Highly accurate simulations of asymmetric black-hole scattering and cross validation of effective-one-body models

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EOB@Work25

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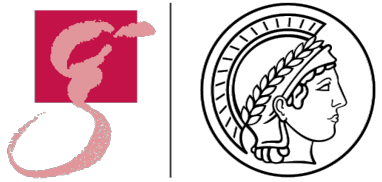
SIMULATING EXTREME SPACETIMES

Black holes, neutron stars, and beyond...



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BBH scattering motivation

Clean binary systems with well-defined asymptotic ‘in’ and ‘out’ states:

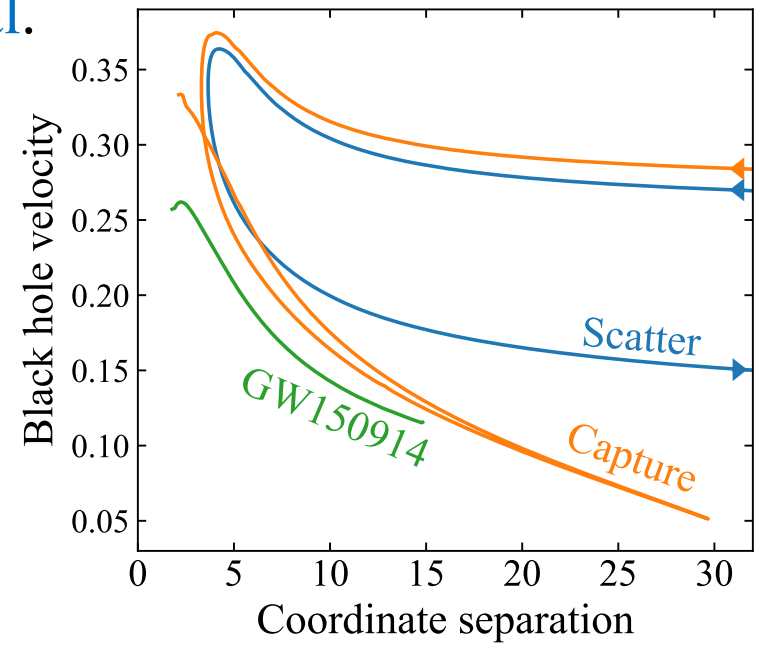
- Can parameterise systems in terms of asymptotic quantities e.g. energy & ang. mom.
- Can define asymptotic observables e.g. scattering angle.
- Straightforward comparisons with other methods (e.g. EOB).

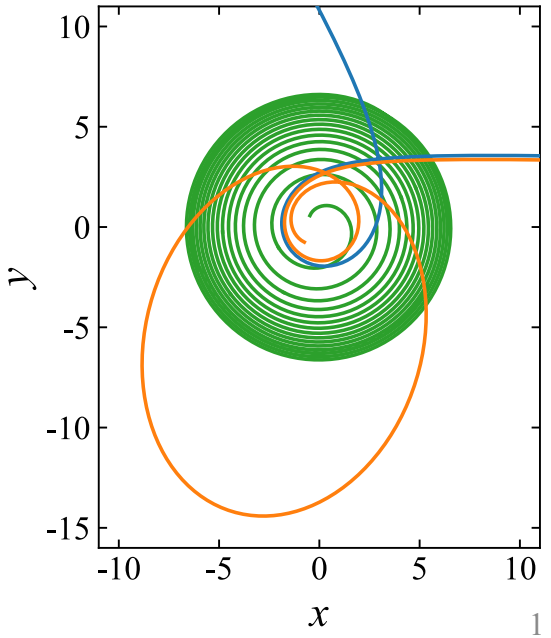
Higher energy region of binary parameter space:

- Probe the strong gravitational potential.
- c.f. high-energy particle scattering is used to probe nuclear interaction.

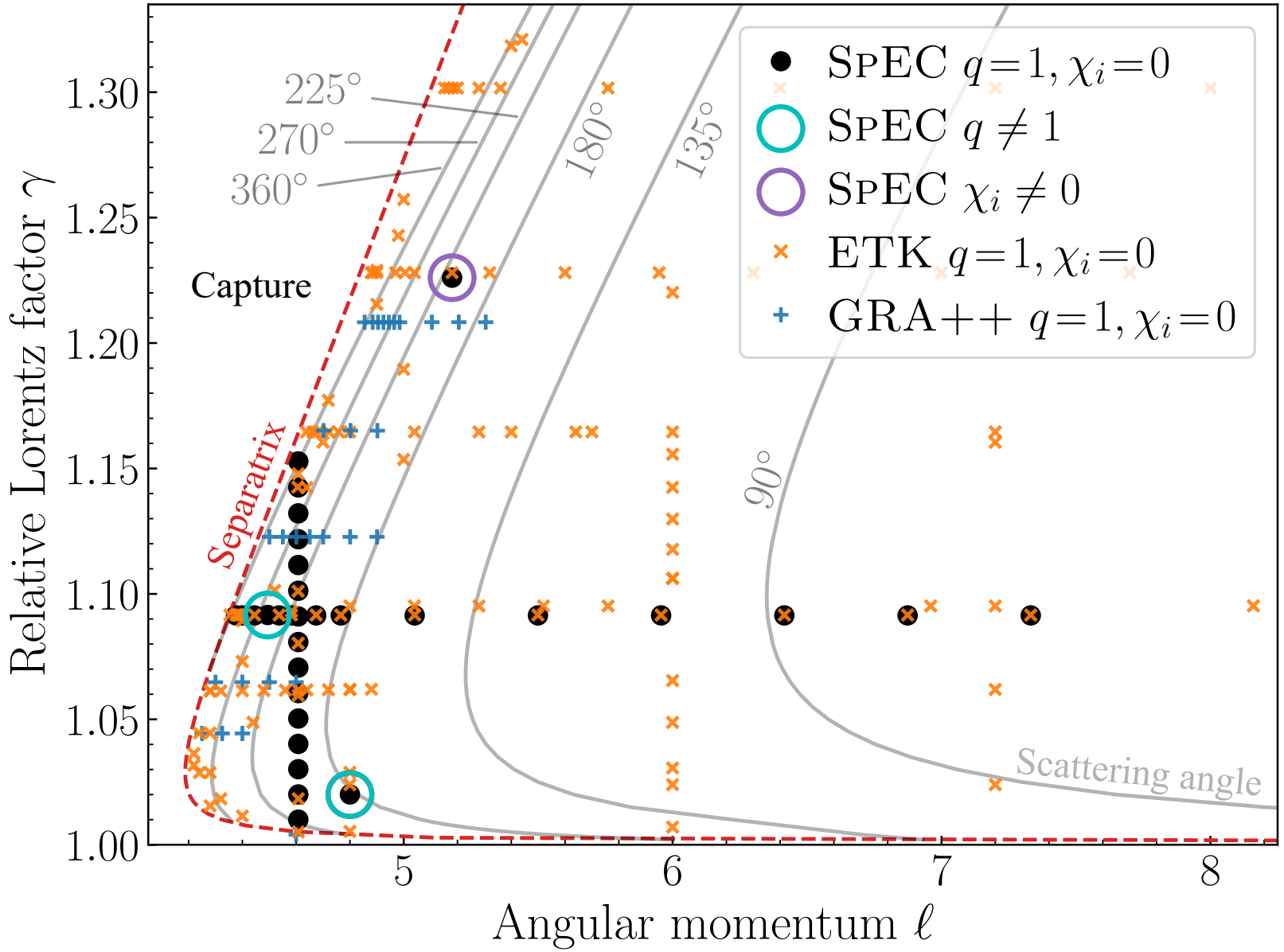
Compare with BH scattering calculations from particle physics:

- QFT/Amplitudes methods.





NR BBH scattering parameter space coverage



Spectral Einstein Code (SpEC):

[**OL**+ 25]

Einstein Toolkit (ETK):

[Damour+ 14, Jaraba+ 21, Hopper+ 22, Rettegno+ 22, Yeong-Bok+ 23, Kankani+ 24, Swain+ 24, …]

GR-Athena++ (GRA++):

[Albanesi+ 24]

Separatrix fit from [Kankani+ 24]

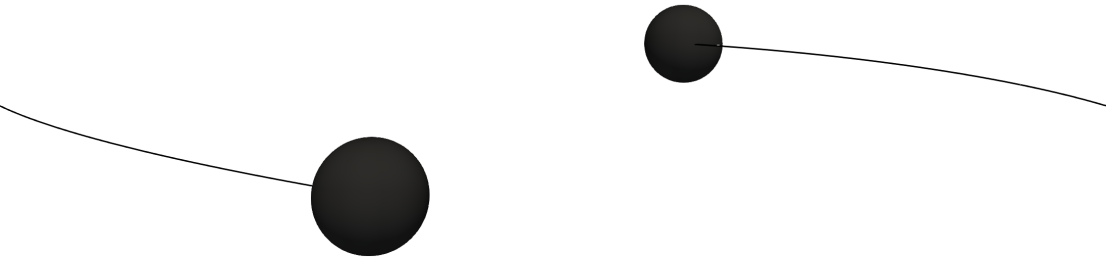
Code comparison: SpEC and ETK

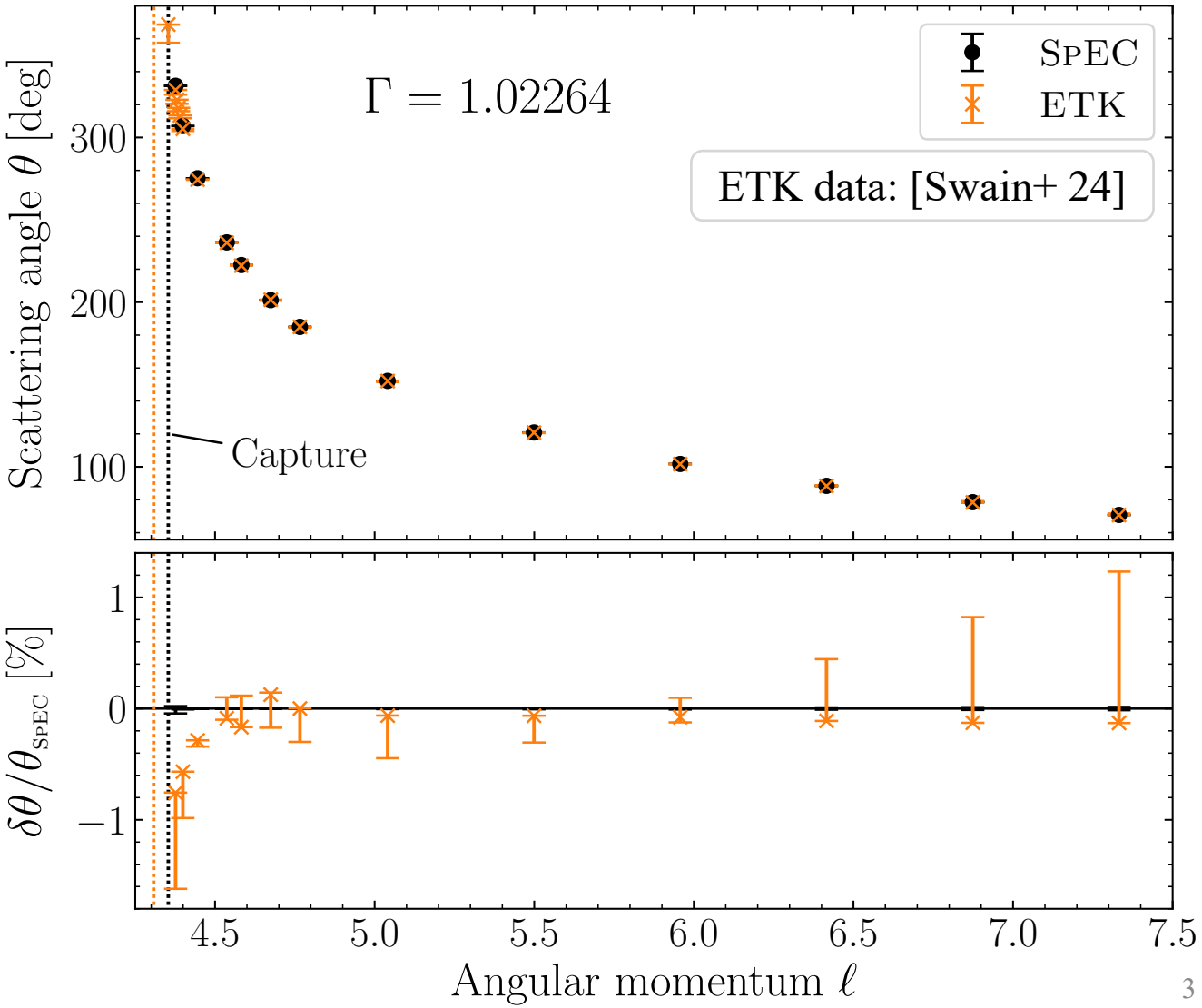
Initial conditions:

- Fixed energy.
- Equal mass.
- Non-spinning.

Good agreement between codes ($\lesssim 1\%$).

Smaller errors in SpEC due to larger initial separation.





Evolved effective one body models

Effective one body (EOB) relies on an expanded Schwarzschild (or Kerr) Hamiltonian:

$$H = \sqrt{p_{r_*}^2 + A(r)\left[\frac{p_\varphi^2}{r^2} + \left(\frac{m_1 m_2}{m_1 + m_2}\right)^2 + Q(r)\right]}$$

A and Q potentials usually expanded via post-Newtonian and calibrated to NR.

System solved numerically using Hamilton's equations with radiation reaction forces:

Dissipative terms

$$\dot{r} = \frac{\partial H_{\rm EOB}}{\partial p_r} \qquad \dot{\varphi} = \frac{\partial H_{\rm EOB}}{\partial p_\varphi} \qquad \dot{p}_r = -\frac{\partial H_{\rm EOB}}{\partial r} + \mathcal{F}_r \qquad \dot{p}_\varphi = \frac{\partial H_{\rm EOB}}{\partial \varphi} + \mathcal{F}_\varphi$$

Two evolved EOB models for scattering: `SEOBNRv5` and `TEOBResumS-Dalí` (`v1.1.0`).

Quasicircular fluxes

Eccentric fluxes

Closed-form effective one body models

Alternatively can use expanded or resummed post-Minkowskian (PM) potential from mass-shell constraint:

$$p_r^2 = p_\infty^2(E) - \frac{J^2}{r^2} + w(E, J, r)$$

Angular momentum

Fix coefficients of PM expanded w by matching to PM expanded scattering angle:

$$\theta = -\pi - 2\int_{r_{\rm min}}^{\infty} dr \frac{\partial}{\partial J} p_r$$

The potential w contains both conservative and dissipative information from the scattering angle.

Two models:

$w_{\rm EOB}$

Uses PM-expanded w.

[Damour & Rettegno 23, Rettegno+ 24]

SEOB-PM

Uses PM-resummed w from SEOB-PM Hamiltonian, that reduces to the test-body limit.

[Buonanno, Jakobson & Mogull 24]

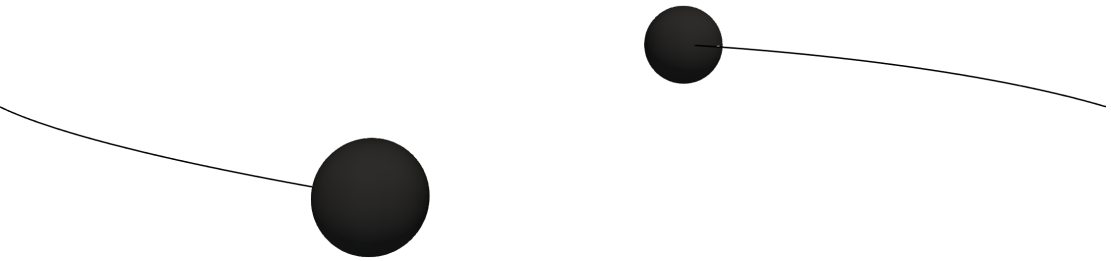
Comparison to EOB: Equal mass

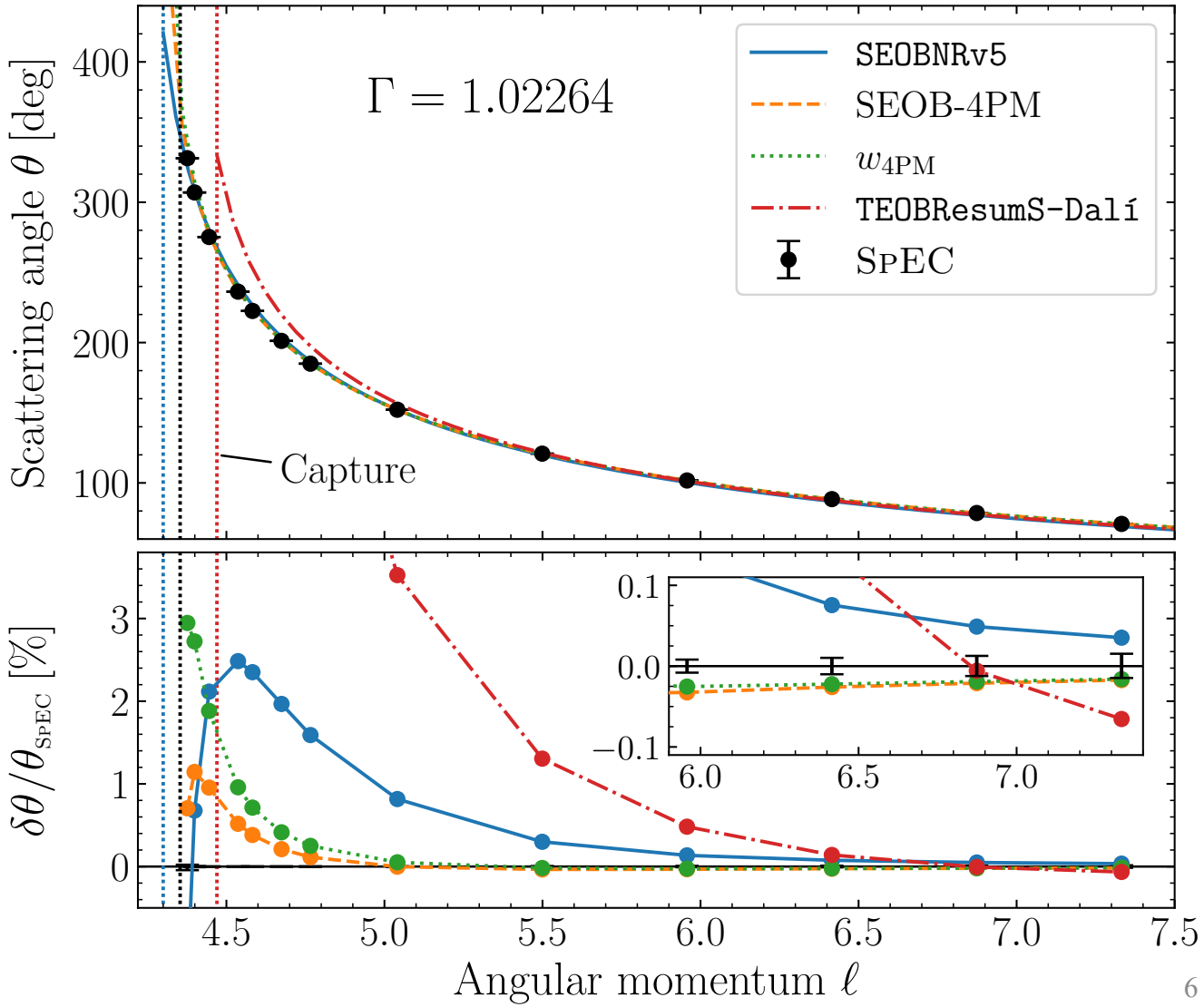
Initial conditions:

- Fixed energy.
- Equal mass.
- Non-spinning.

Very good agreement between SpEC and EOBs in weak field.

Good agreement persists into strong field ($\lesssim 3\%$).





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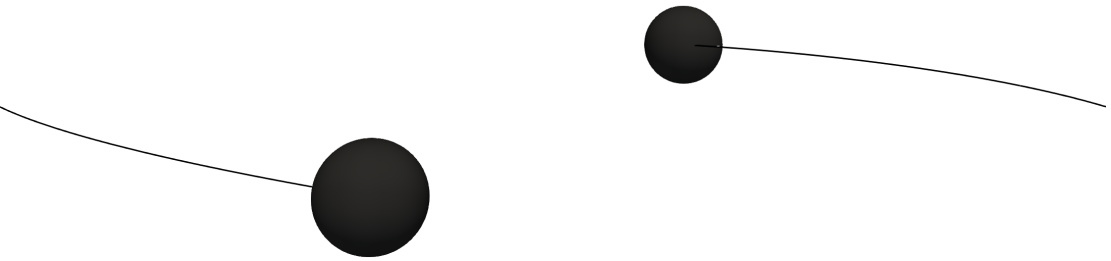
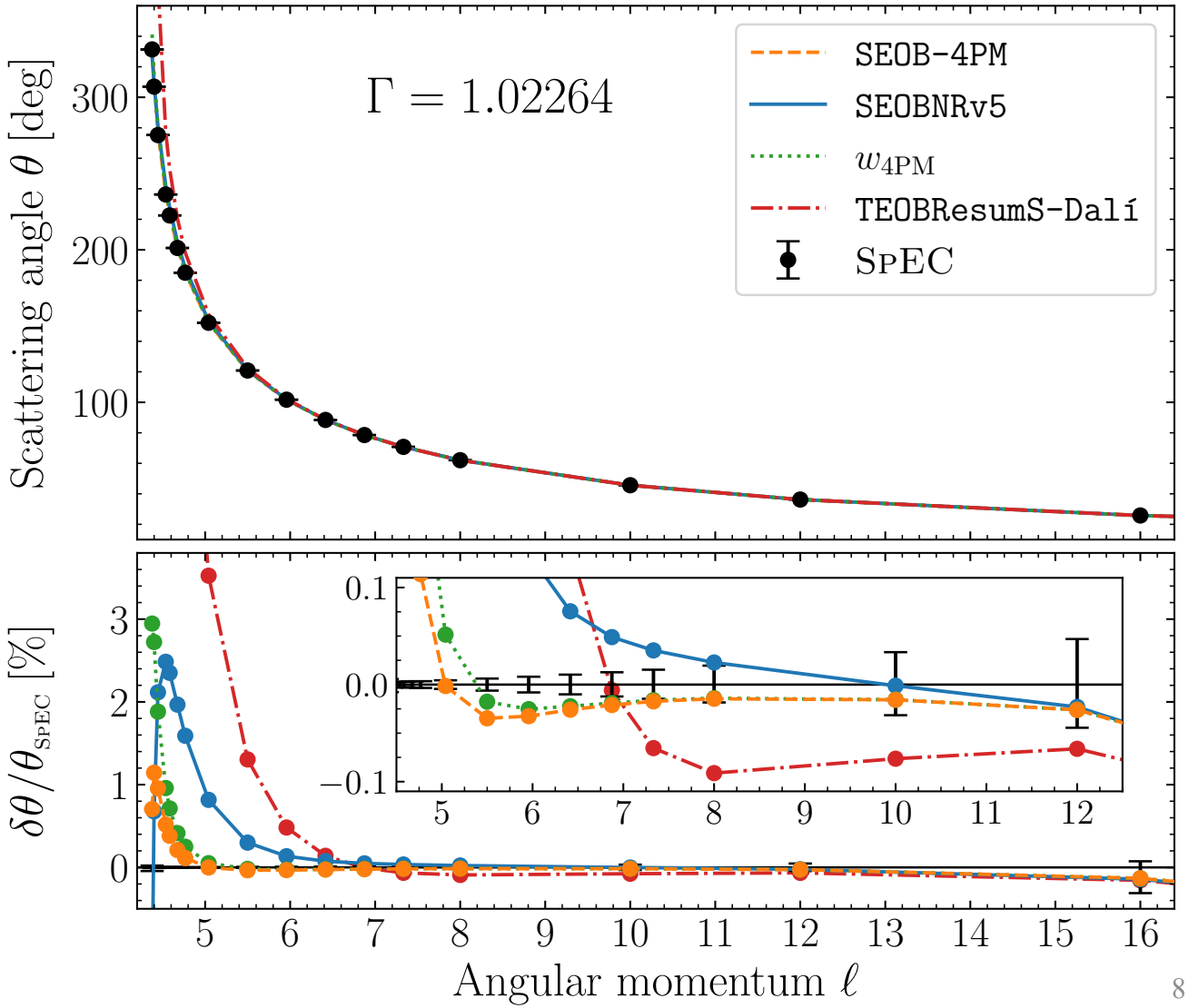




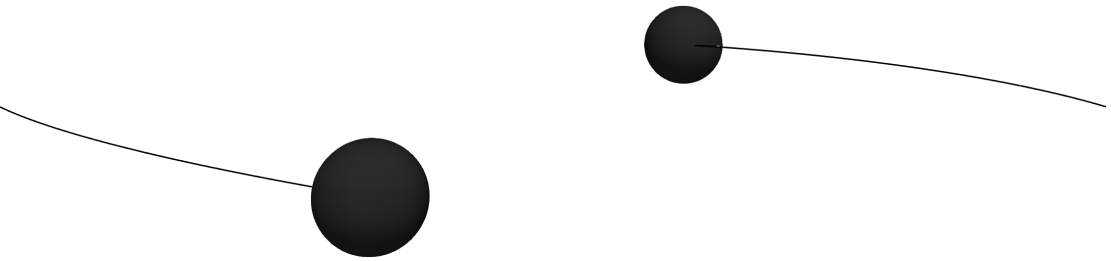
Comparison to EOB: Equal mass

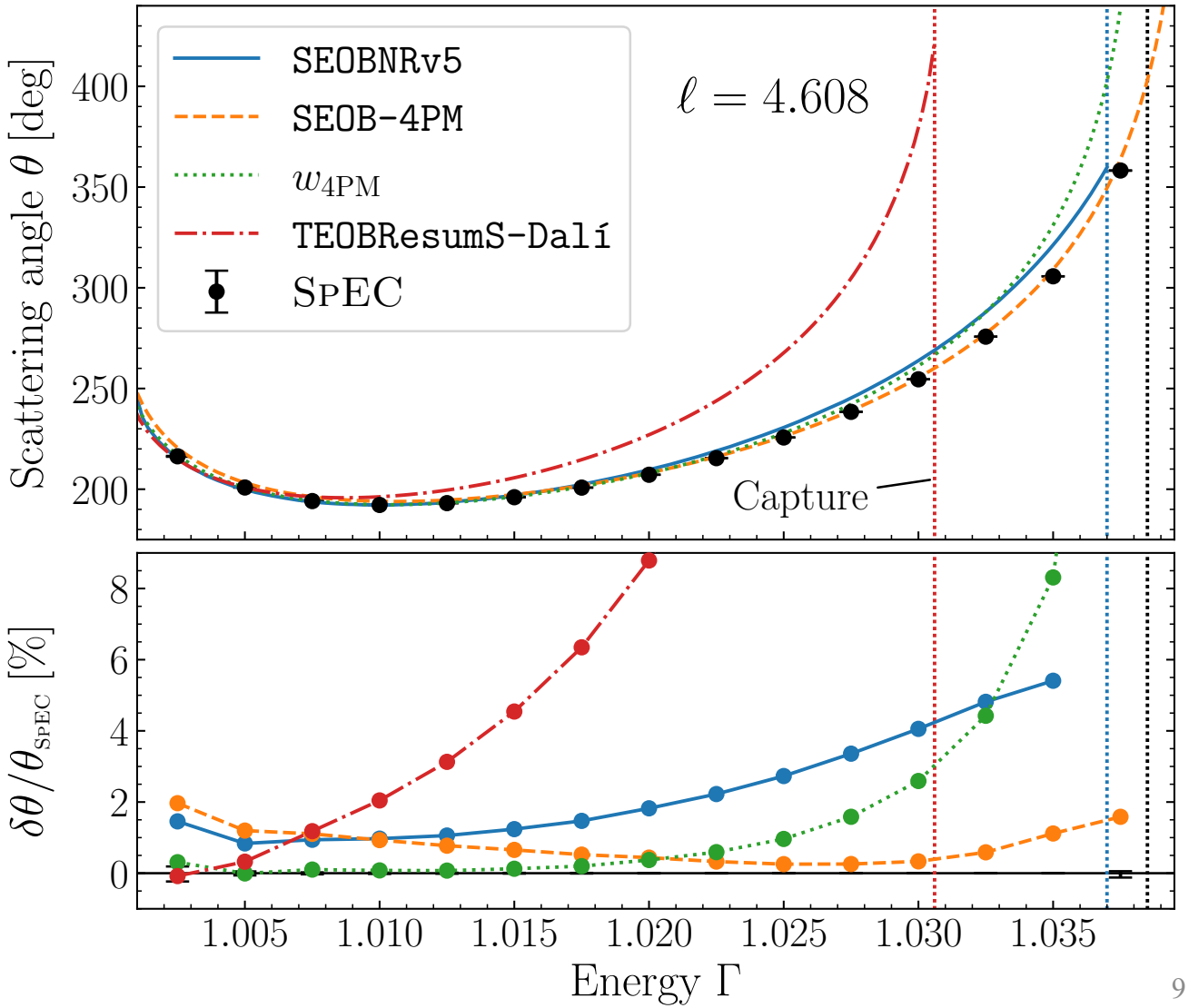
Initial conditions:

- Fixed angular momentum.
- Equal mass.
- Non-spinning.

Good agreement between SpEC and EOBs in at low energy.

Agreement at large energies is very model dependent.





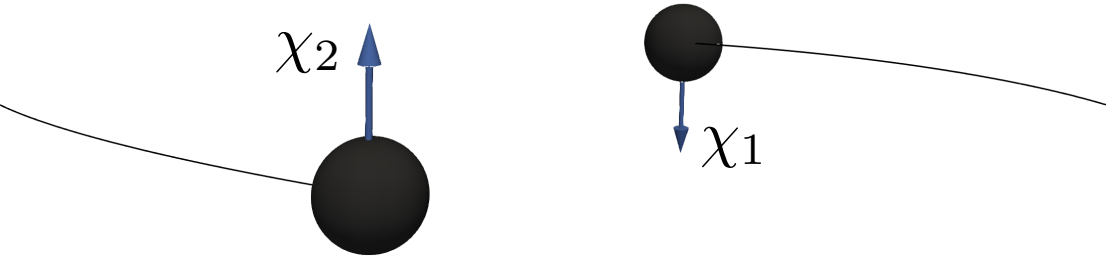
Comparison to EOB: Anti-parallel spin

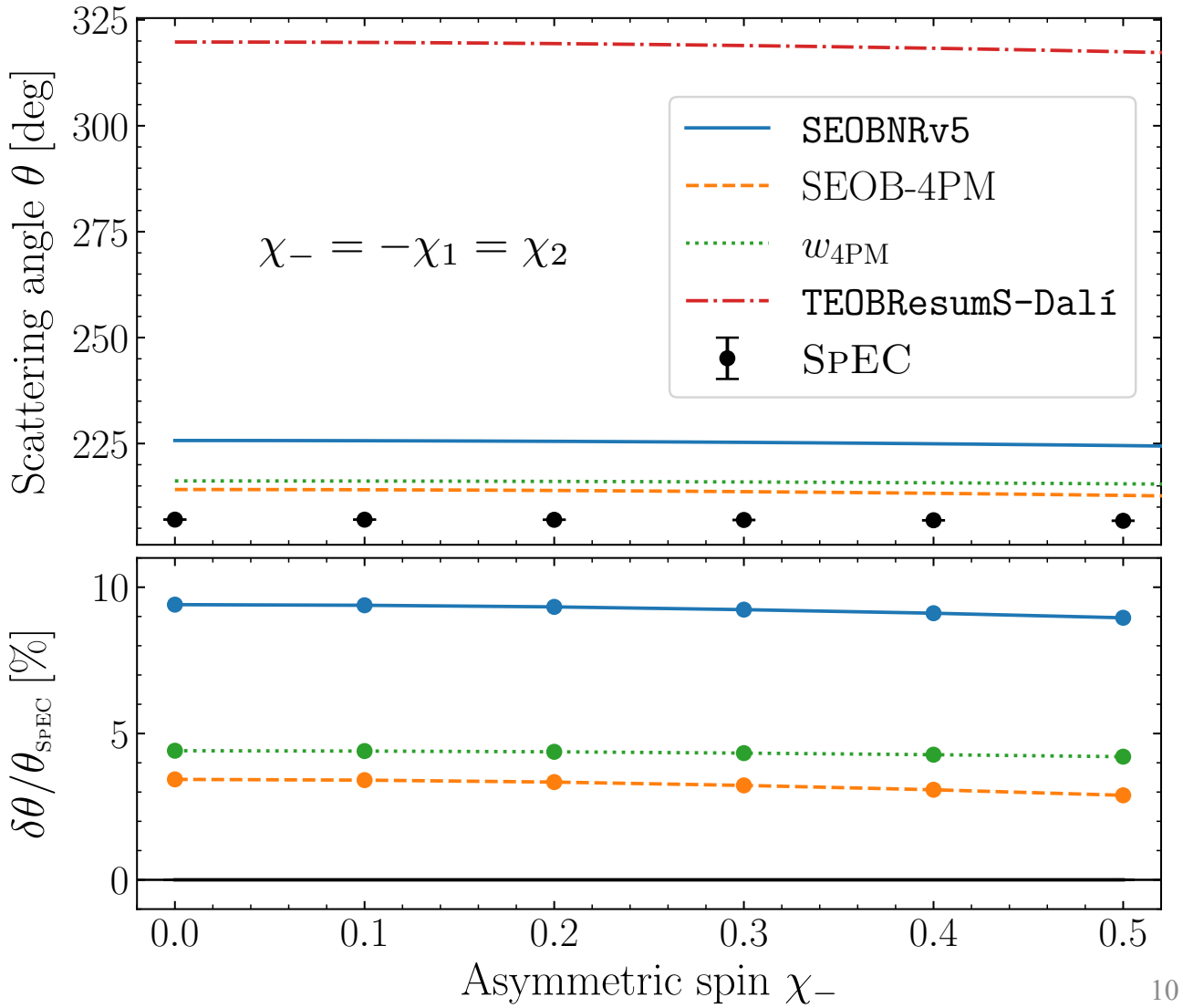
Initial conditions:

- Fixed energy.
- Fixed orbital angular momentum.
- Spin aligned with ang momentum.
- Equal mass.

Good agreement between SpEC and most EOBs.

Agreement constant across different values of spin.





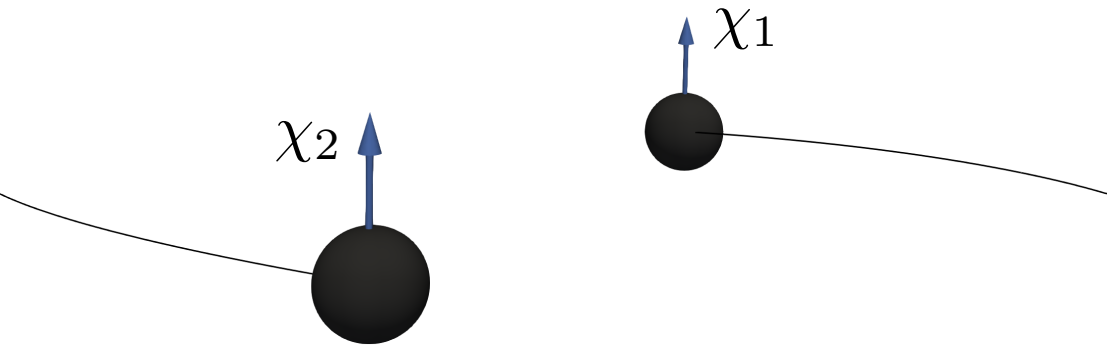
Comparison to EOB: Parallel spin

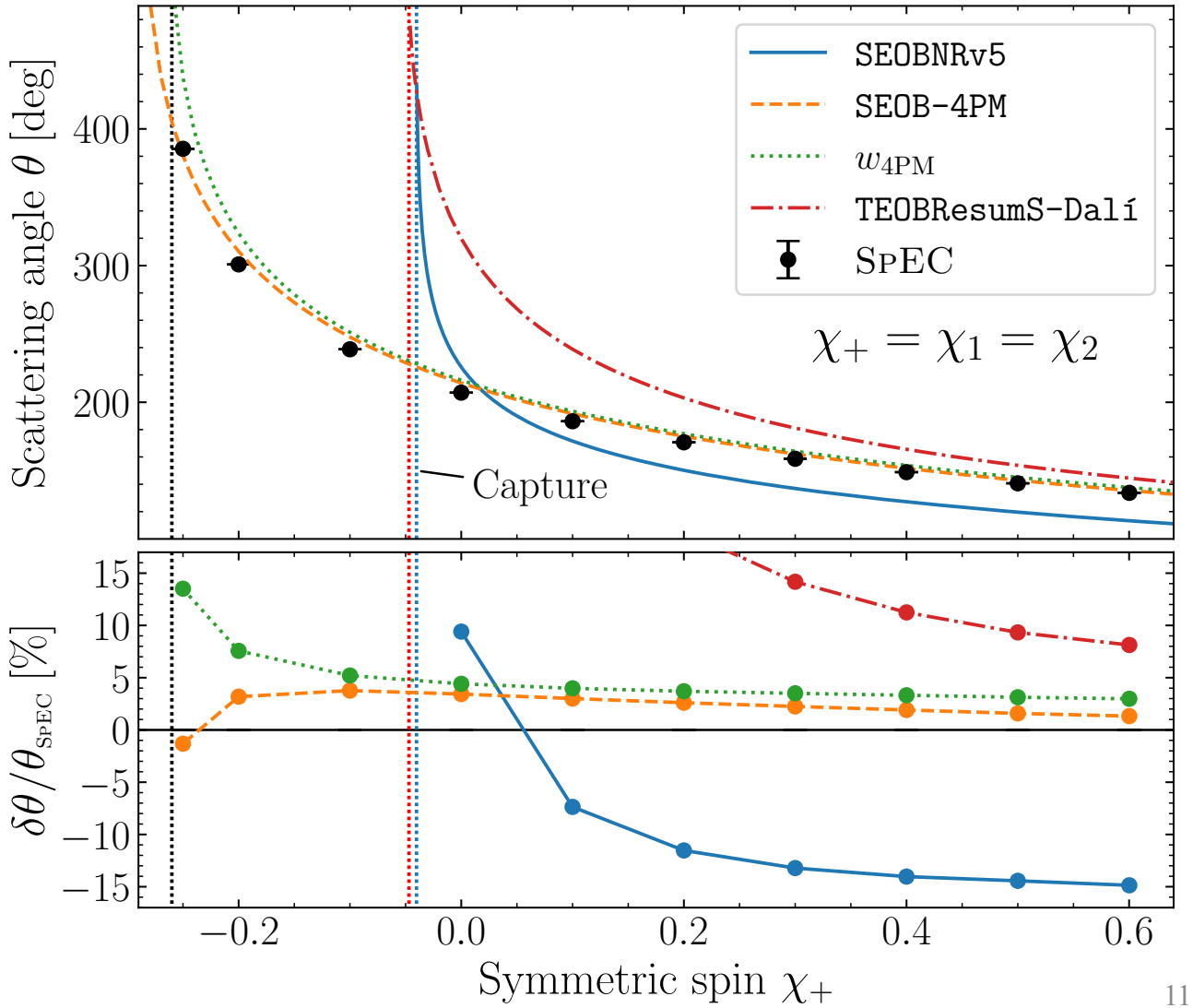
Initial conditions:

- Fixed energy.
- Fixed orbital angular momentum.
- Spin aligned with ang momentum.
- Equal mass.

Good agreement between SpEC and closed form EOBs.

Strong disagreement between SpEC and evolved EOBs.



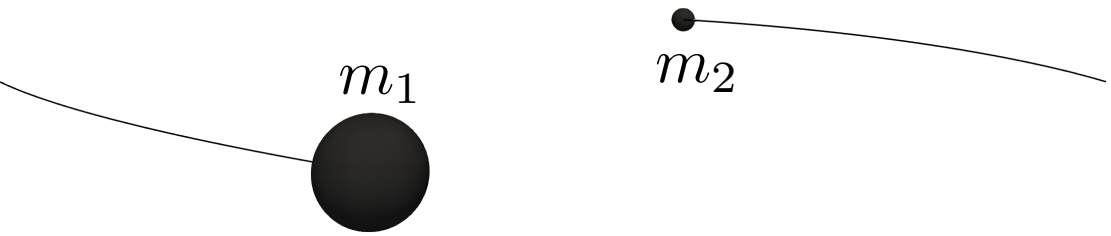


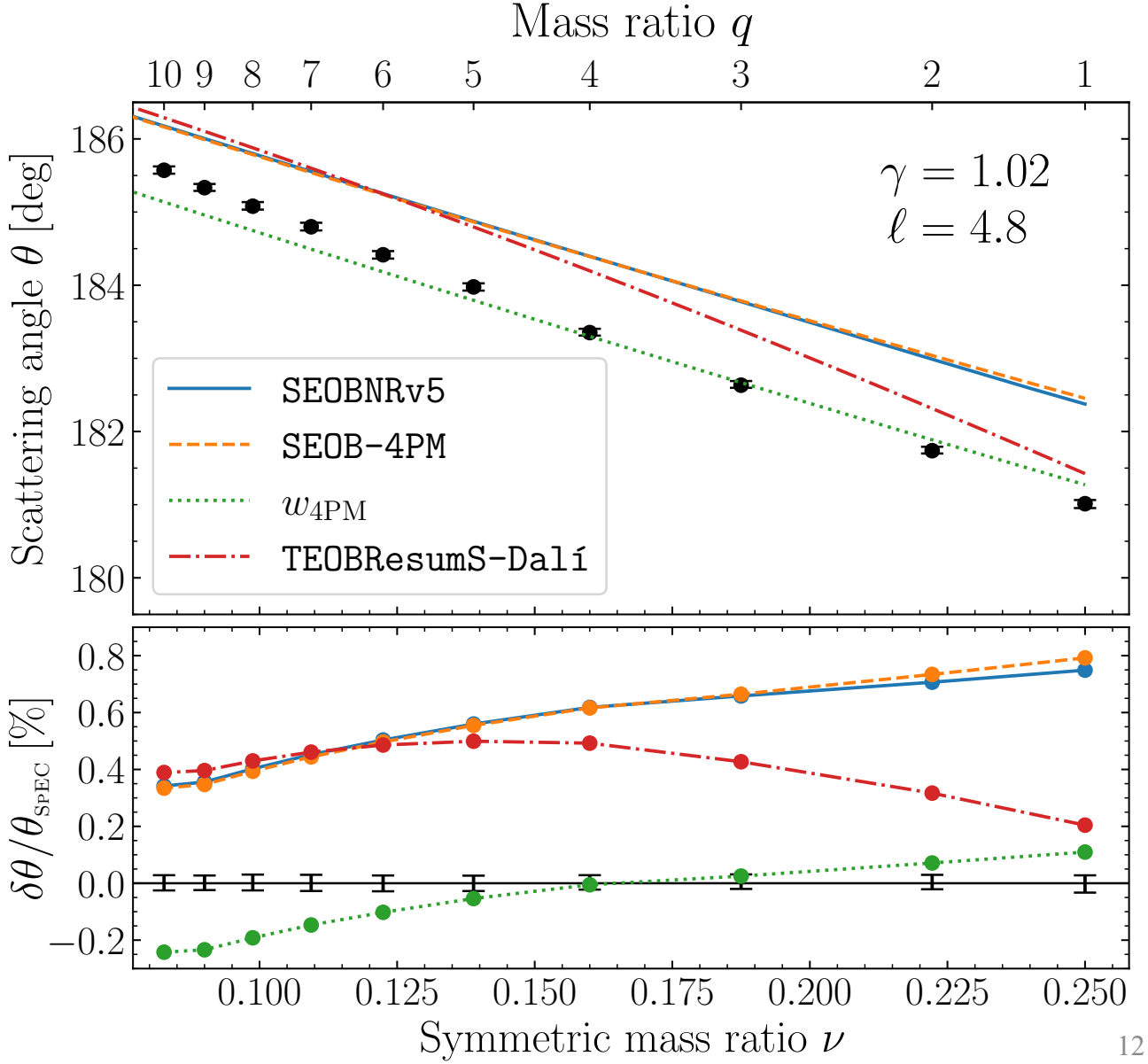
Comparison to EOB: Unequal mass

Initial conditions:

- Fixed relative Lorentz factor.
- Fixed rescaled angular momentum.
- Non-spinning.

Very good agreement between SpEC and EOBs (<1%).





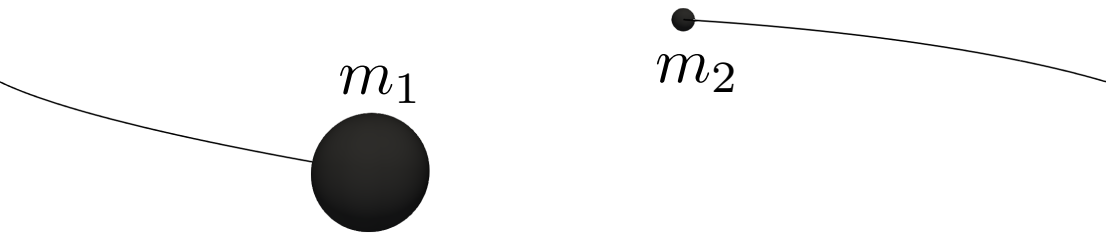
Comparison to EOB: Unequal mass

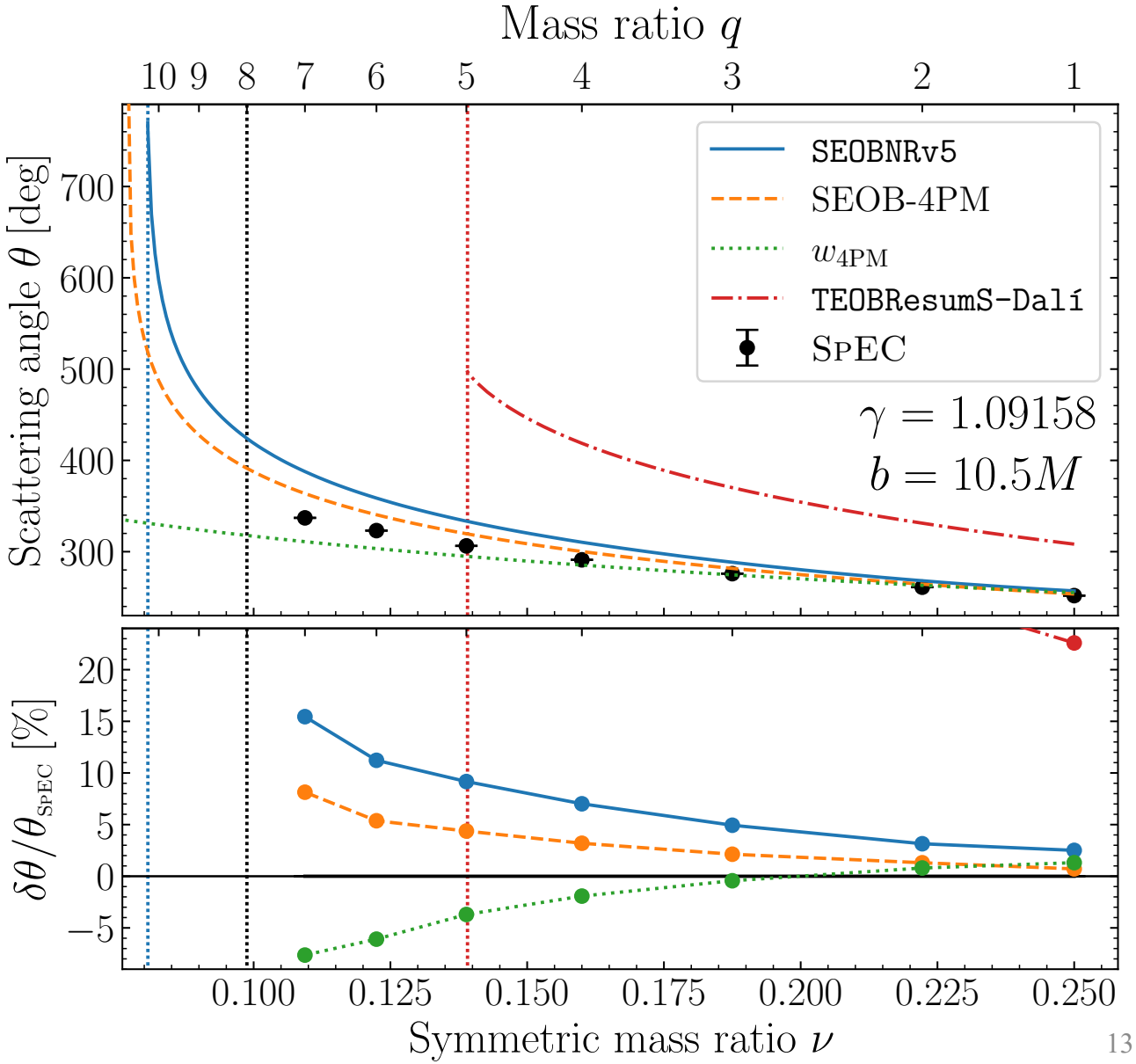
Initial conditions:

- Fixed relative Lorentz factor.
- Fixed impact parameter.
- Non-spinning.

Good agreement between SpEC and most EOBs at equal mass.

Agreement get worse at disparate masses.





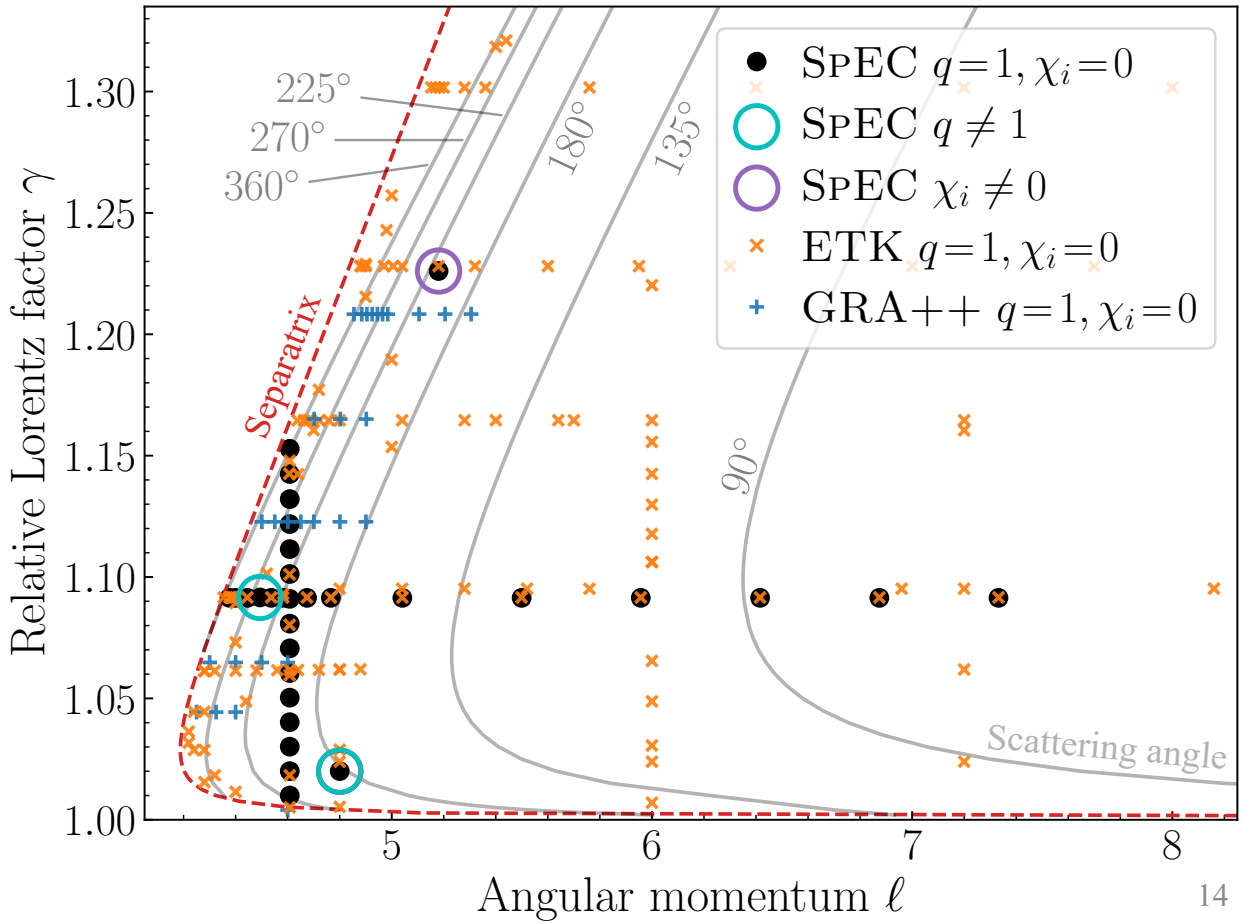
Future work

Expand NR coverage of parameter space with SpEC:

- Better coverage of equal mass, non-spinning – near separatrix and higher energies.
- More unequal mass simulations.
- More aligned spin simulations.
- Generic spin simulations.

Calibration of SEOBNR models utilising gauge-invariance of unbound NR simulations:

- Scattering orbits.
- Dynamical captures.



Questions for future work

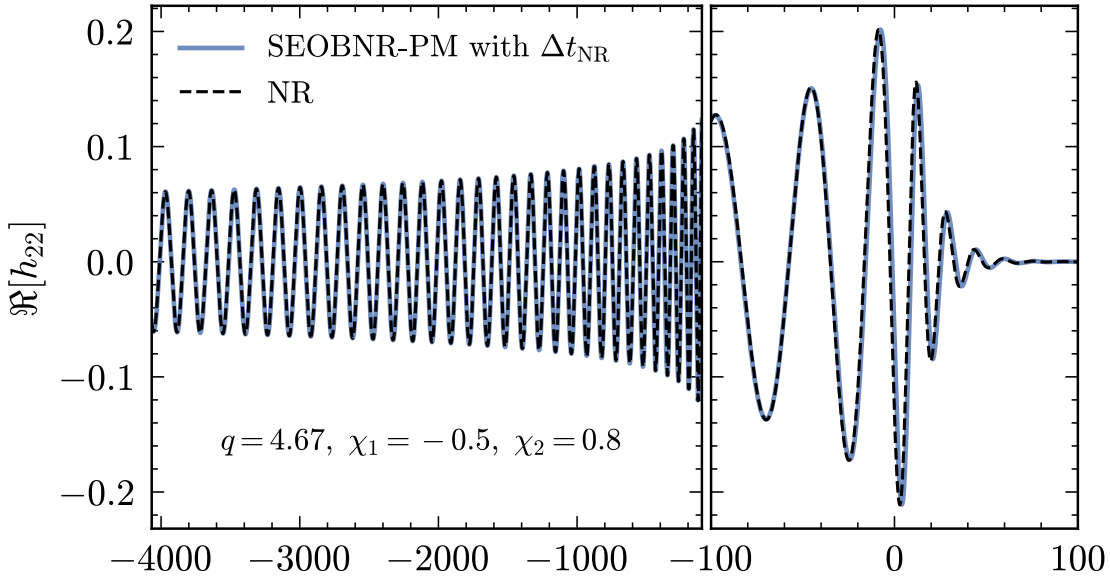
Why do the evolved models break down so quickly when adding spin?

Why does the quasicircular evolved model tend to have better agreement with NR than the eccentric model?

- How does TEOBResumS-GIOTTO compare to TEOBResumS-Dalí?
- Would eccentric corrections to SEOBNRv5 increase or decrease agreement to NR?

How well do the PM-based evolved EOB models [Buonanno+ 24, Damour+ 25] describe scattering?

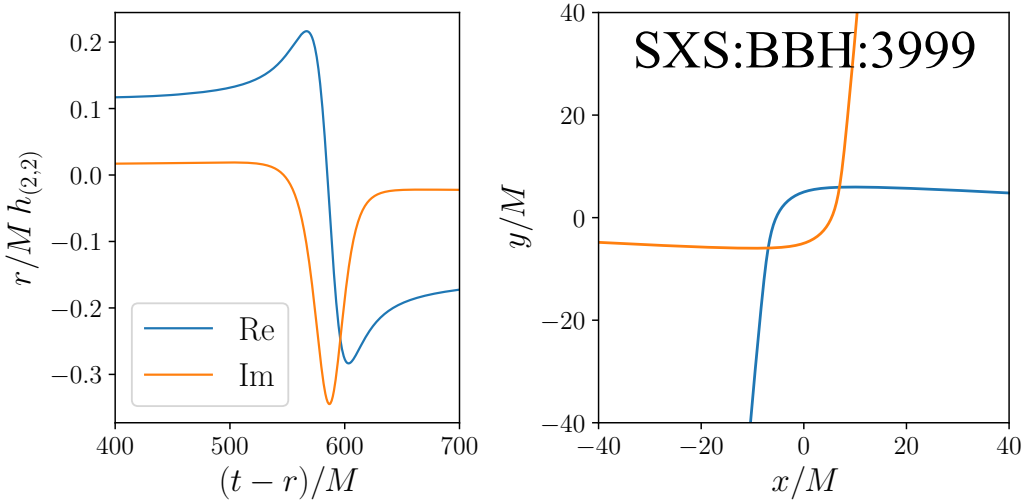
How much can calibrating to scattering NR simulations be leveraged to decrease mismatches for eccentric orbits?

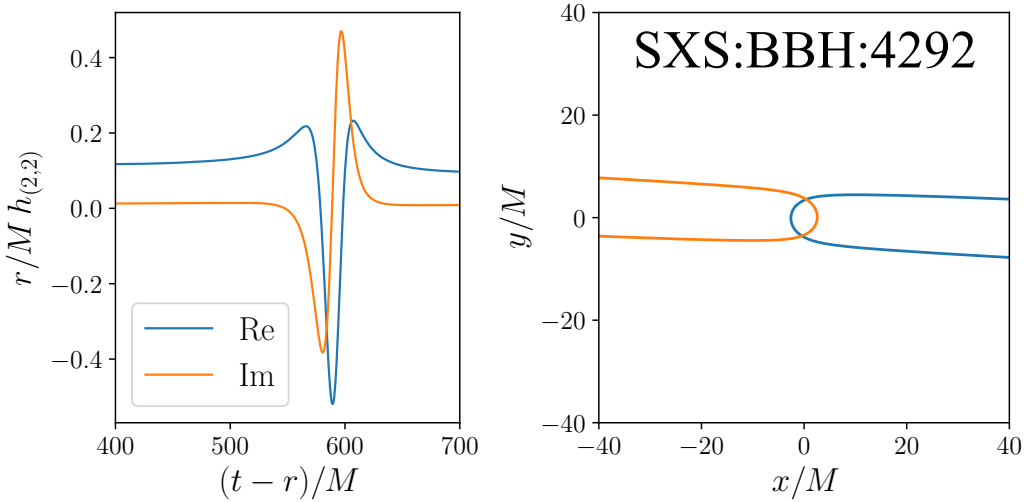


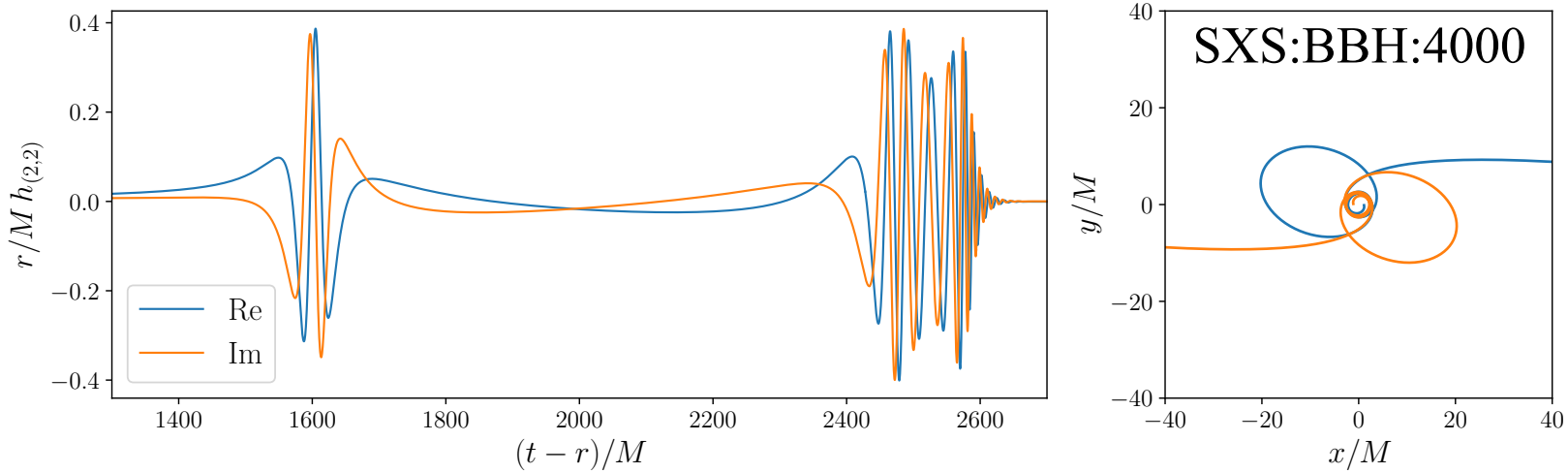
[Buonanno+ 24]

SXS catalog

Unbound simulations now available in the SXS catalog: https://data.black-holes.org







Takeaways

60 new highly-accurate NR simulations of BBH scattering up to mass ratio 10

Good agreement between SpEC and the Einstein Toolkit ($\lesssim$ 1% rel diff)

Good agreement between SpEC and quasicircular evolved EOB model ($\lesssim$ 8% rel diff)

Good agreement between SpEC and PM-based closed-form EOBs across param space ($\lesssim$ 5% rel diff)

Mixed agreement between SpEC and eccentric evolved EOB model

Public unbound simulations available via the SXS catalog

Both evolved EOB models break down quickly with aligned spin

For more details see arXiv:2507.08071