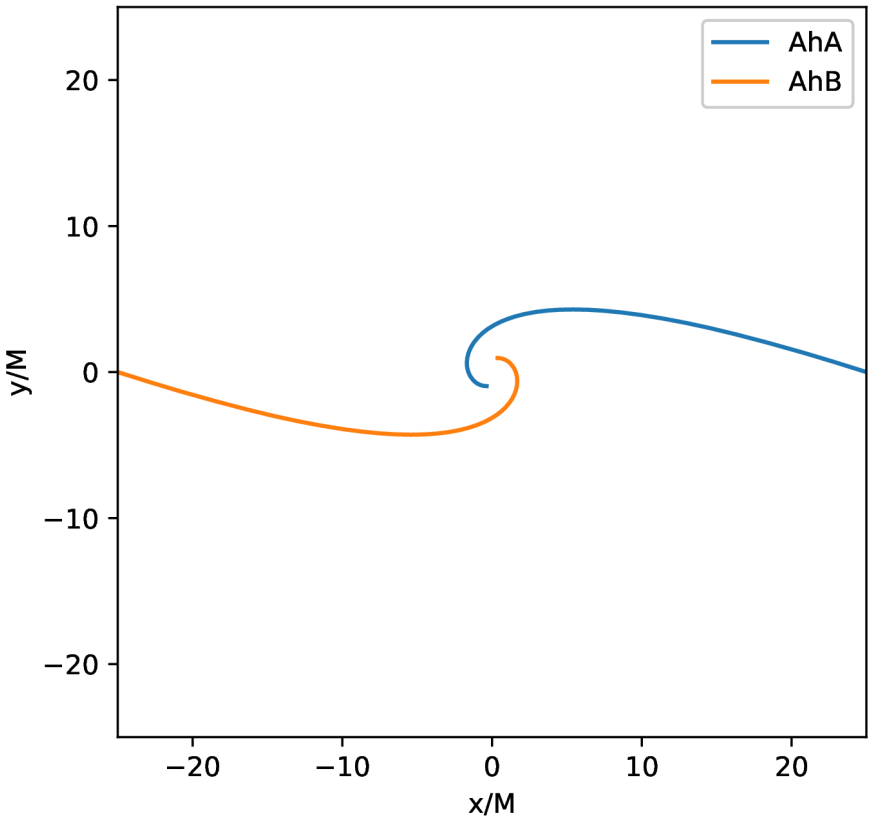
Motivation

- Hyperbolic-like encounters are astrophysically rare events
- Mostly expected near the centre of galaxies
- Validation/Calibration of post-Newtonian and effective-one-body predictions [Damour *et al.* - PRD **89** 081503 (2014), Nagar *et al.* - PRD **103** 064013 (2021)]

Setup

- Spectral Einstein Code (SpEC)
  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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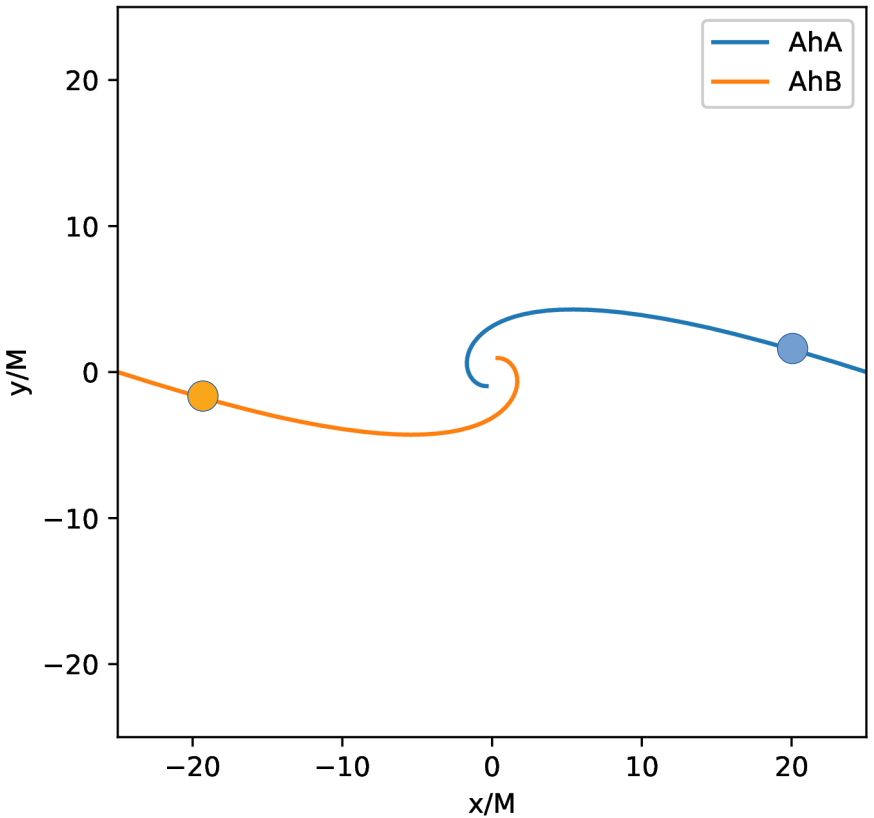

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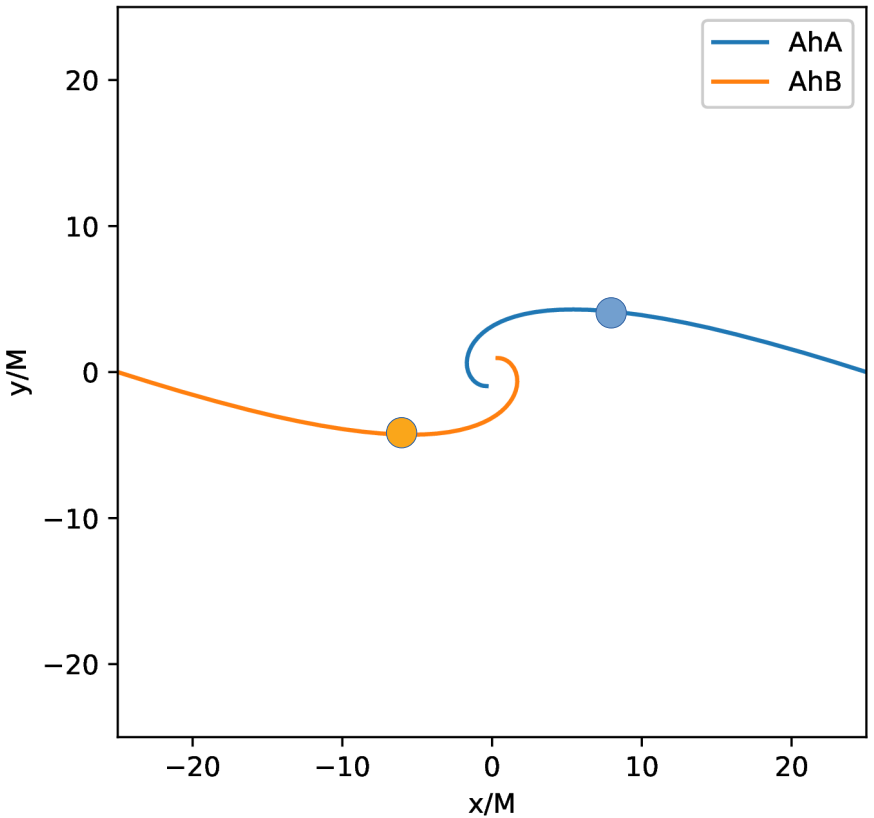

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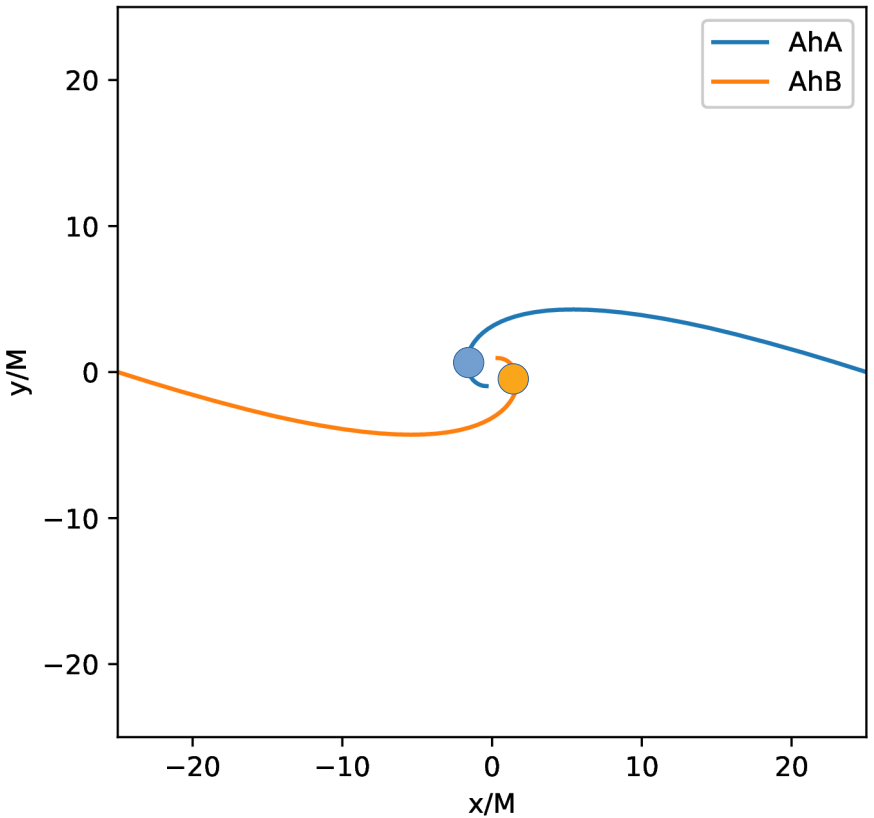

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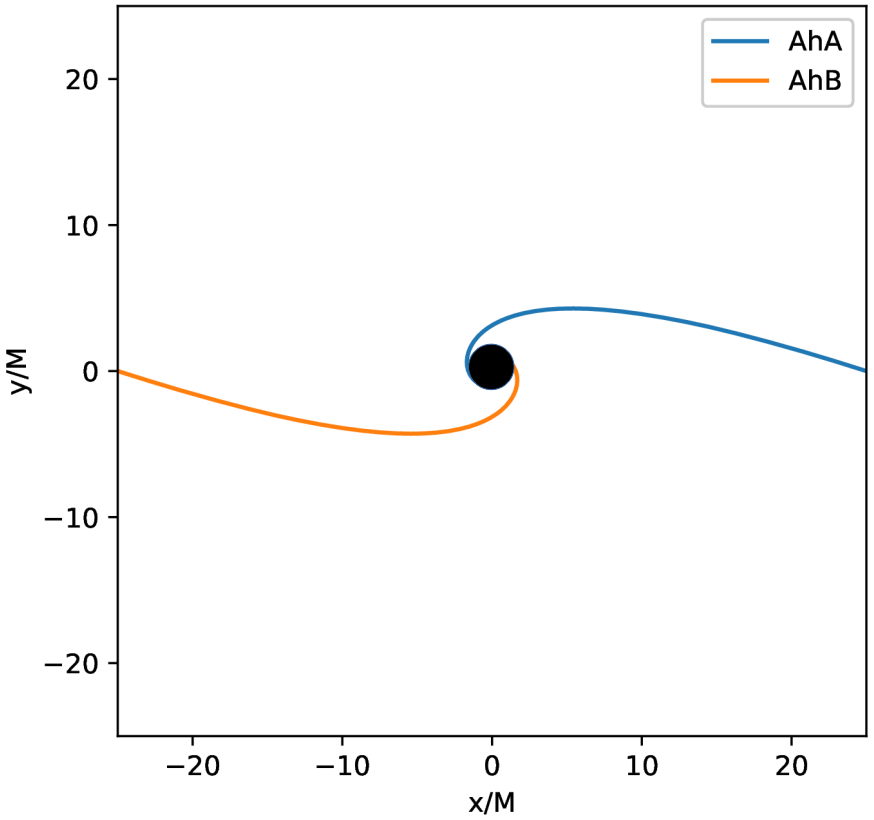
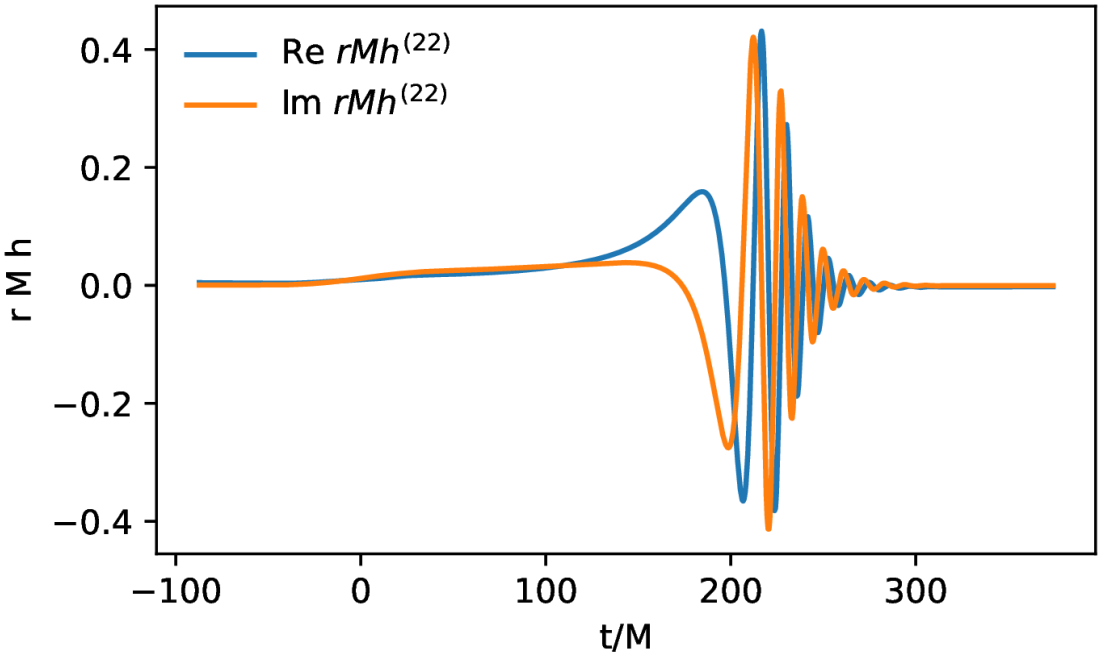
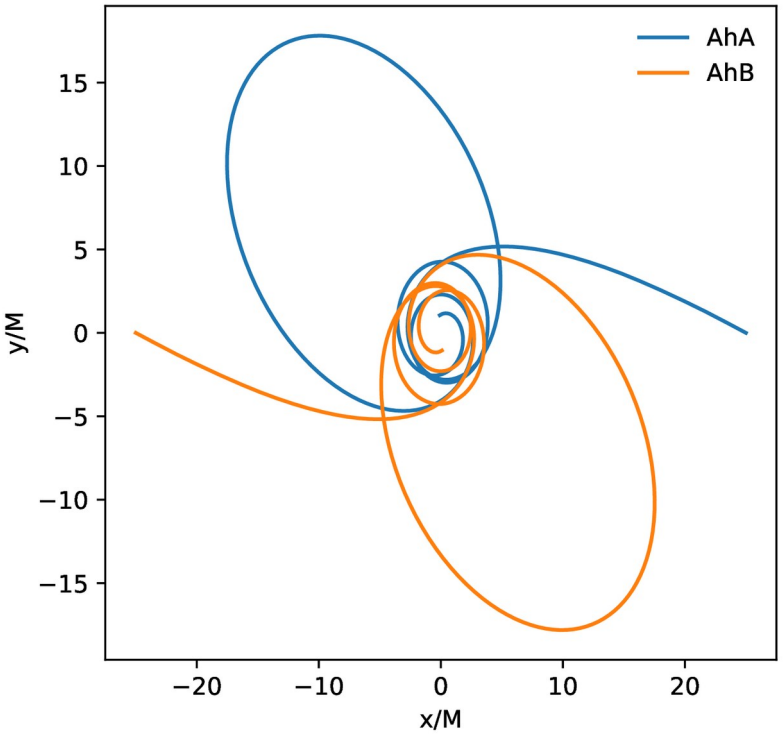
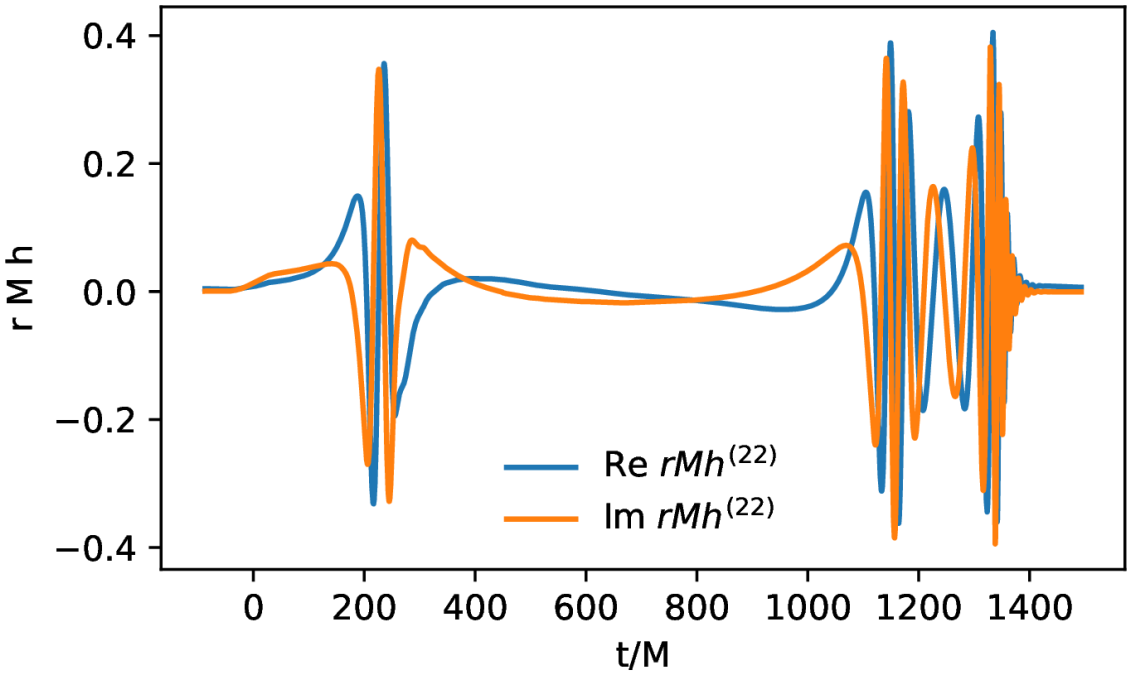


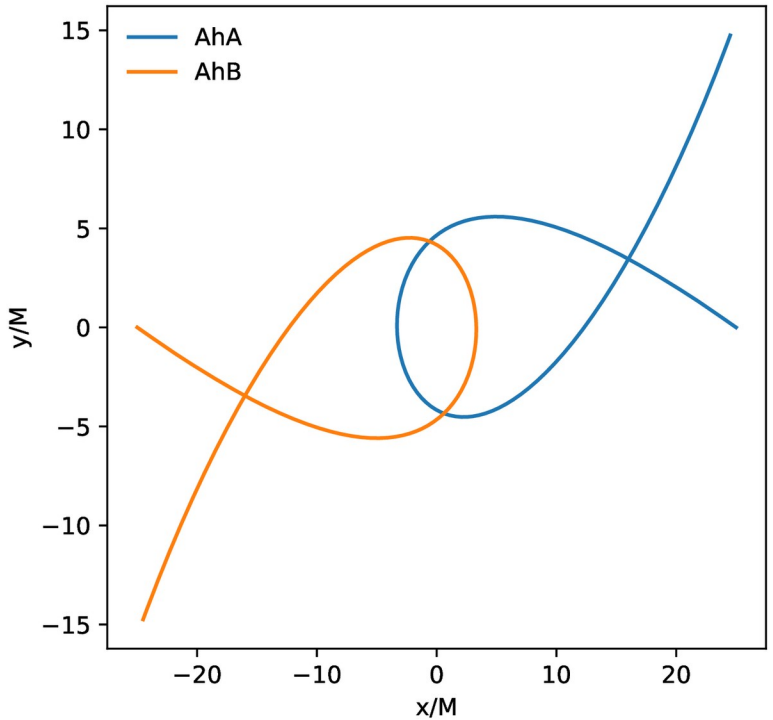


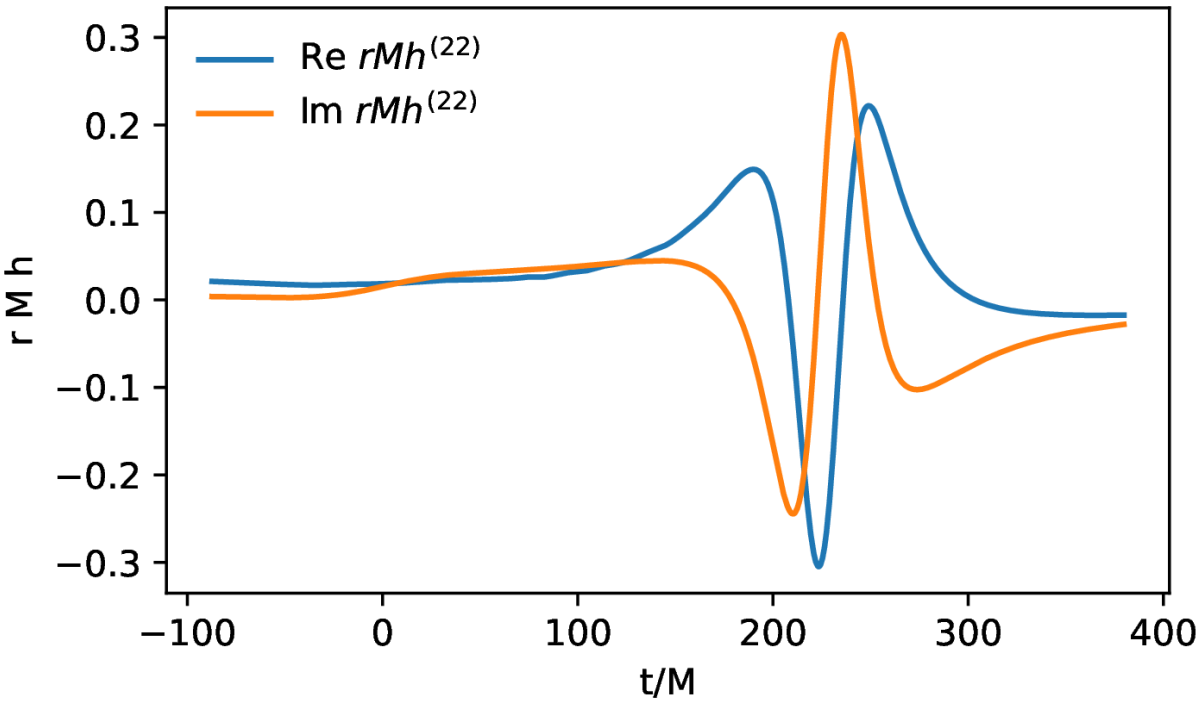
$E_{orb} = 0.00052\ M$ $J_{orb} = 1.007\ M^2$





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





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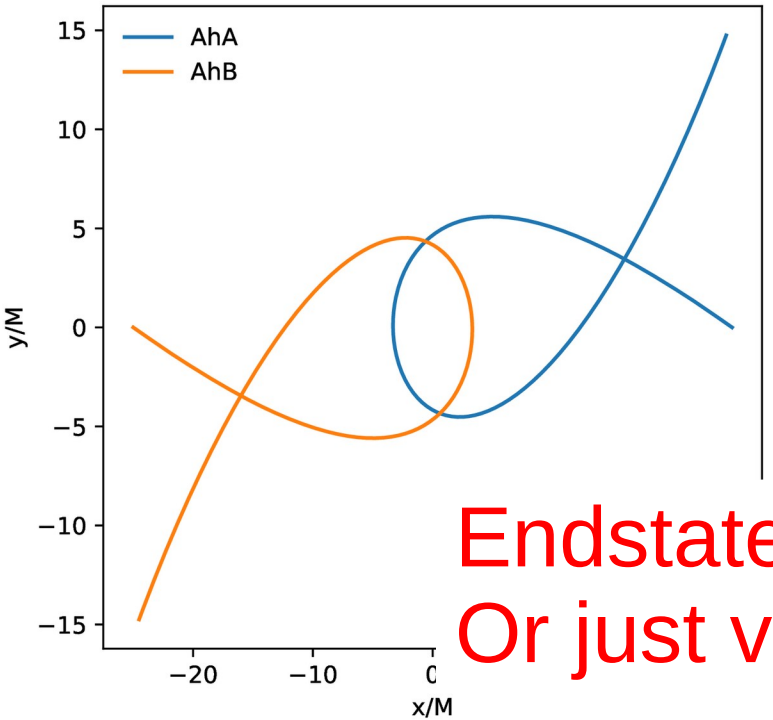
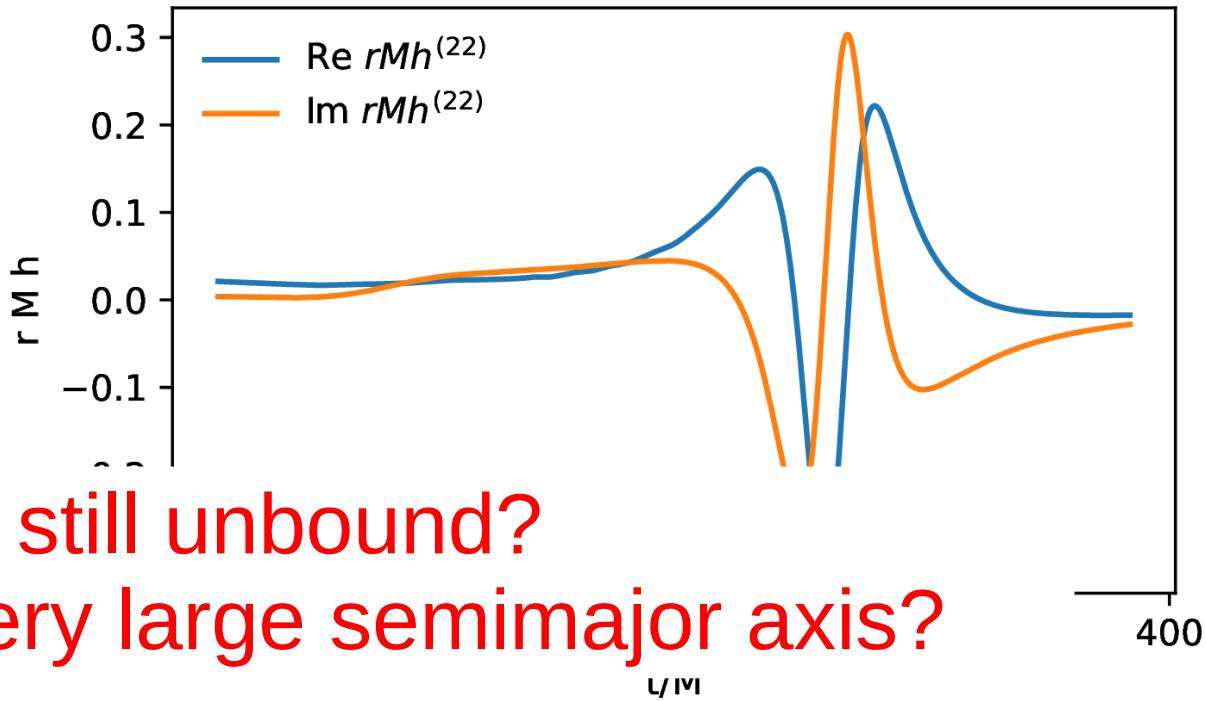




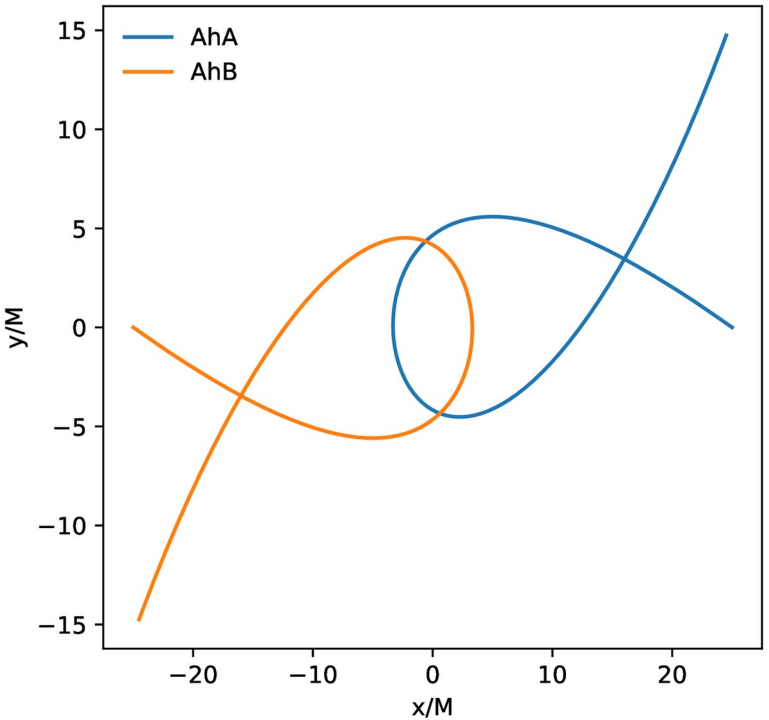
Endstate still unbound?
Or just very large semimajor axis?

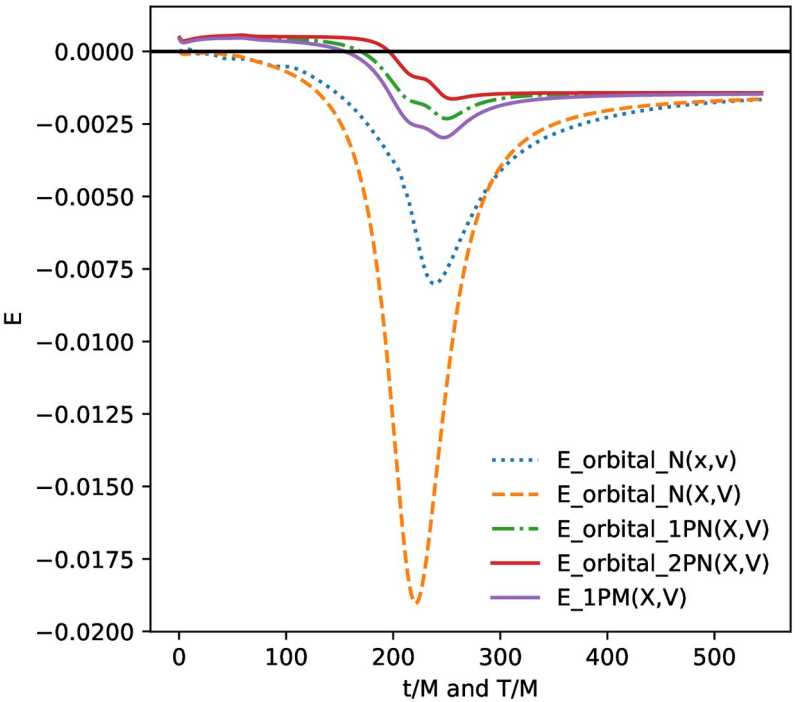
Computation of Orbital Energy

- Co-evolve harmonic coordinates X^μ
  [Prayush Kumar]
- Use PN expressions for orbits in harmonic coordinates [Memmesheimer *et al.* - PRD **70** 104011 (2004)]

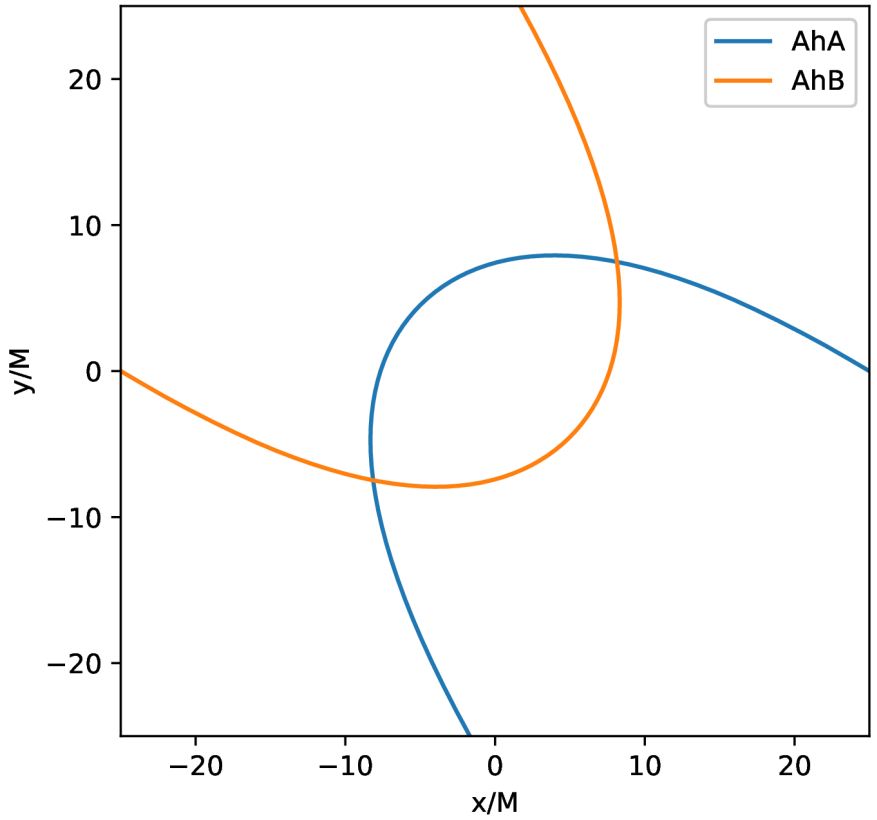
$\rightarrow \quad E_{\rm orb}(X^\mu, V^\mu) \qquad J_{\rm orb}(X^\mu, V^\mu)$

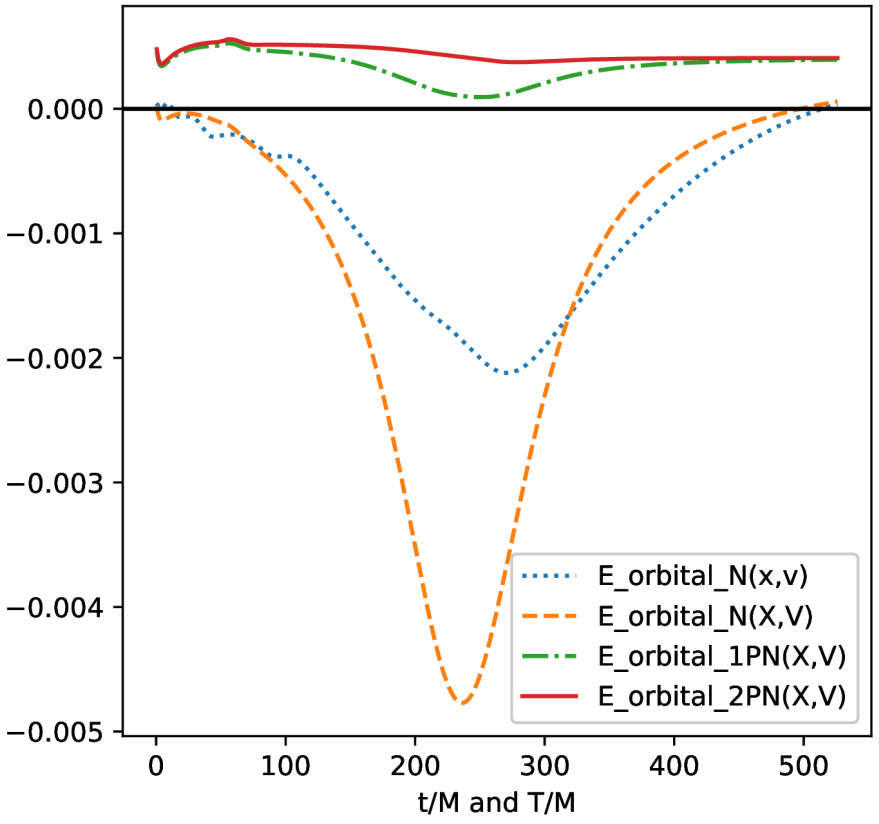
$E_{orb} = 0.00052\ M \qquad J_{orb} = 1.076\ M^2$





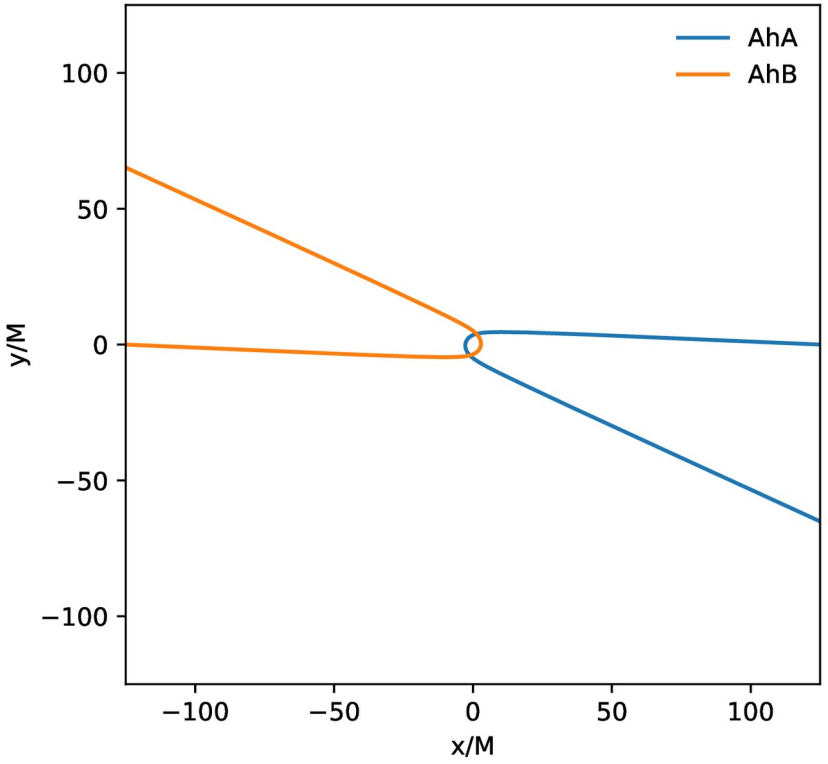
E_{orb} = 0.00052 M J_{orb} = 1.425 M^2

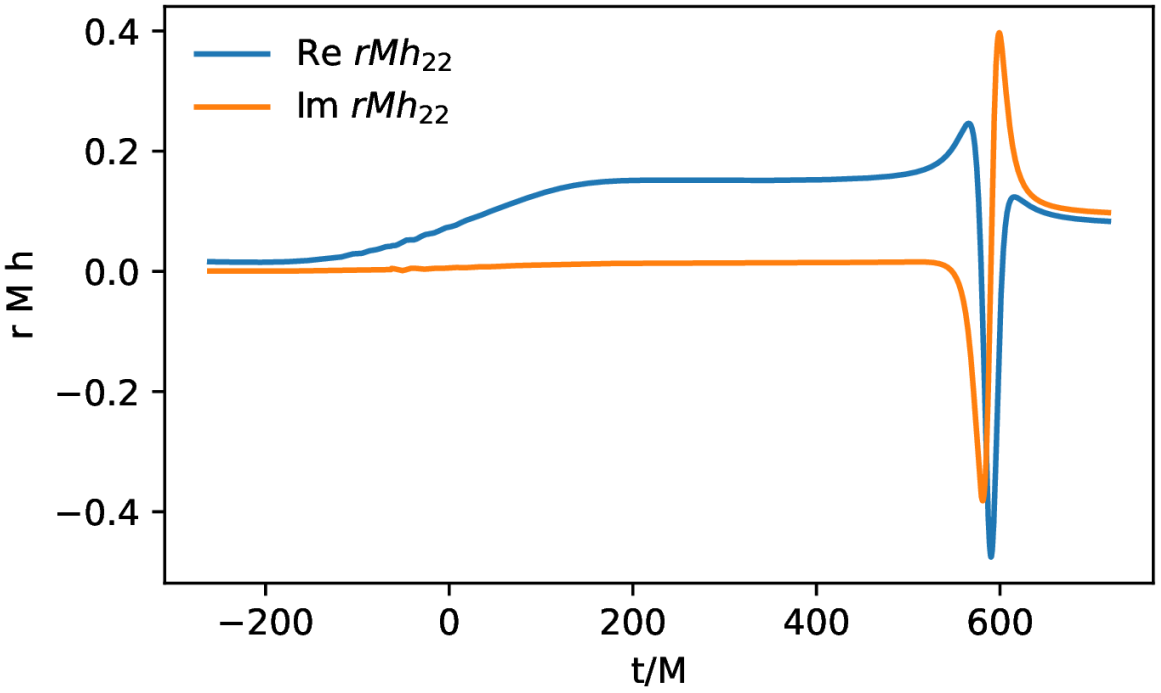




Towards Higher Energies

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



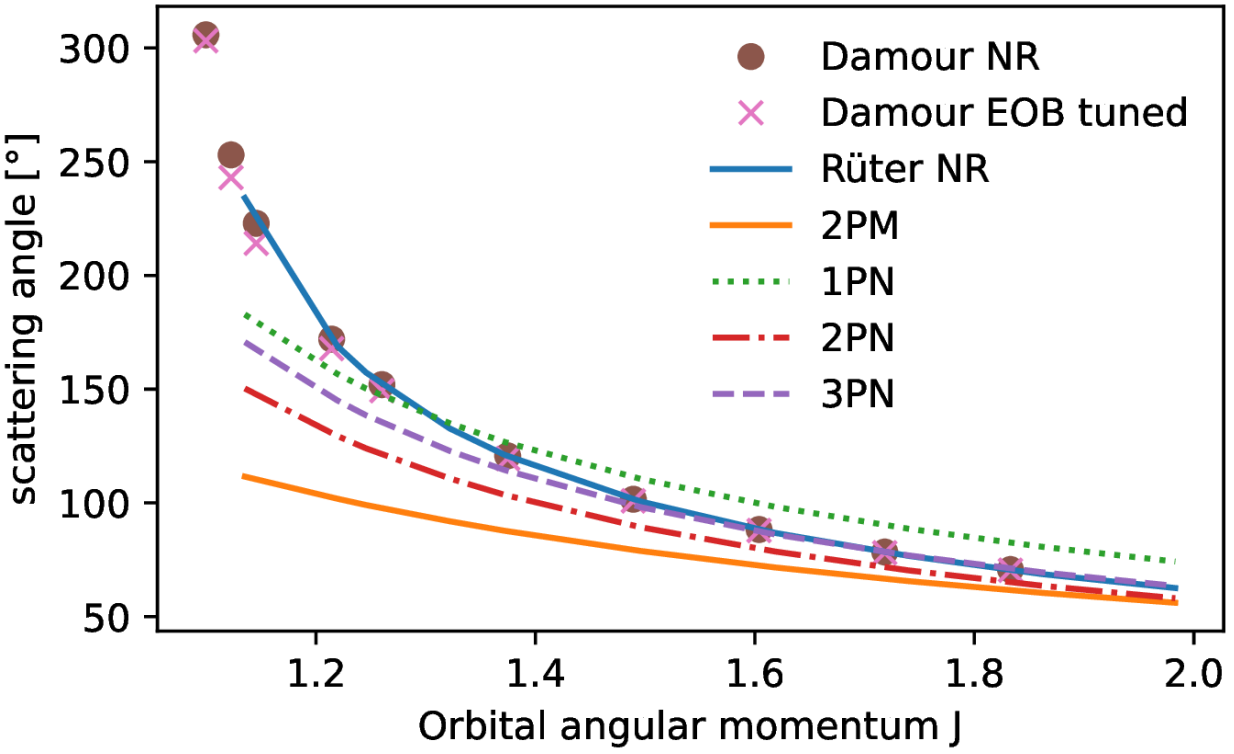


Scattering Angle: E_{orb} = 0.0226 M

Damour NR
Damour *et al.* - PRD 89, 081503 (2014)

Damour EOB tuned
Nagar *et al.* - PRD 103, 064013 (2021)

PN
Memmesheimer et al. PRD 70, 104011 (2004)

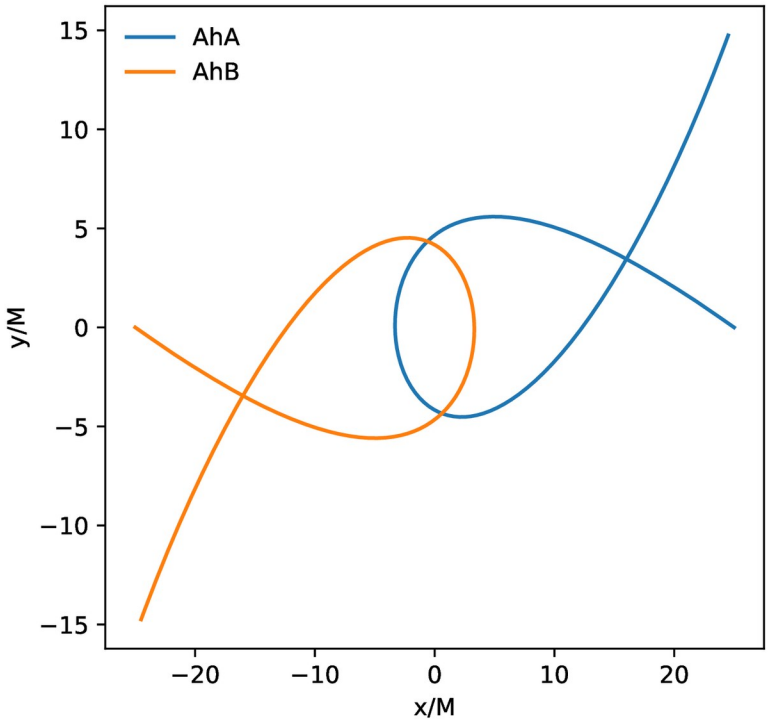


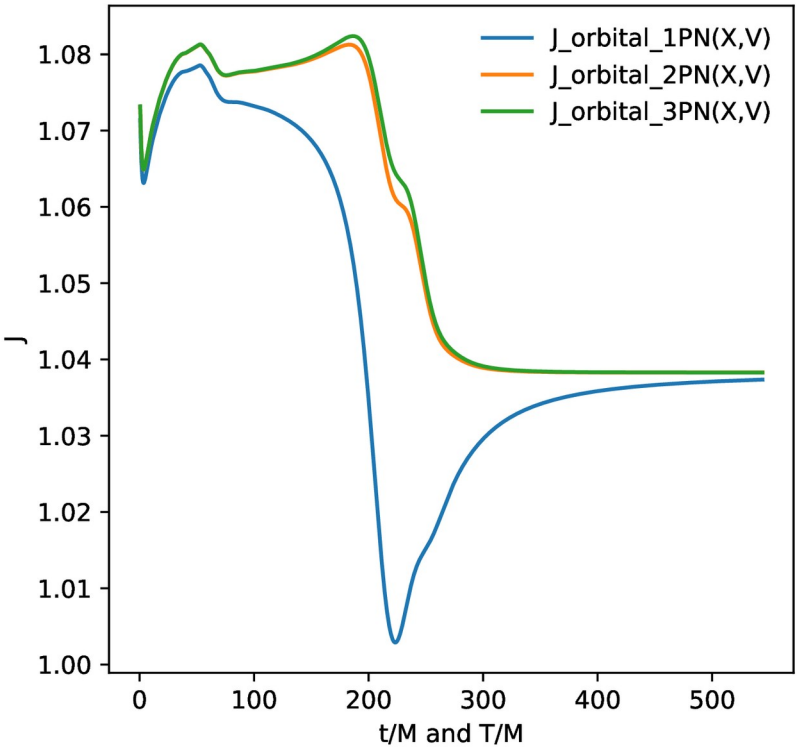
Conclusion

- Accurate waveforms for hyperbolic encounters and captures
- Use co-evolved harmonic coordinates to analyse orbital parameters E, J, χ
- Future: configurations with spin

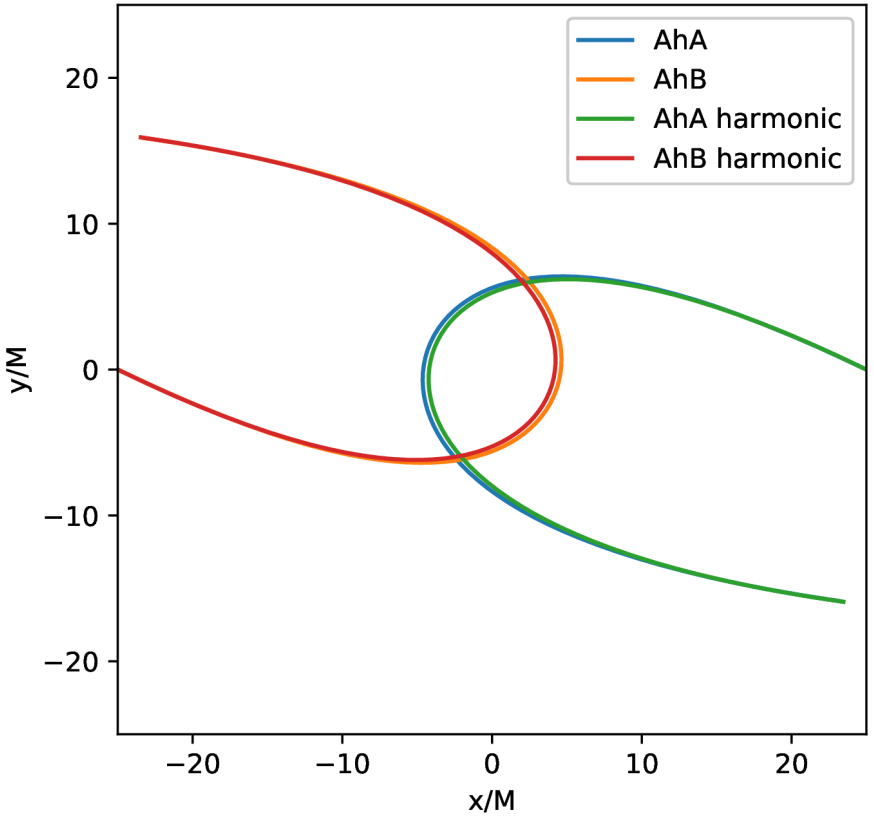
Bonus Slides

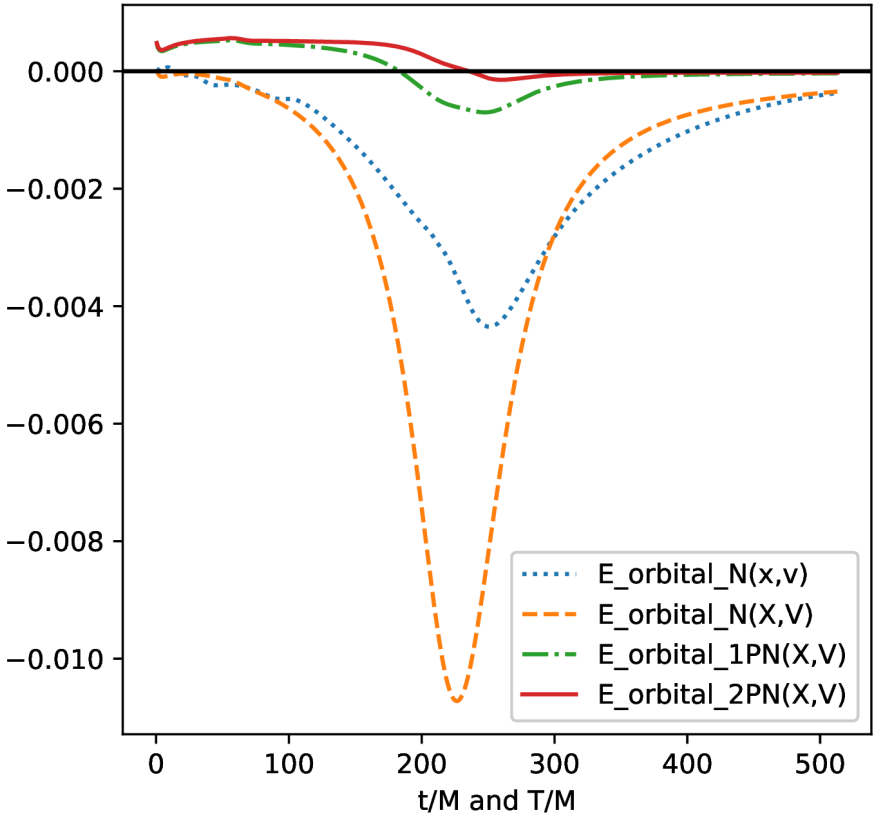
$E_{orb} = 0.00052\ M$ $J_{orb} = 1.076\ M^2$





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



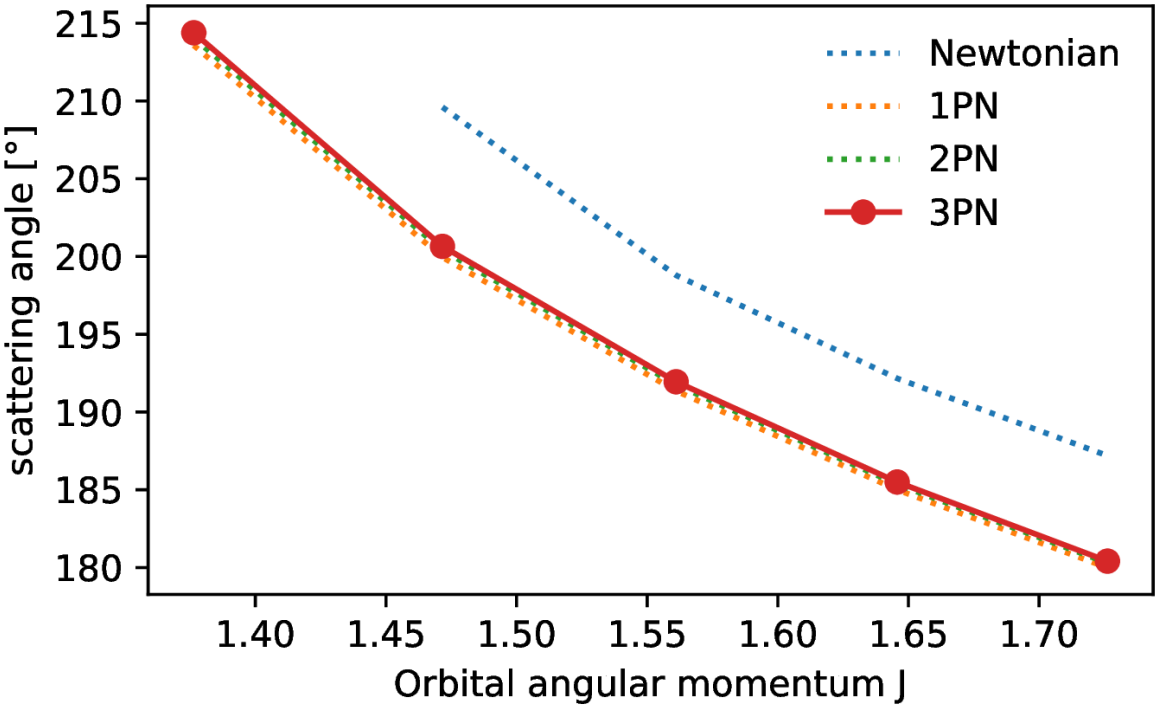


Scattering Angle: E_{orb} = 0.000157 M

Extrapolate orbit to t=±∞ at different PN orders

Use harmonic coordinate quasi-Keplerian orbits [Memmesheimer PRD 70 104011]

→ scattering angle

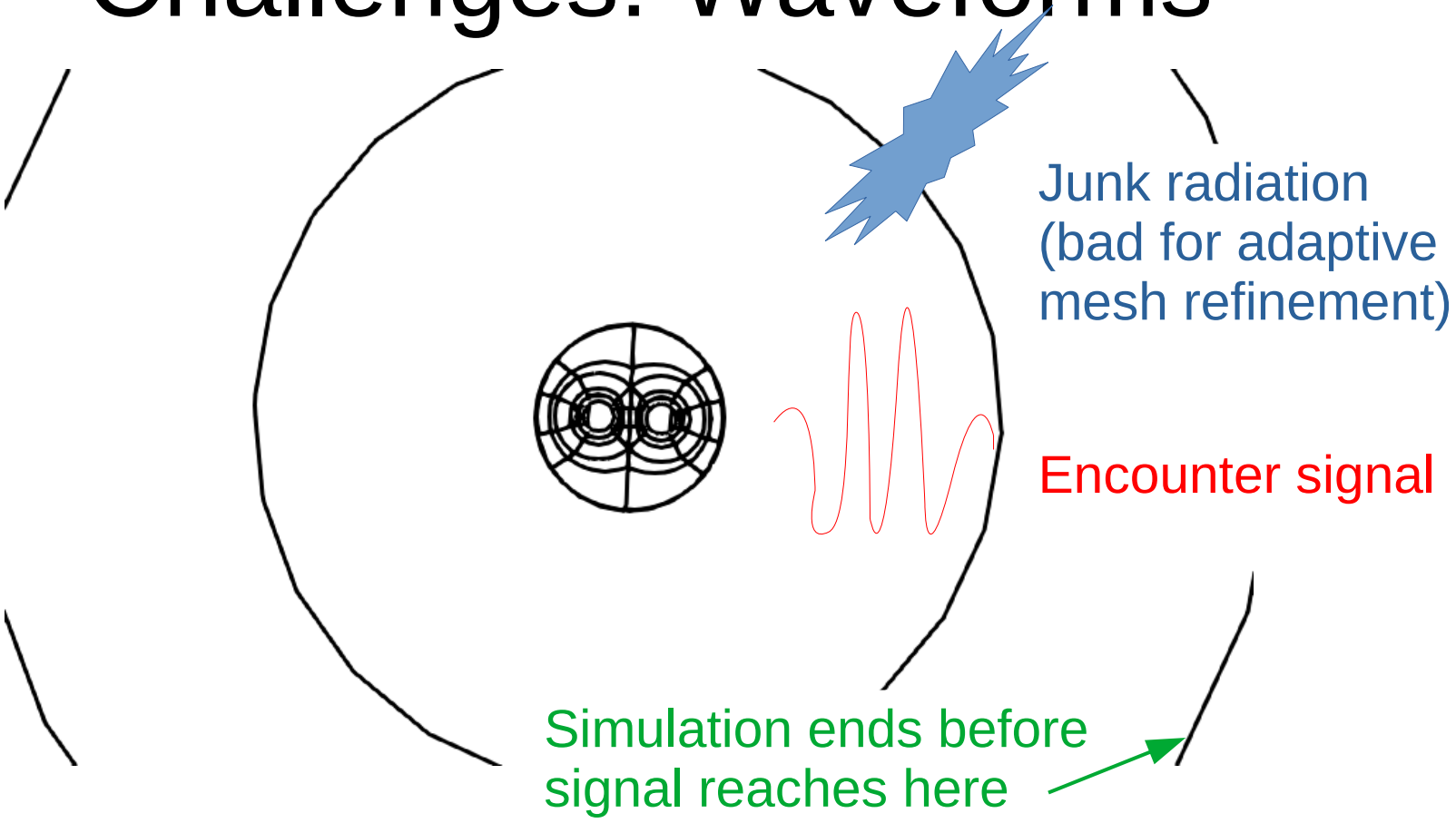


Challenges when simulating hyperbolic-like encounters

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