Time-domain RWZ and Teukolsky solvers with *test BH* sources on generic orbits

S.Bernuzzi (Jena FSU)

with

E.Harms, G.Loukes-Gerakopoulos (Prague), A.Nagar (INFN Torino), A.Zenginoglu

BHPToolkit Spring 2020 workshop

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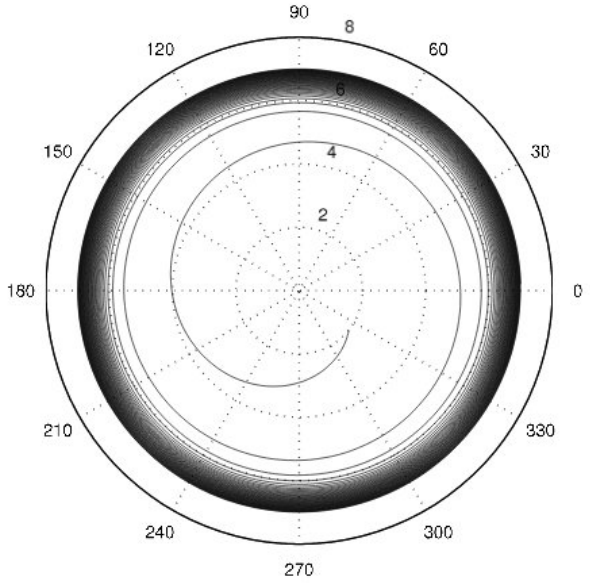
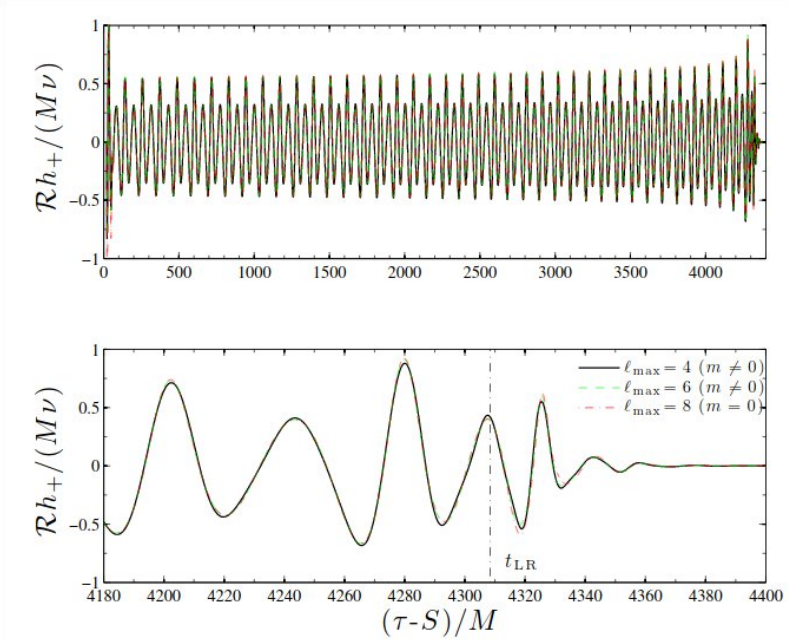
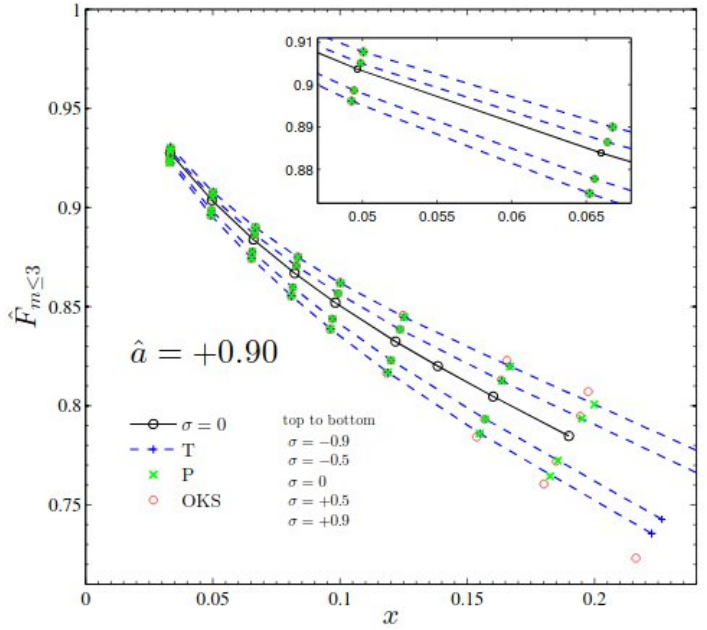
Merger waveform for large-mass-ratio BBH

- Effective-one-body development
  - Analytical resummed waveform & fluxes in $q \to \infty$ ($\nu \to 0$) limit
  - Inform merger multipolar waveform (non quasicircular corrections)
- Gravitational recoil
- Quasi-normal modes excitation in mergers (incl. fitting formulas for BBH)
- Kerr Tails





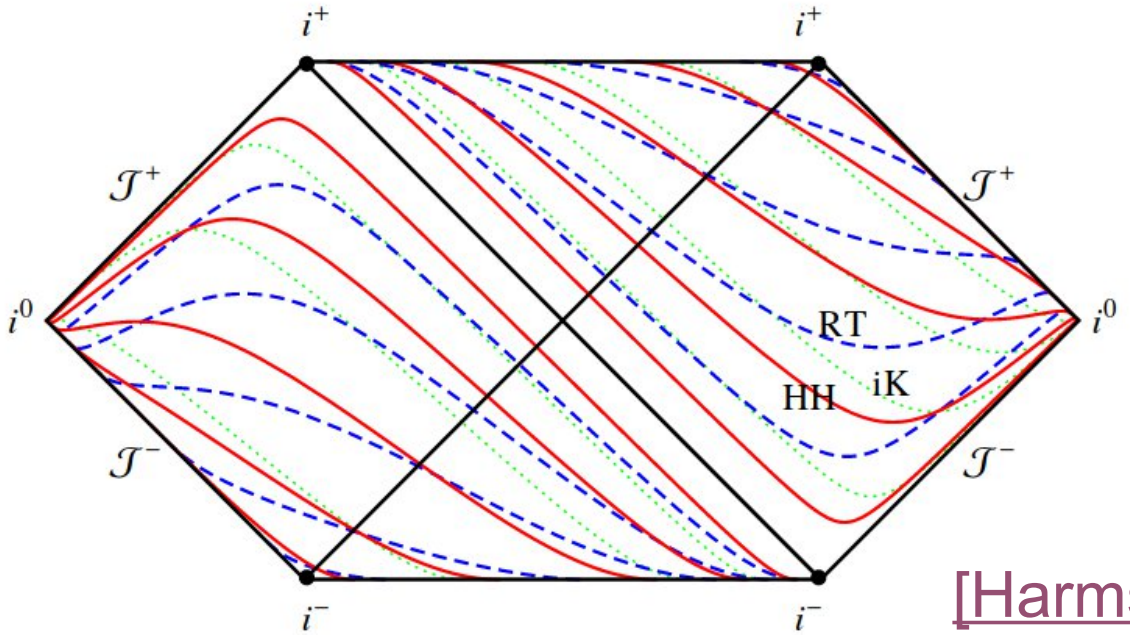


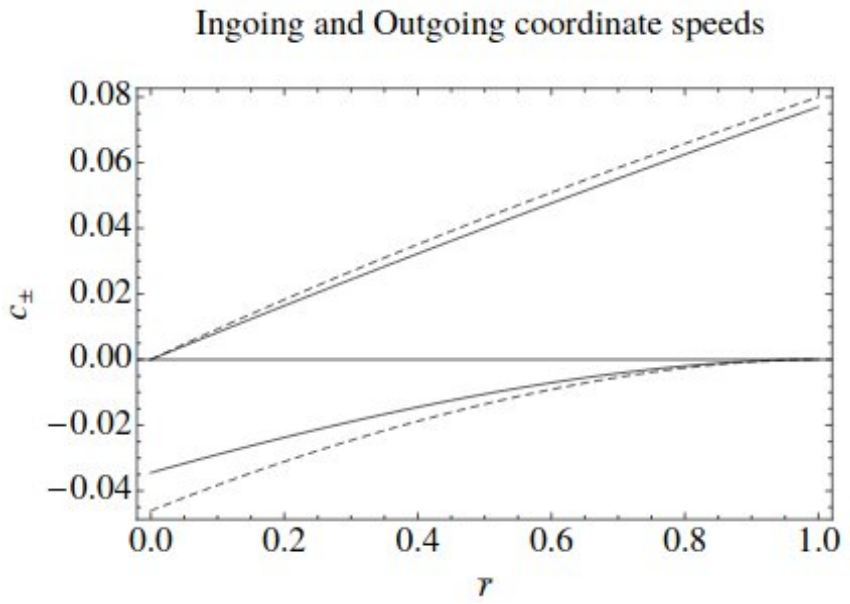
Hyperboloidal horizon-penetrating slicing

- Conformal compactification & scri-fixing coords [Zenginoğlu 0712.4333]

$$t \;\rightarrow\; t \;+\; h(r)\,; \quad r \;\rightarrow\; \frac{r}{\Omega(r)}$$

- Height function: invariance of outgoing null rays [SB+ 1107.5402]
- Include scri and horizon in computational domain
- IBVP does not need boundary conditions!





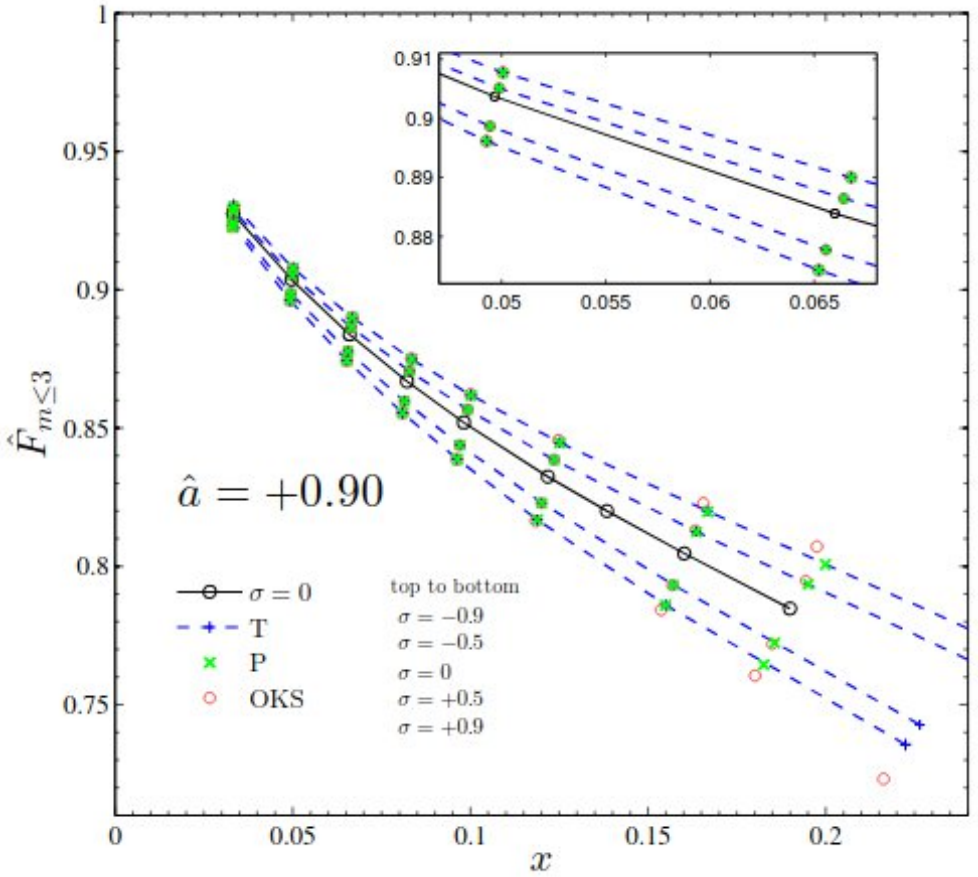
[Harms+ 1406.5983]

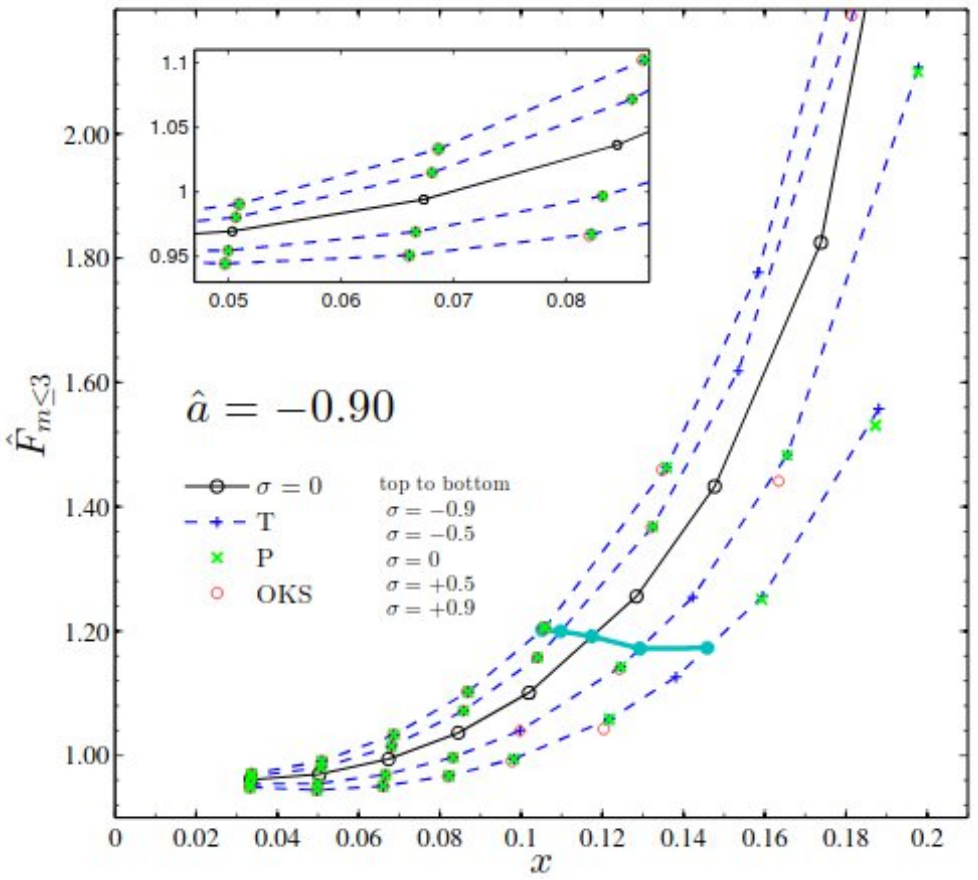
Teukode

- *m*-decomposed (2+1)D Teukolsky equation
- Hyperboloidal + horizon-penetrating coordinates
- Generic *test BH* source (in pole-dipole approximation)
  - Generic orbits
  - Gaussian-regularized or discrete Dirac function representations
- Time-domain solver: Method of lines + high-order discretization
- MPI+OMP parallel; typical grids $O(1000^2)$
- Not yet part of BH Perturbation Toolkit but open to interested people, e.g.
  - Loukes-Gerakopoulos&Zelenka: waveforms from chaotic orbits
  - Colleoni, Keitel, Husa: Phenom* waveforms and BH fits
  - ...

Applications' showcase

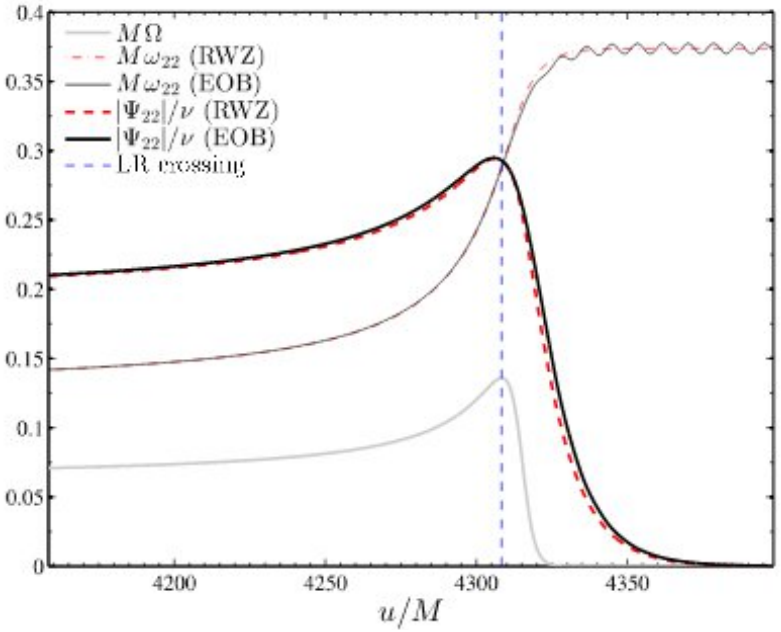
Circular fluxes of spinning body on Kerr

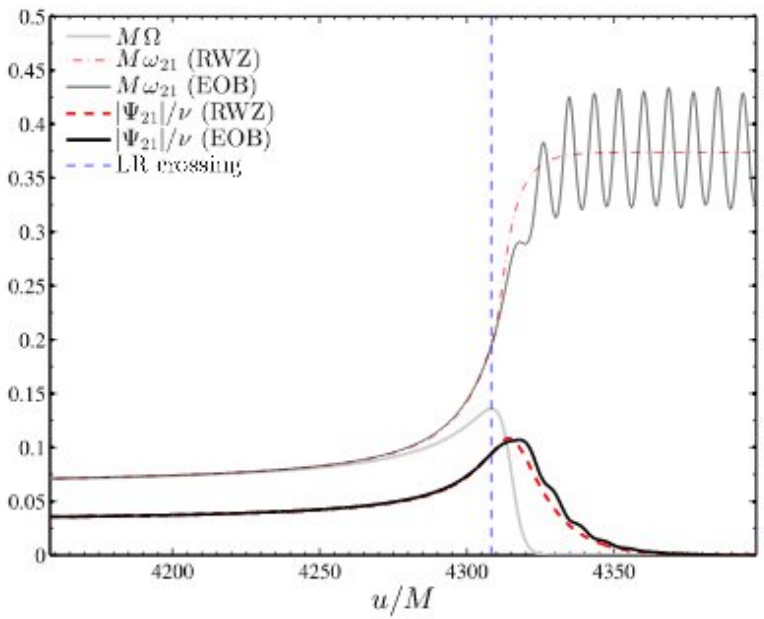




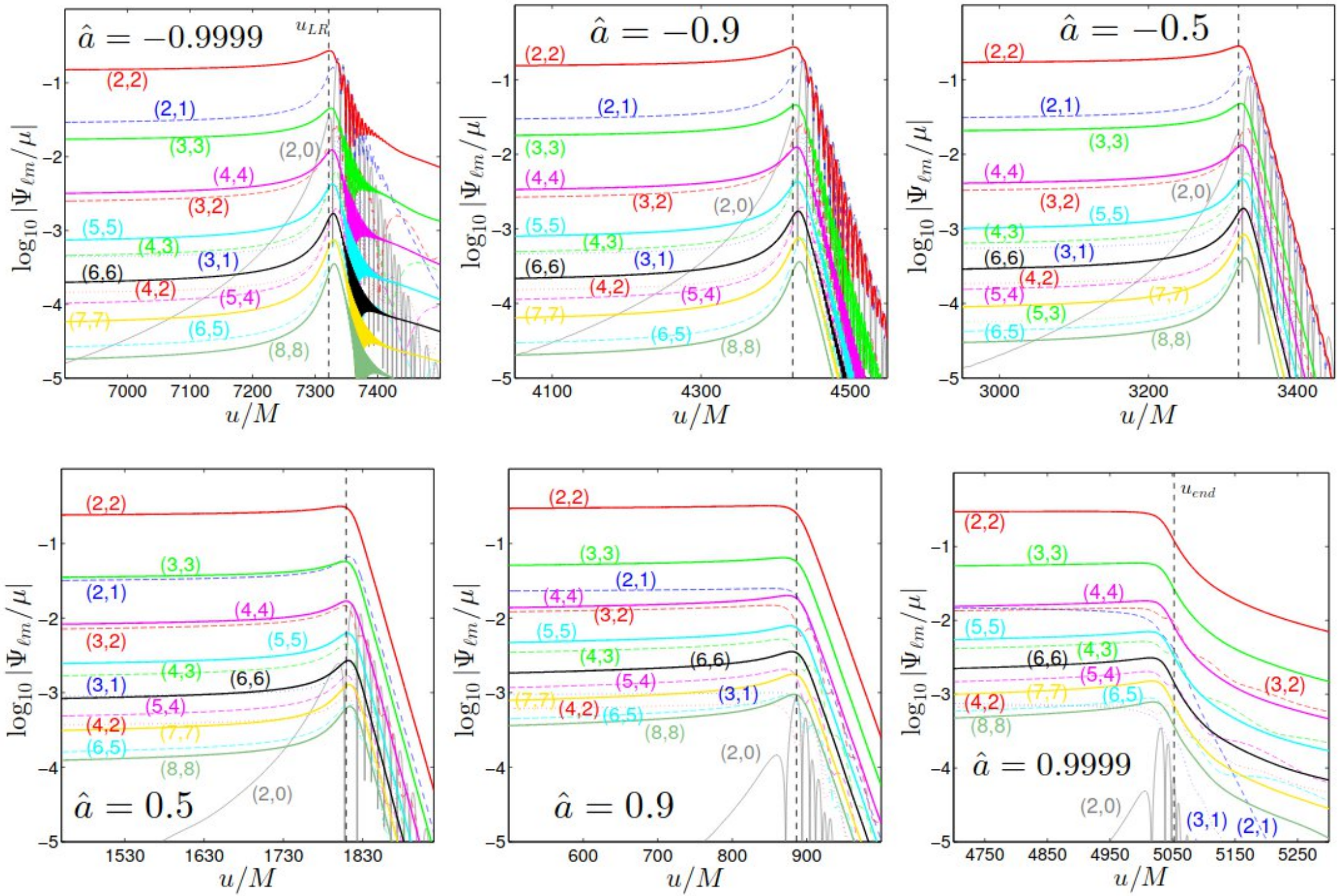
[Lukes-Gerakopoulos+ 1707.07537]

Merger waveform & ringdown

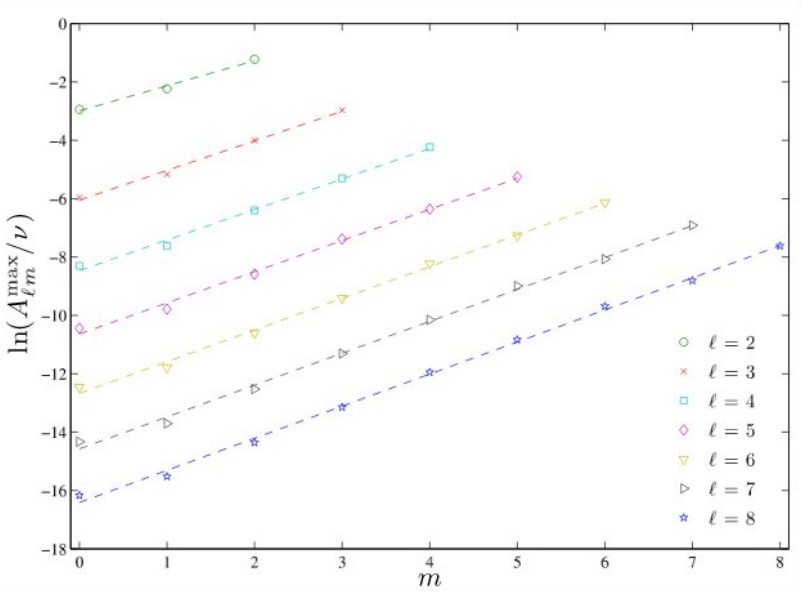




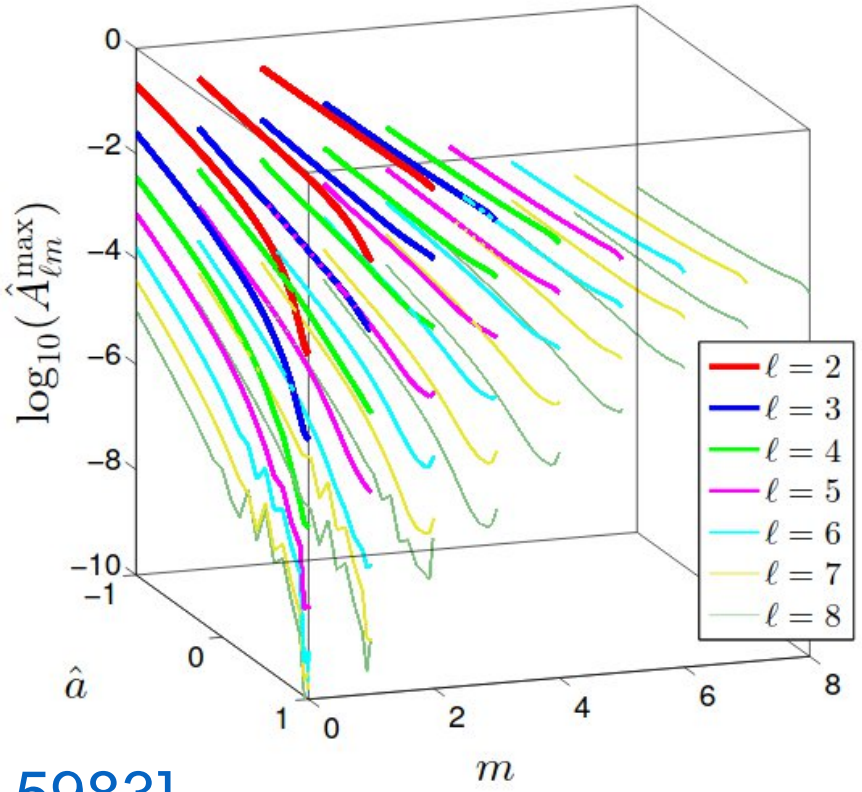
- EOB NQC corrections [SB+ 1012.2456] [Damour+ 1212.4357]
- Absorbed fluxes [SB+ 1207.0769] (Schwarzschild) [Harms+ 1406.5983] (Kerr)
- QNM excitation [SB+ 1003.0597] (Schwarzschild) [Harms+ 1406.5983] (Kerr)

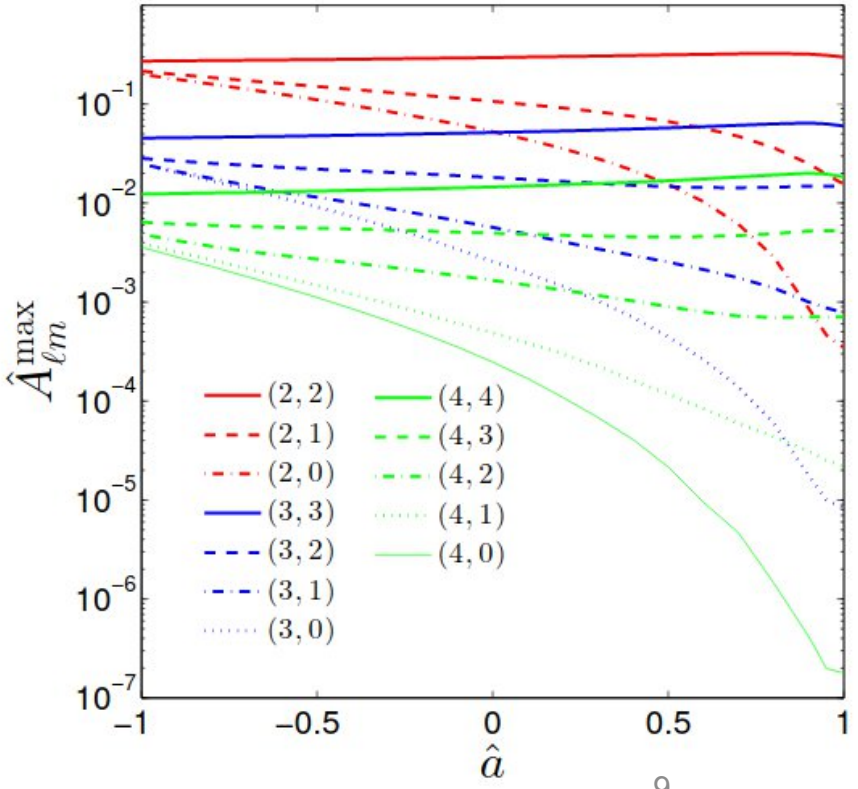

$\hat{a} = -0.9999$
u_{LR}
$\hat{a} = -0.9$
$\hat{a} = -0.5$
$\hat{a} = 0.5$
$\hat{a} = 0.9$
$\hat{a} = 0.9999$
u_{end}
$\log_{10}|\Psi_{\ell m}/\mu|$
u/M
(2,2)
(2,1)
(3,3)
(2,0)
(4,4)
(3,2)
(5,5)
(4,3)
(3,1)
(6,6)
(4,2)
(5,4)
(7,7)
(6,5)
(8,8)

Multipolar amplitudes @ merger



$$A_{lm} \cong e^{m-2l} \quad (a = 0)$$ [SB+ 1012.2456]

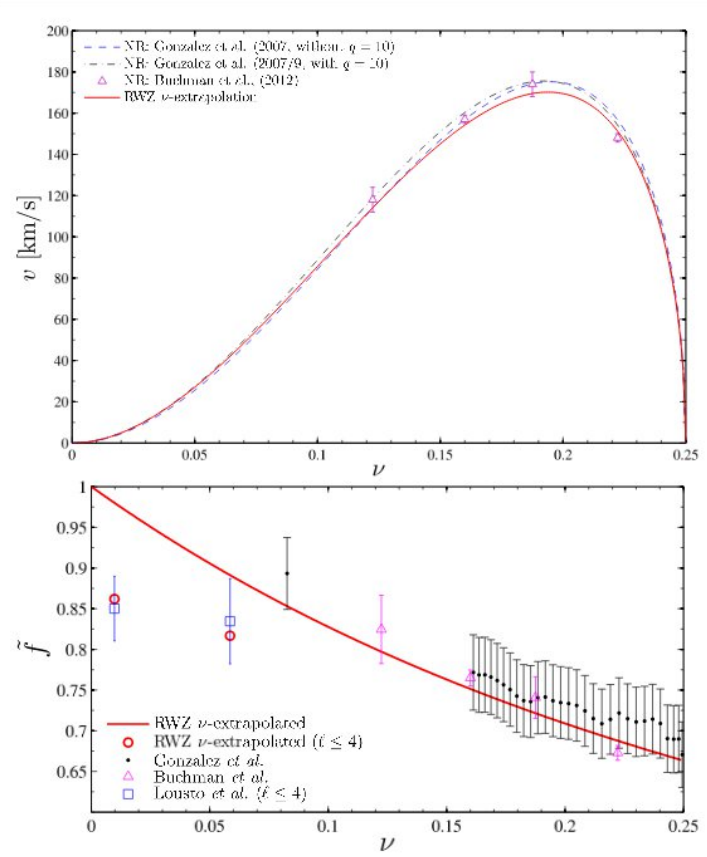


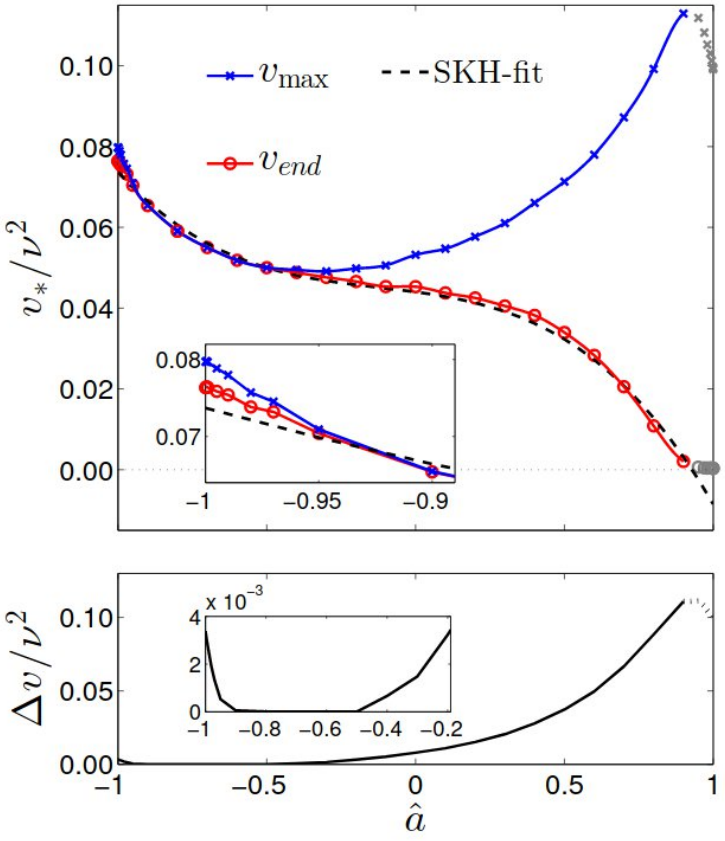


[Harms+ 1406.5983]

Gravitational recoil ("kick")

- Kick + antikick, already there in pert.theory [SB+ 1003.0597]
- Analytical extrapolation to comparable masses [Nagar 1306.6299]
- Antikick strikes back for $a = -0.9999$ [Nagar+ 1407.5033]





QNM & Tail decay on Kerr

[Harms+ 1301.1591]

- EM & GW perturbations; axisym. & nonaxisym,
- Initial data: Non. vs. Compact support; Non. vs. Stationary initial
- Tails @ scri, horizon and finite radius: verified all analytical predictions
- Rapidly rotating background: weakly damped QNM
- QNM extremal case: ~1/T @ scri , amplified at horizon