11 Orbit inspiral of unequal-mass BHBs

U. Sperhake

CSIC-IEEC Barcelona
California Institute of Technology
University of Mississippi
FSU Jena

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B. Brügmann, D. Müller,
E. Berti, M. Kesden

“These go to eleven”

Motivation

- Obtain *accurate, long* waveforms for unequal mass ratios for use in GW DA
- Comparison with alternative codes
- Matching to PN
- Calibrate accuracy: convergence, extraction radius, eccentricity
- Study non-dominant multipoles
- Optimize efficiency

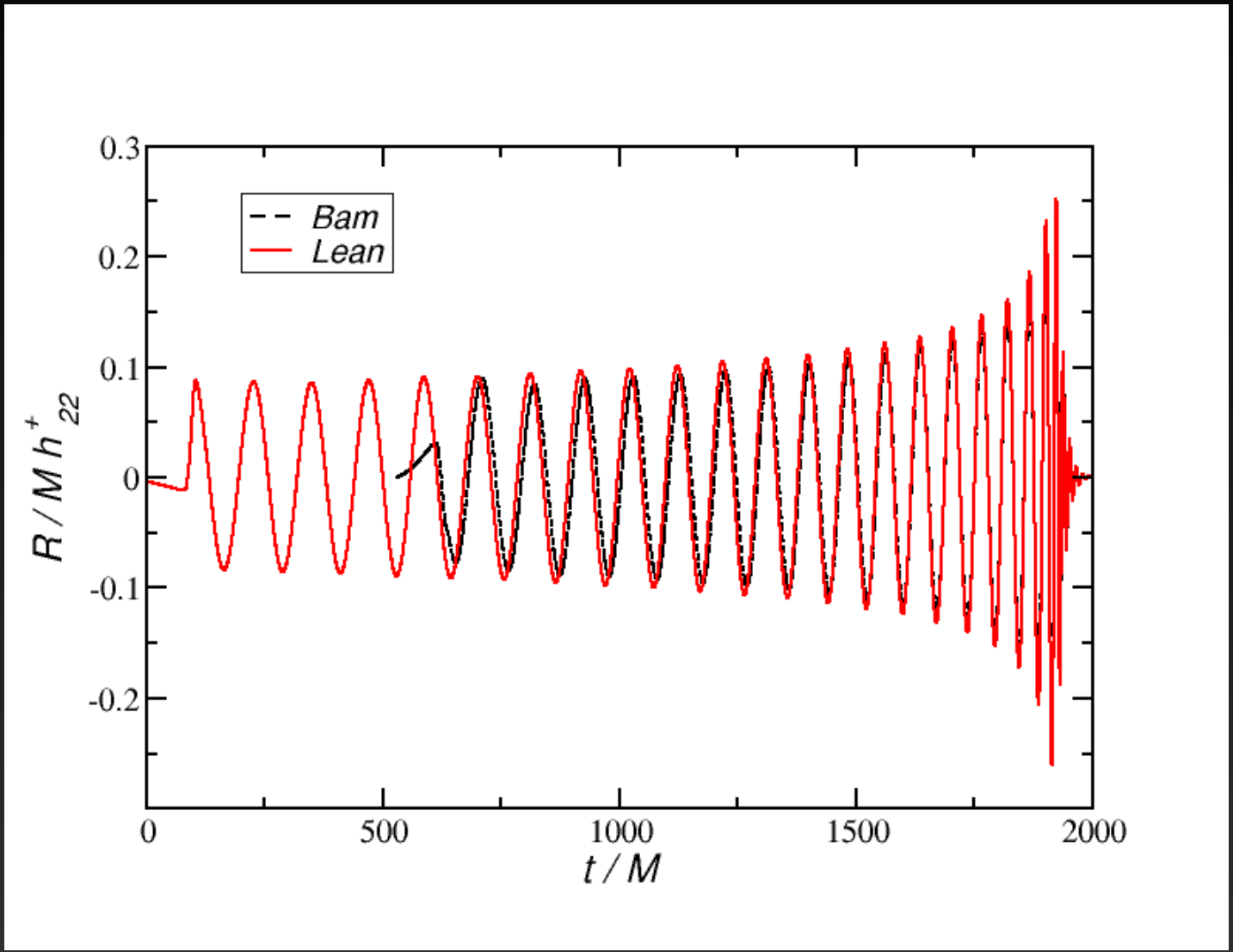
Binary parameters

- mass ratio $q = 4$
- initial orbital frequency $M\omega = 0.05$
- grid setup:
  $\{(307.2, 153.6, 102.4, 32, 16) \times (3.2, 1.6, 0.8, 0.4, 0.2), h\}$
  $h = M/180,\ M/200,\ M/220,\ M/240$
- extraction radii: $R_{ex} = 56,\ 64,\ 72,\ 80,\ 88,\ 96,\ 104,\ 112\ M$
- gauge: $\partial_t \alpha = \beta^m \partial_m \alpha - 2\alpha K$

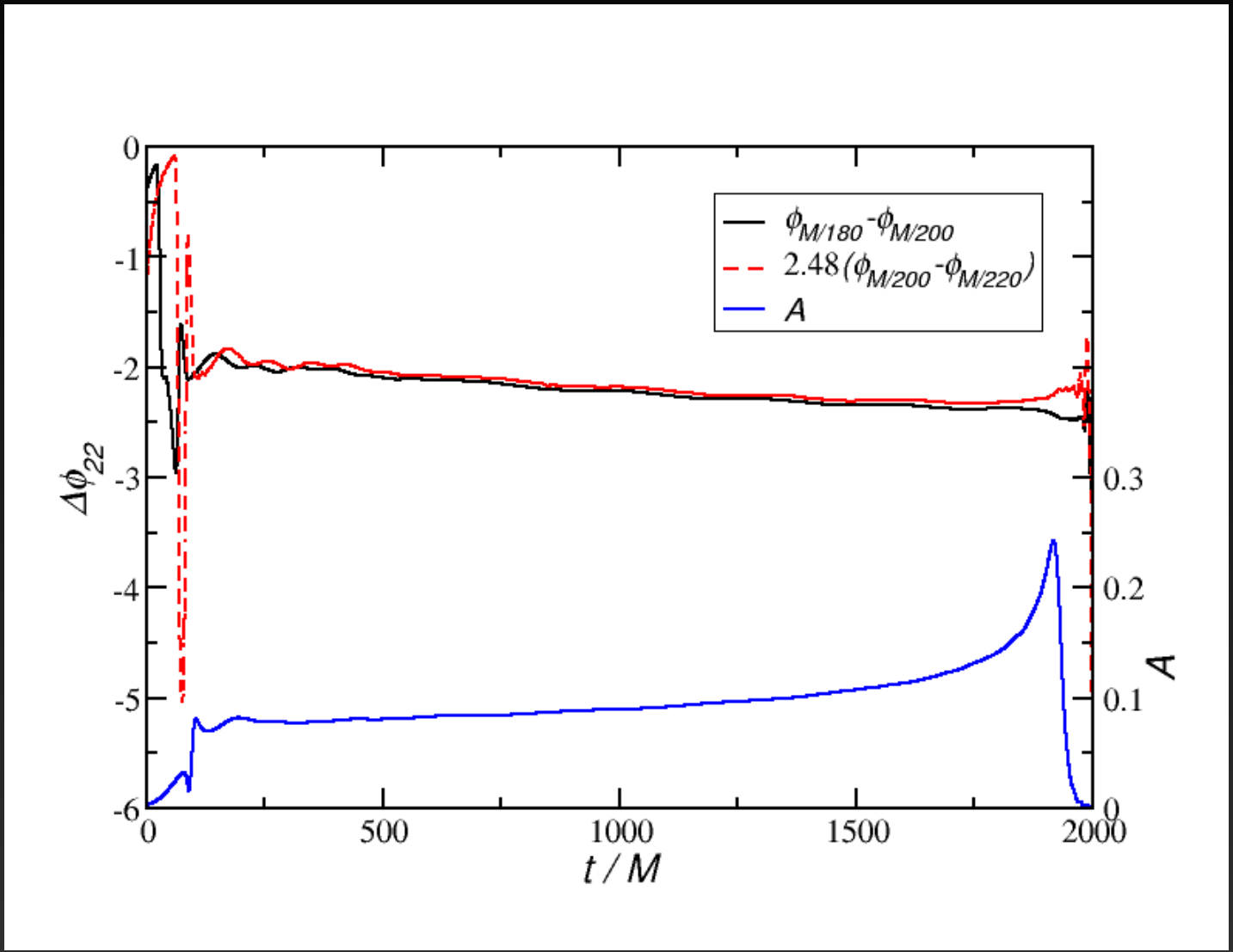
  $$\partial_t \beta^i = \beta^m \partial_m \beta^i + \tfrac{3}{4} \tilde{\Gamma}^i - \eta \beta^i$$

  $M\eta = 1.75$

BAM, LEAN waveforms



Convergence of $\ell = 2$, $m = 2$ mode: Phase



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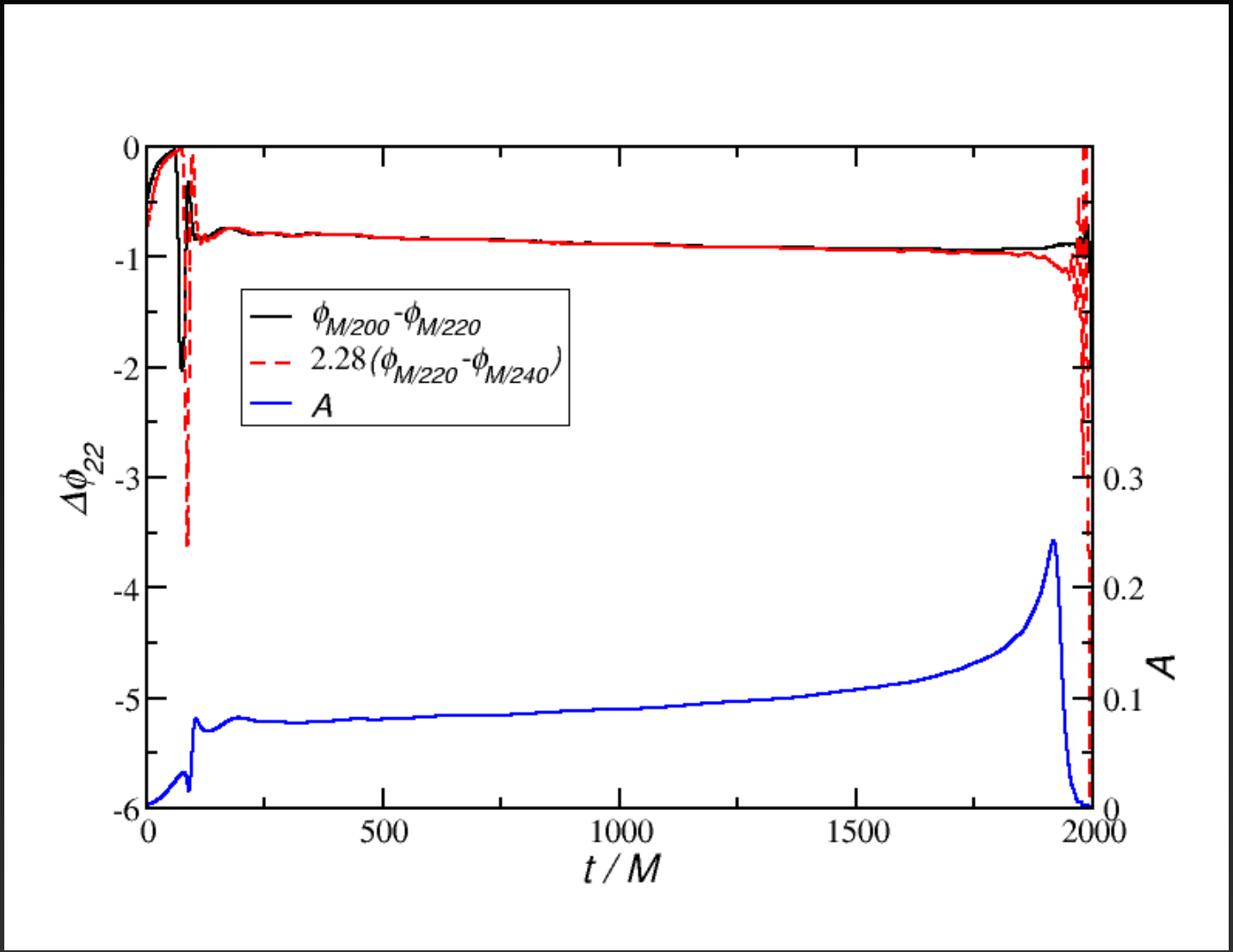

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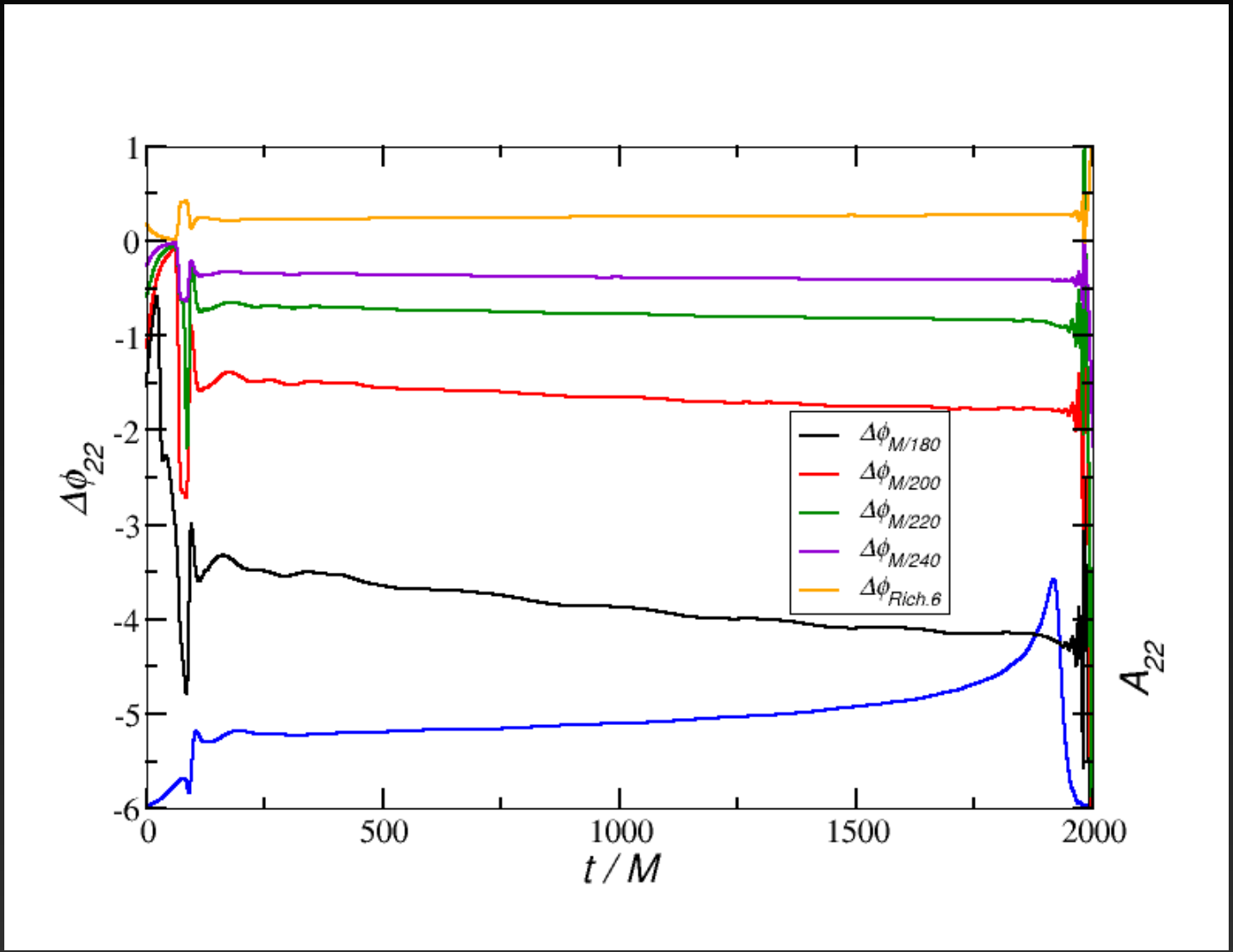
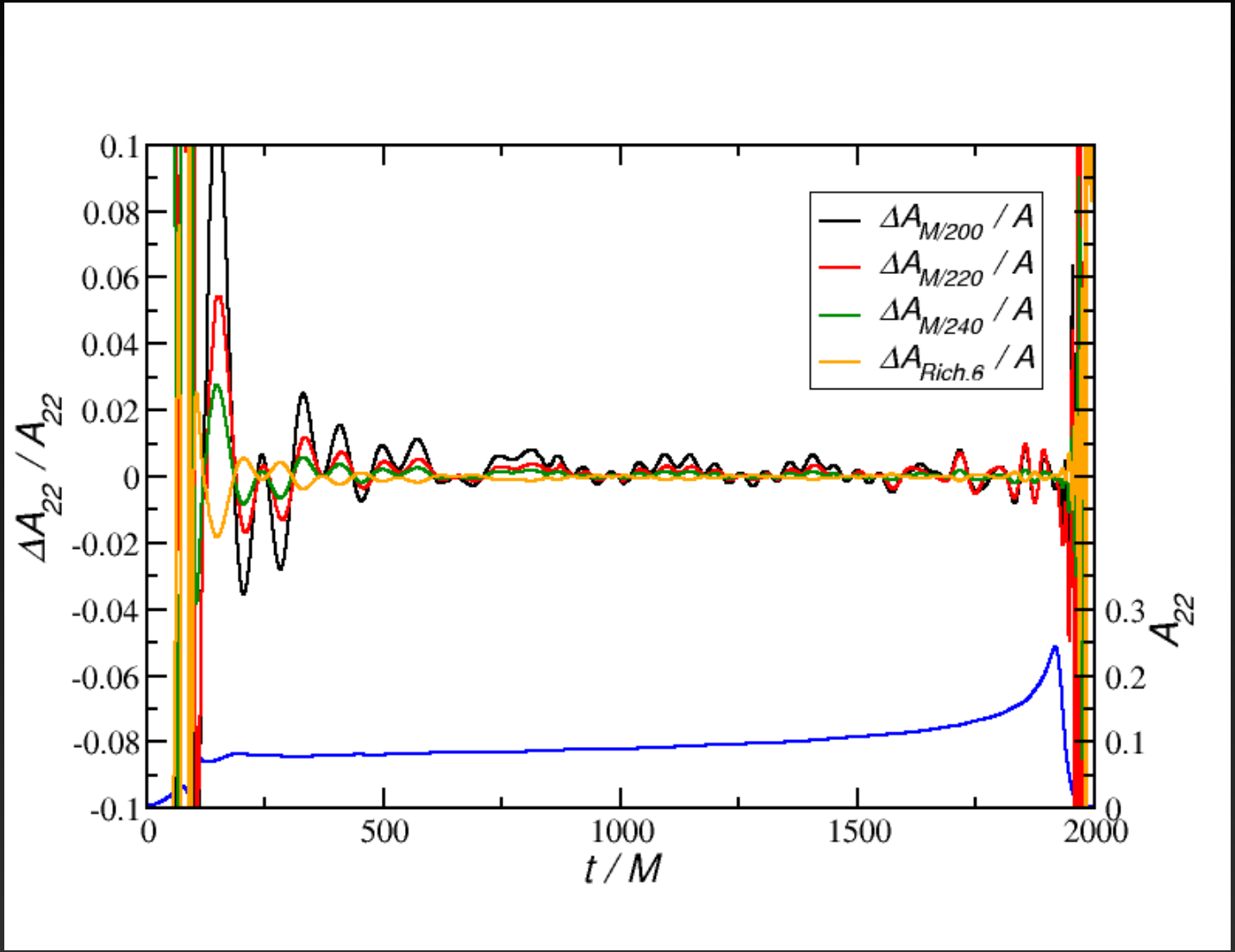


Convergence of $\ell = 2$, $m = 2$ mode: Amplitude



Discretization errors: summary

- $R_{\rm ex} = 88\ M$
- $\Delta\phi_{22} \approx 0.2$ rad
- $\Delta A_{22}/A_{22} \approx 0.5$ %
- little variation over $t \approx 250\ M ... 2000\ M$
- Errors larger during first orbits, late ringdown

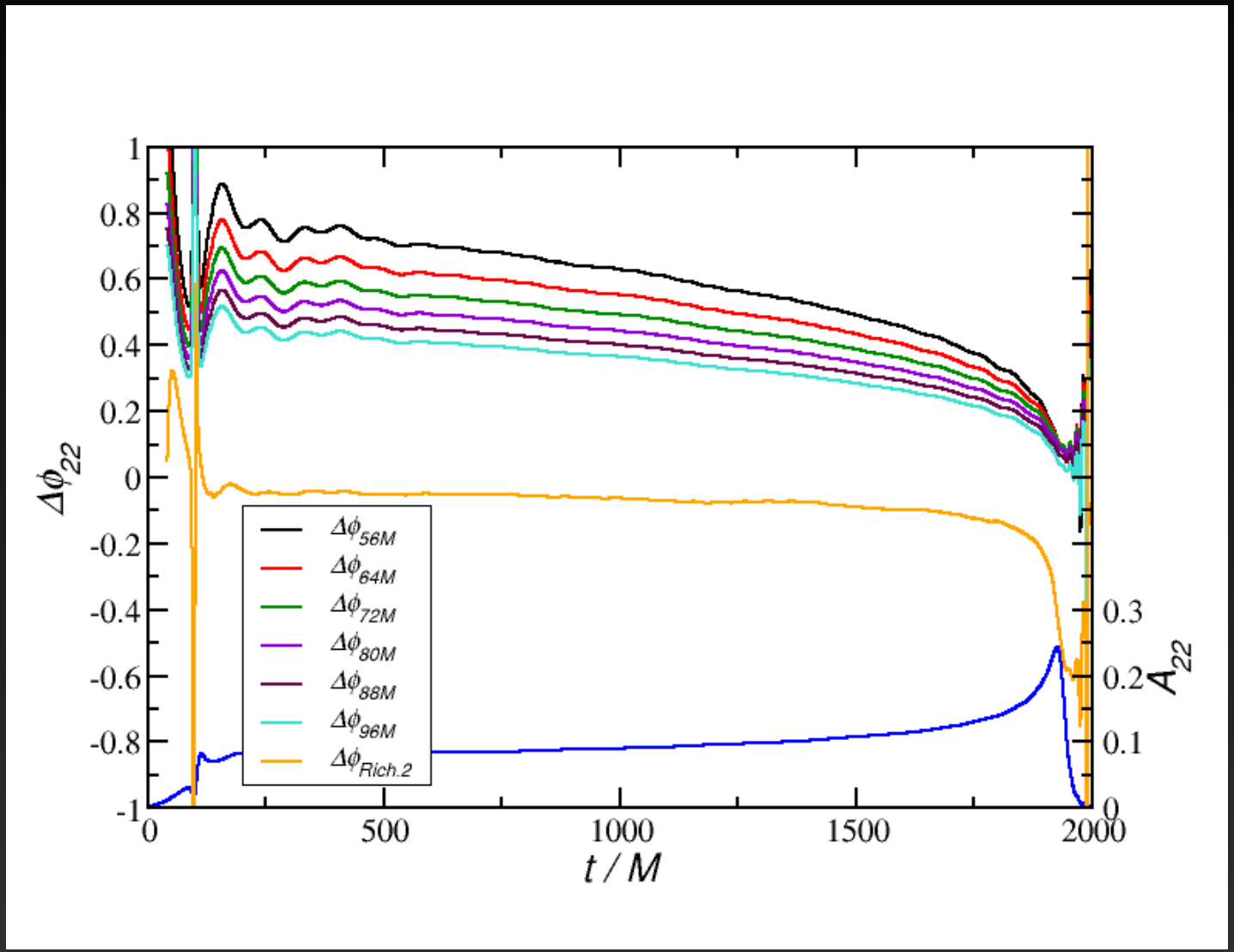
Error due to extraction radius

- Fix $h = M/240$
- $R_{\rm ex} = 56M,\ 64M,\ 72M,\ 80M,\ 88M,\ 96M$
- Extrapolate assuming $f = f_0 + f_1/r$

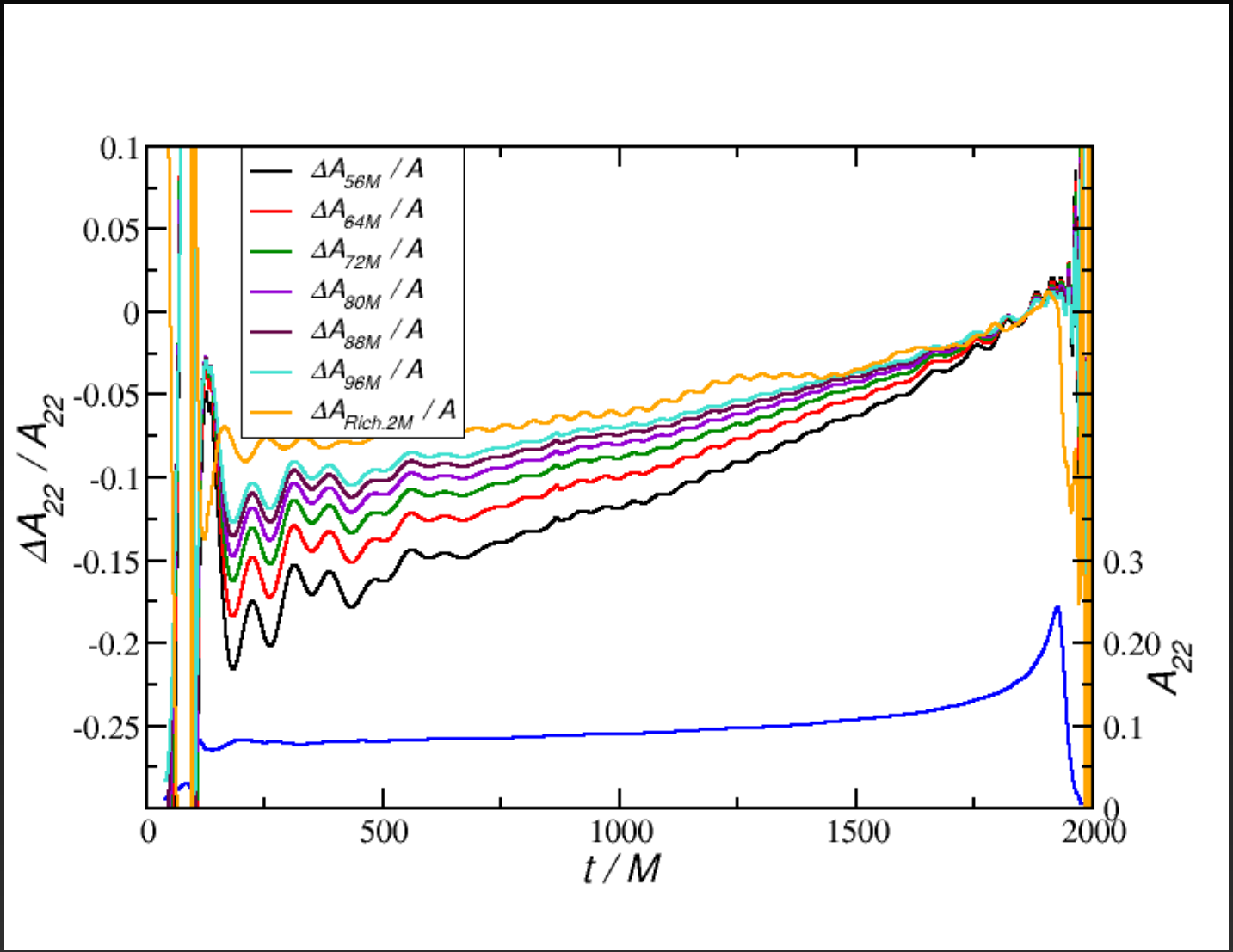
  or $f = f_0 + f_1/r + f_2/r^2$
- Use f_0 as estimate at infinity
- Caution: Do not use underresolved extraction radii!

  Amplitudes would be contaminated due to dissipation.

Extraction of $\ell = 2$, $m = 2$ mode: Phase



Extraction of $\ell = 2$, $m = 2$ mode: Amplitude



Extraction errors: summary

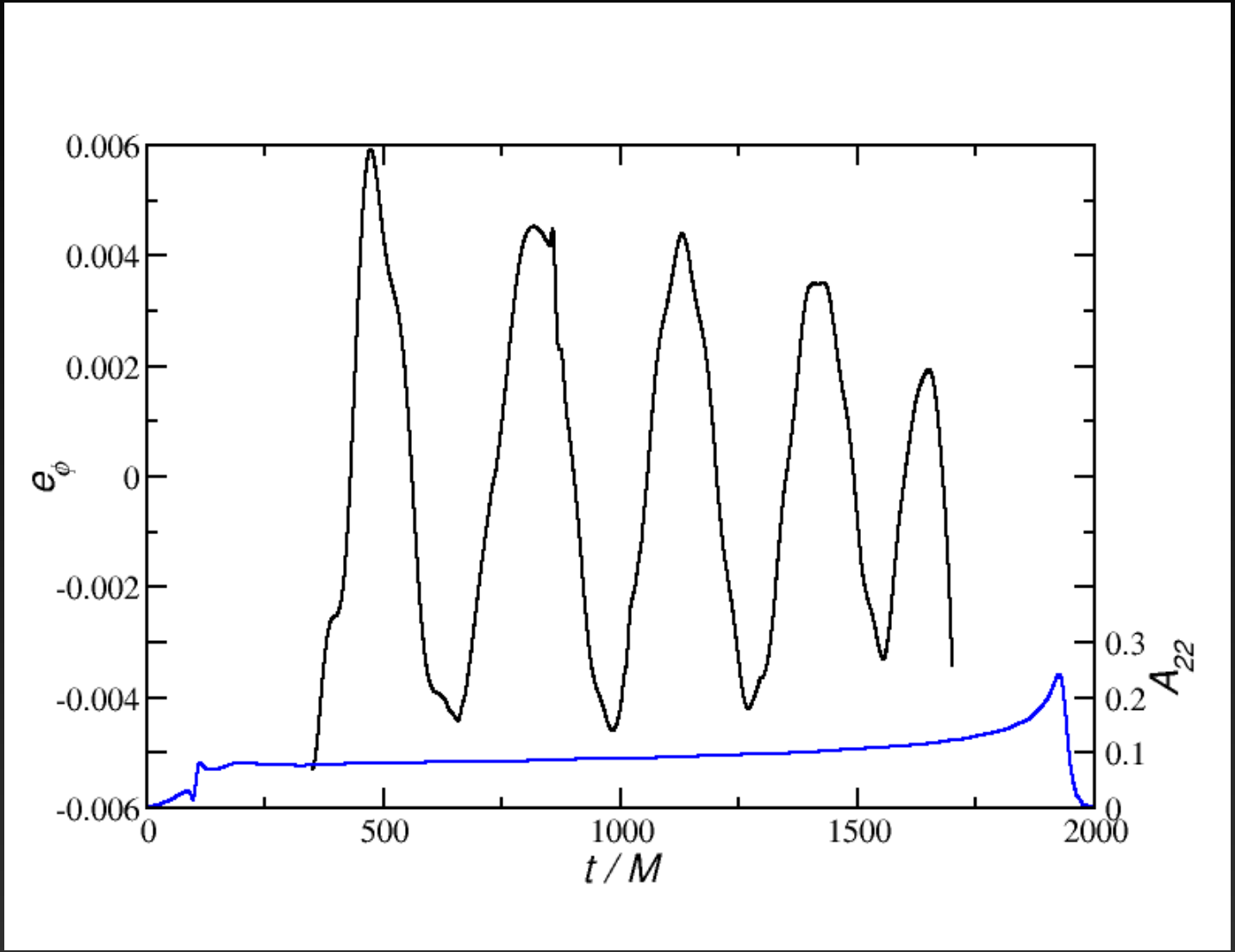
- $h = M/240$
- $\Delta\phi_{22} \lesssim 0.2$ rad
- $\Delta A_{22}/A_{22} \approx 10...1$ %
- little variation in $\Delta\phi$ over $t \approx 250\ M...2000\ M$
- Amplitude errors larger during first orbits, late ringdown

Eccentricity

- Use GW phase of $\ell = 2$, $m = 2$ mode
- $h = M/240$
- $R_{\rm ex} = 96\ M$
- $e_\phi(t) = \frac{\phi_{\rm NR}(t) - \phi_{\rm fit}(t)}{4}$

  Mroué, Pfeiffer, Kidder & Teukolsky (2010)
- Fit $7^{\rm th}$-order polynomial
- Time window: $t = 350...1700\ M$

Eccentricity



PN hybridization

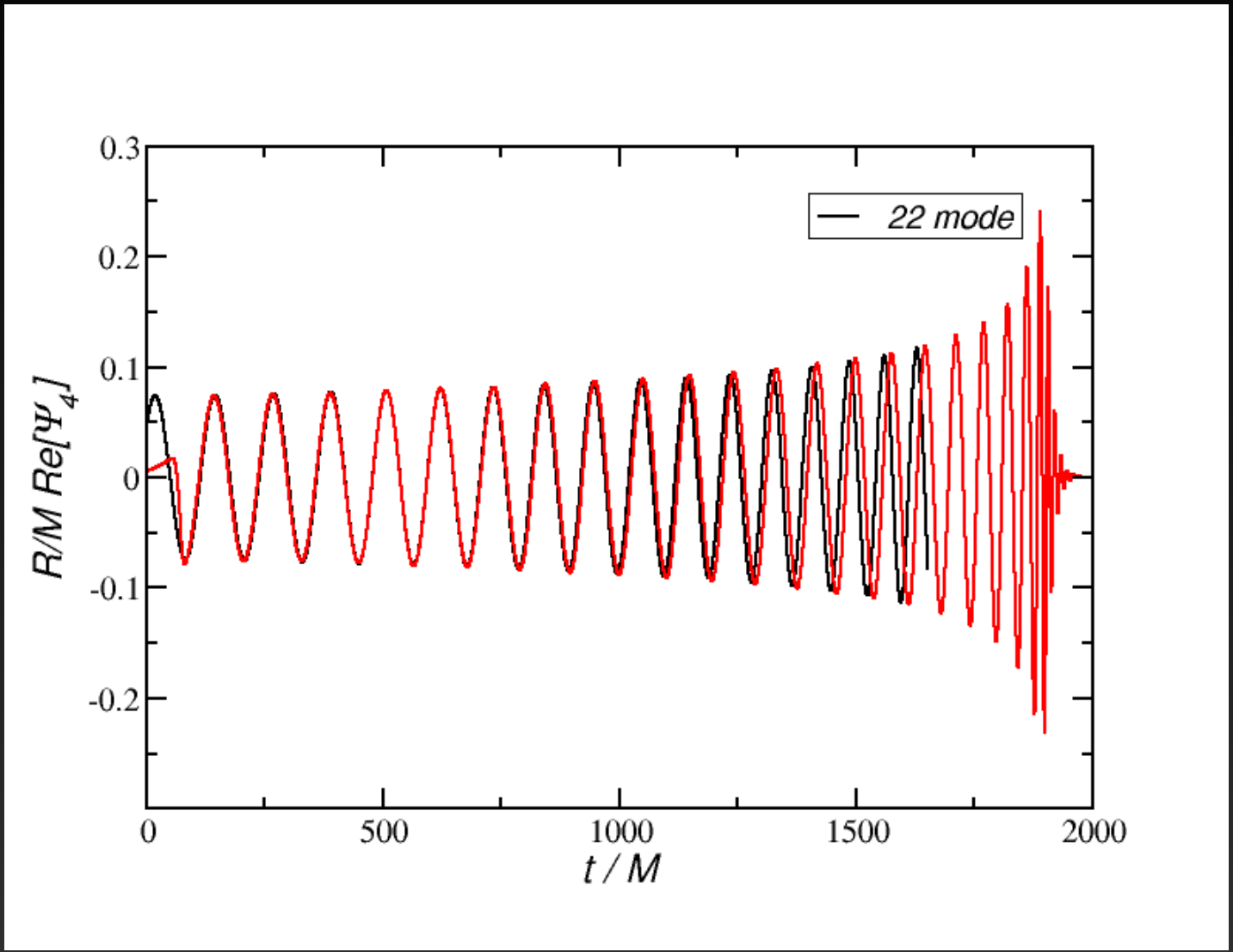
- $\ell = 2$, $m = 2$ and $\ell = 3$, $m = 2$ modes
- $h = M/240$
- Taylor T1, e. g. Boyle *et al.* PRD 76, 124038 (2007)

  Phasing: Blanchet, Liv. Rev. 4, 9 (2006)

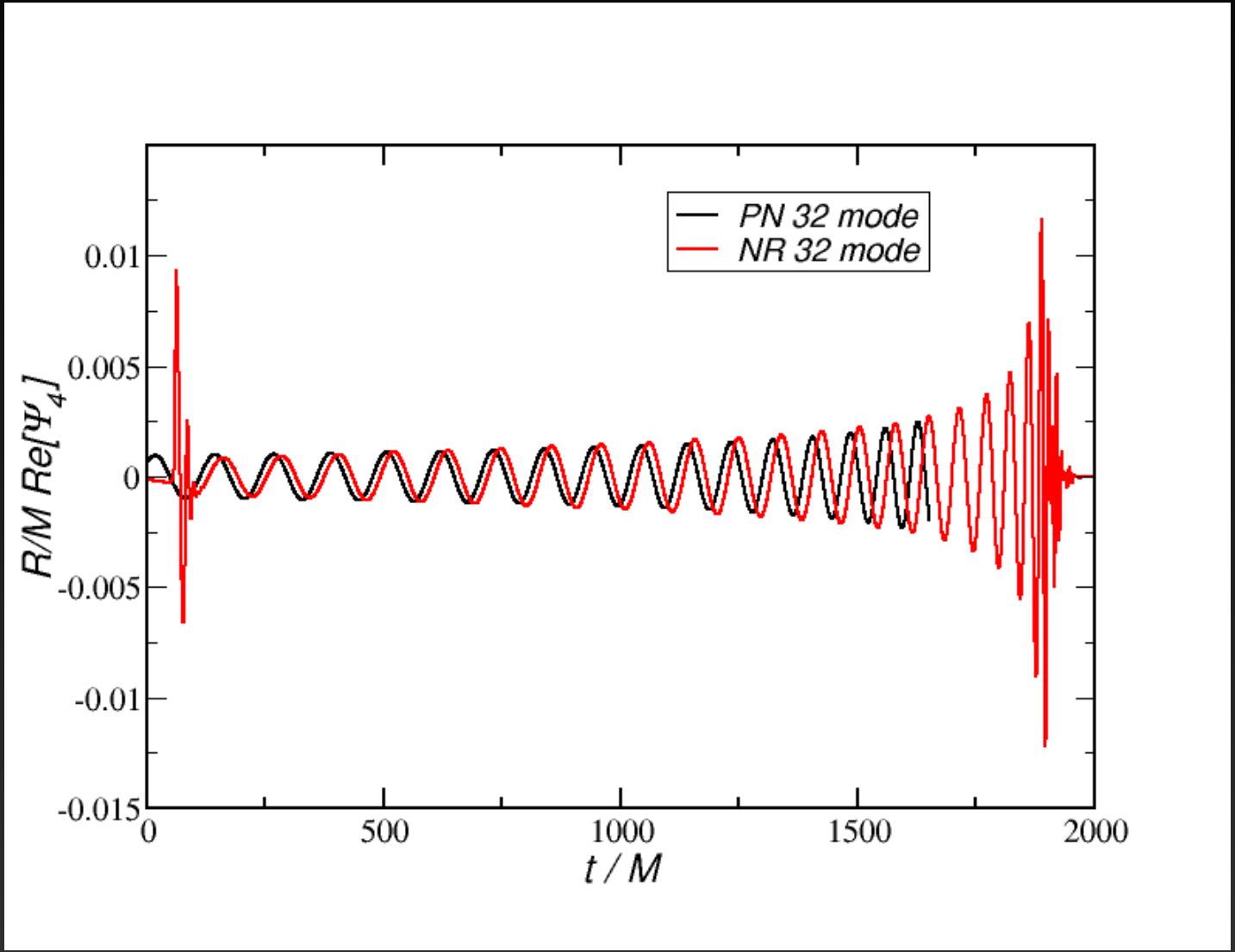
  Amplitudes: Kidder, PRD 77, 044016 (2008)
- Maximize overlap of $\ell = 2$, $m = 2$ multipole using

  Downhill Simplex Method
- Note: This fixes the phase for all modes!
- Time window: $t = 350...700\ M$

$R_{ex} = 56\ M$: PN hybridization $\ell = 2$, $m = 2$



$R_{ex} = 56\ M$: PN hybridization $\ell = 3$, $m = 2$



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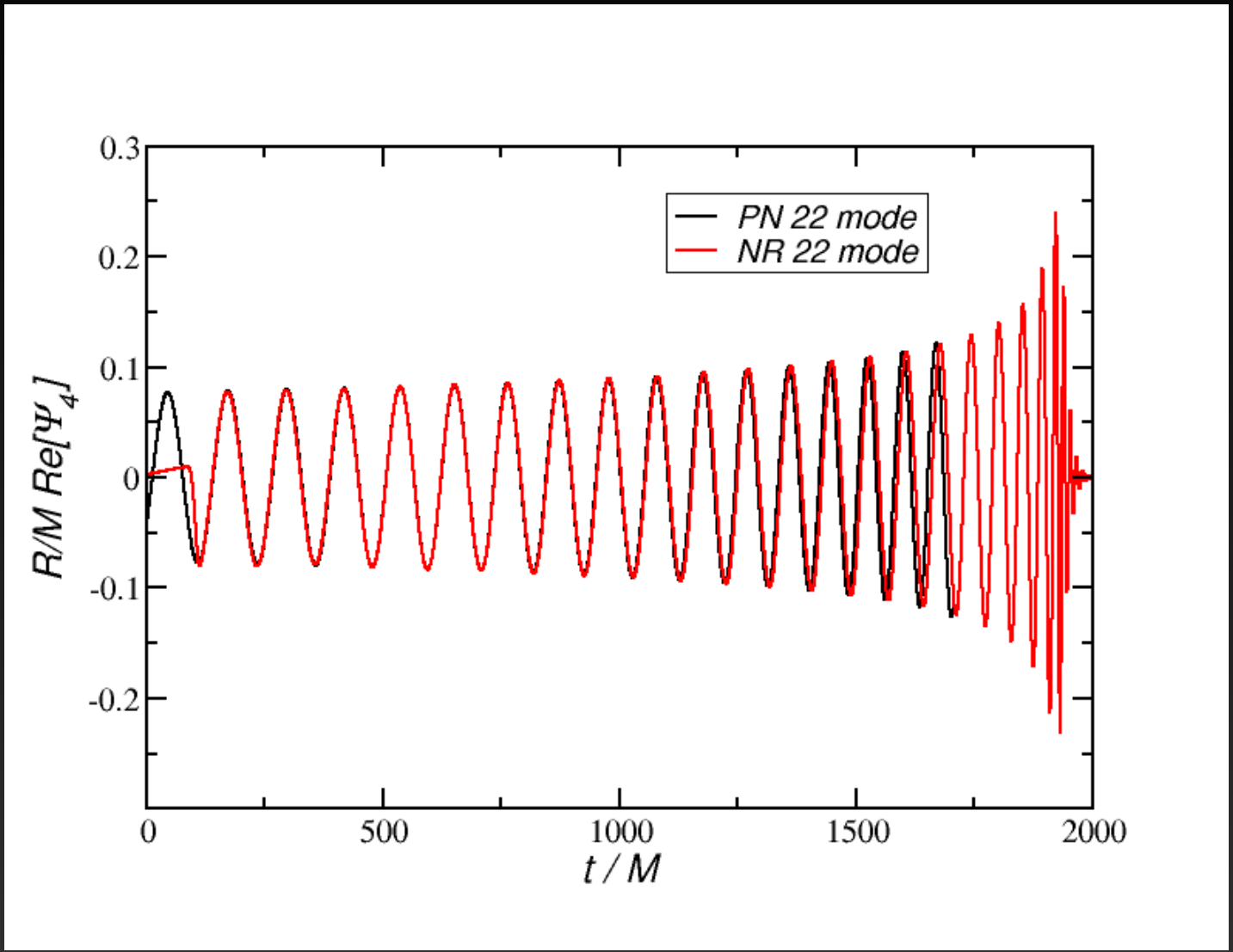

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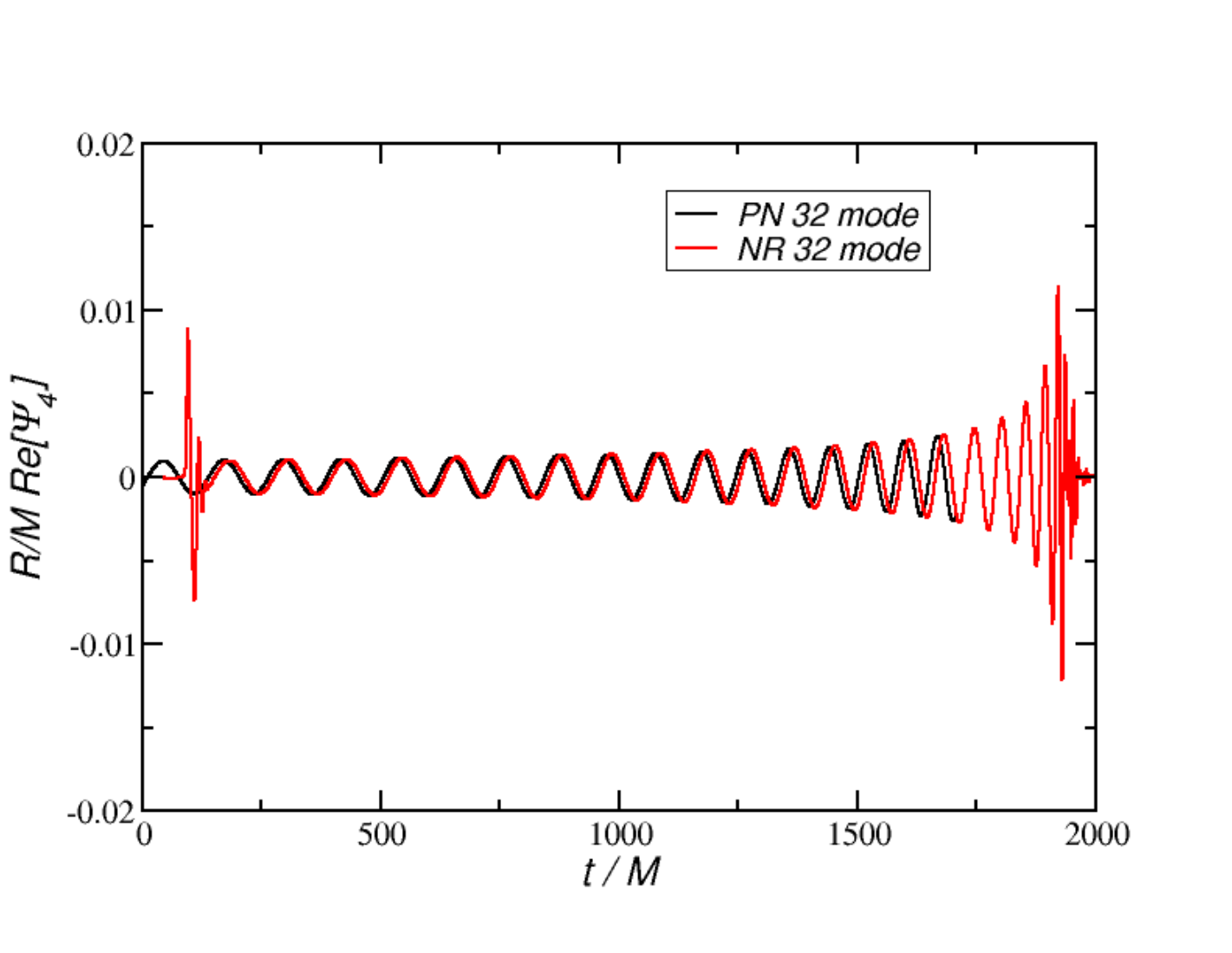
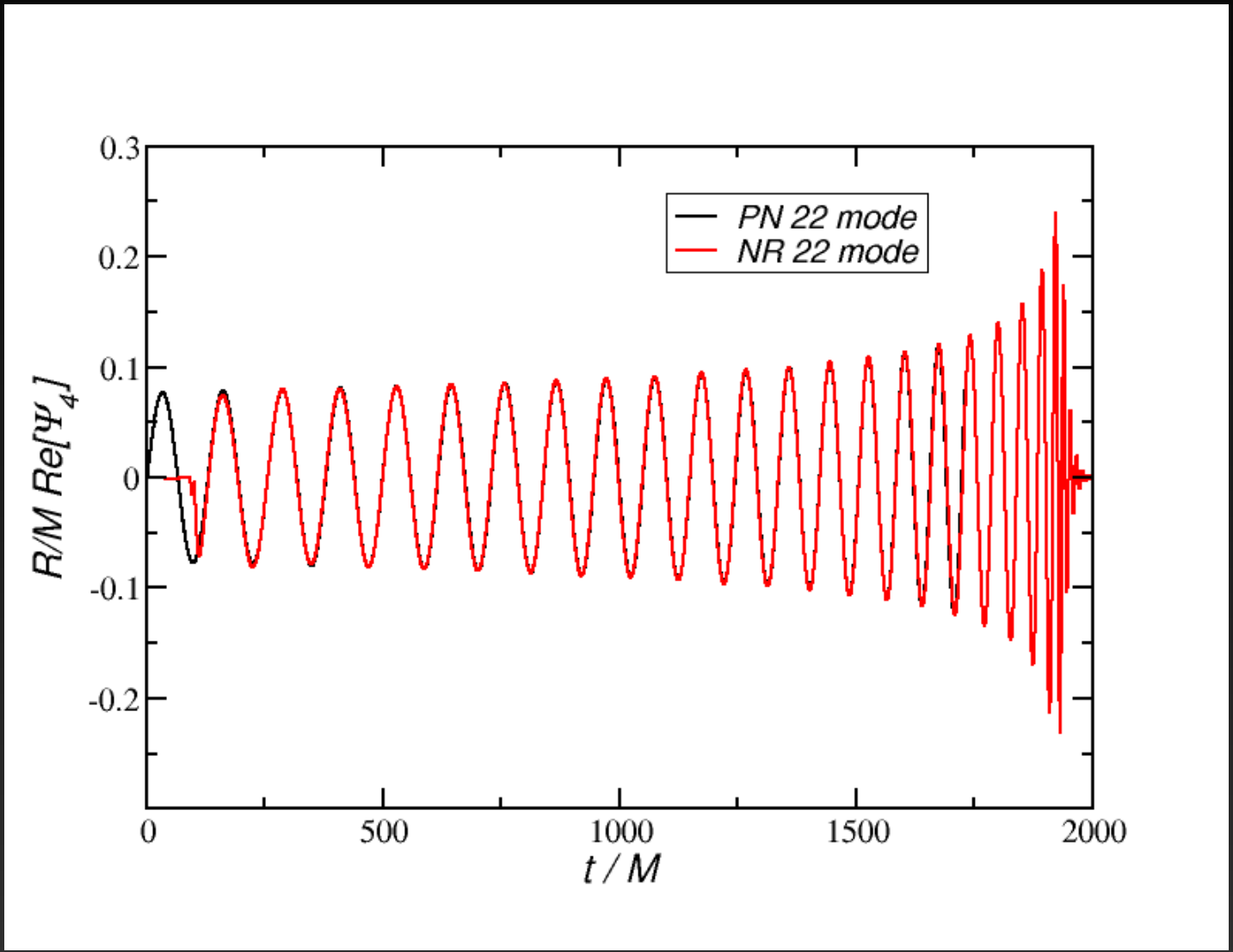


$R_{ex} \to \infty$: PN hybridization $\ell = 2$, $m = 2$



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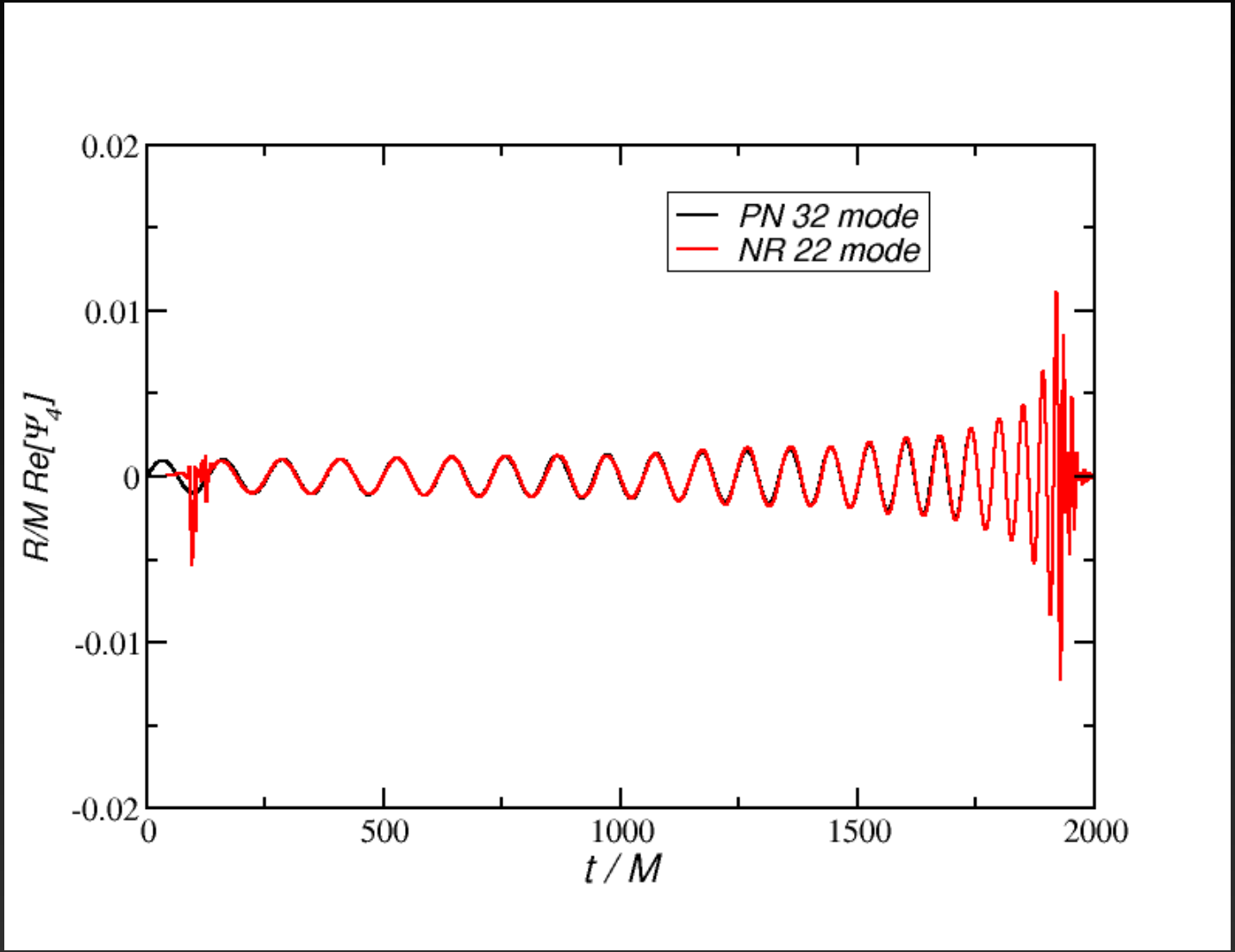


Conclusions

- $q = 4$ binary
- Discretization: $\Delta\phi_{22} \approx 0.2$ rad, $\Delta A_{22}/A_{22} \approx 0.5$ %
- Extraction radius: $\Delta\phi_{22} \lesssim 0.2$ rad, $\Delta A_{22}/A_{22} \approx 10...1$ %
- Eccentricity: $e_\phi \approx 5 \times 10^{-3}$
- Hybridization: xpol $R_{\rm ex} \to \infty$ required for $\ell, \quad m = 2$

Suppression of superkicks

- Numerical Relativity predicts kicks of $\sim 10^3$ km/s
- Larger than escape velocities of even the most massive galaxies
- Galaxies ubiquitously harbor BHs
- How come they are not kicked out in mergers?
- Partial alignment of S_1, L

  Bogdanović *et al.*, ApJ 661, L147 (2007)

  Dotti *et al.*, MNRAS 402, 682 (2010)

- PN evolution from $R = 1000\,M$ on

  Kesden, Sperhake & Berti, PRD 81, 084054 (2010)

  Kesden, Sperhake & Berti, ApJ 715, 1006 (2010)

PN evolution

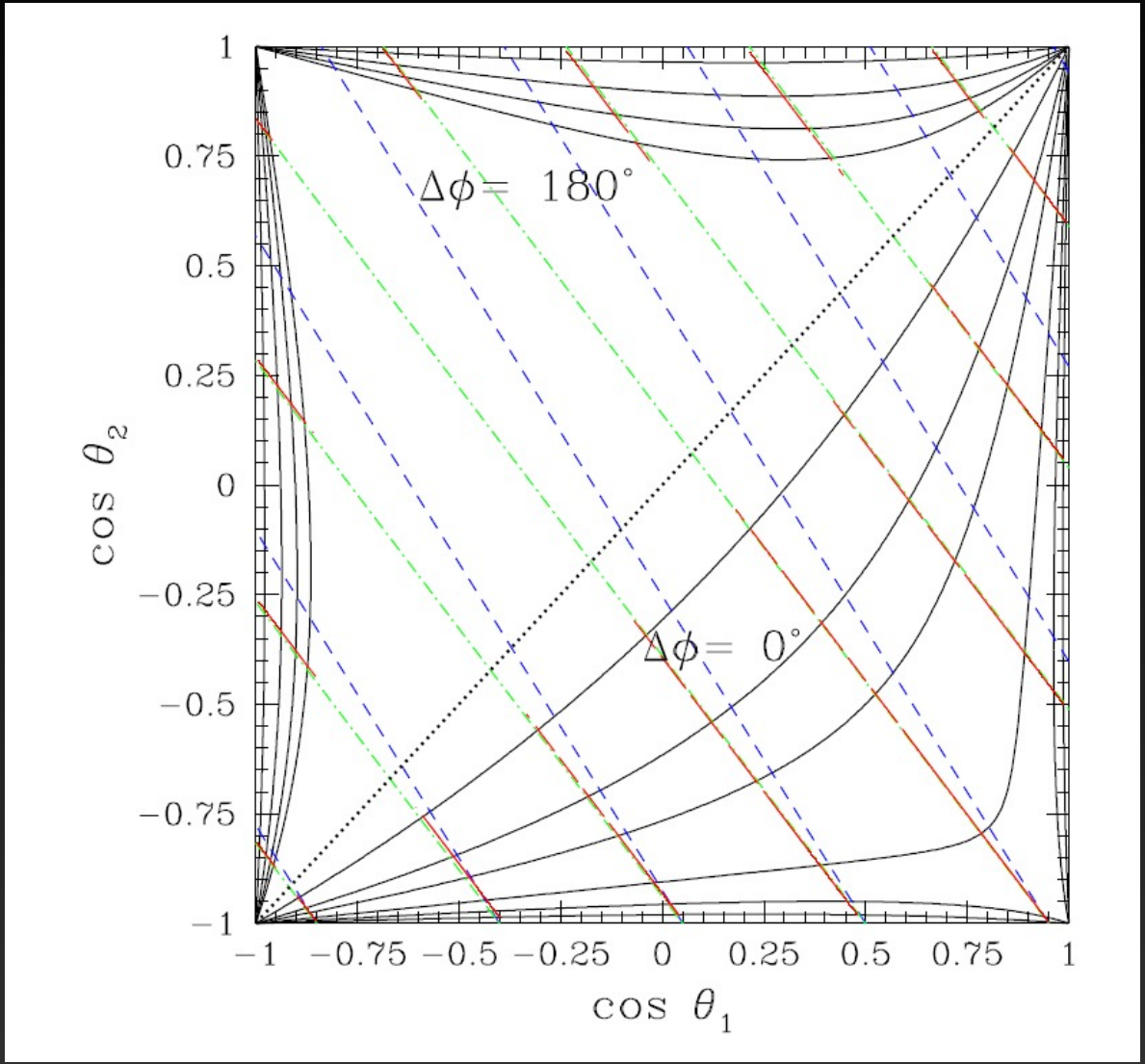
- PN equations of motion for precessing, qc BBHs

  Kidder, PRD 52, 821 (1995)
- Quadrupole-monopole interaction

  Poisson, PRD 57, 5287 (1997)
- Spin-spin interaction

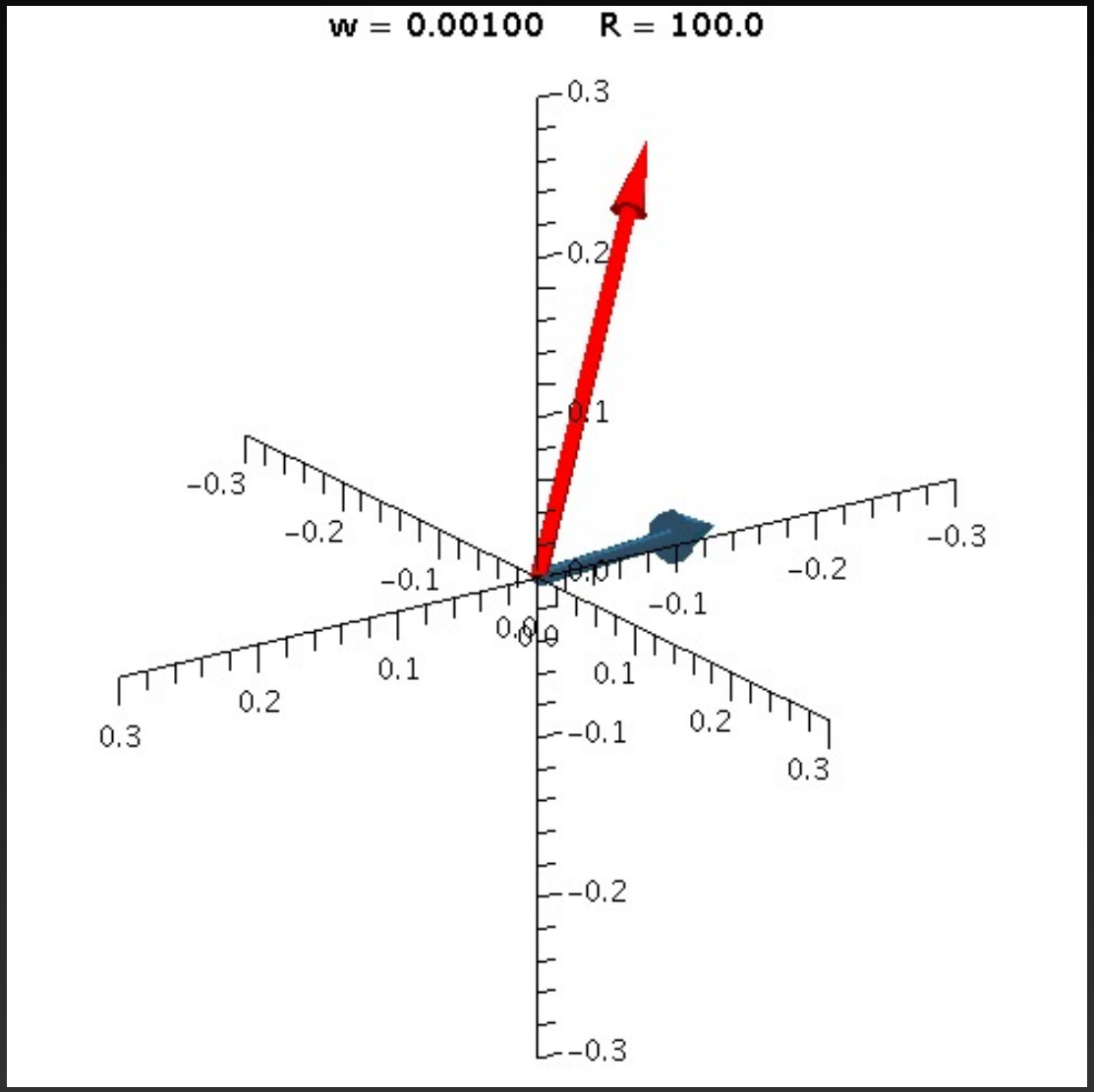
  Mikoczi, Vasuth & Gergely, PRD 71, 124043 (2005)
- Adaptive stepsize integrator StepperDopr5

Evolution in θ_1, θ_2 plane



Time evolution of $\vec{S}_1$, $\vec{S}_2$

$\theta_1 = 10°$, $\theta_2 = 154°$, $\Delta\phi = 264°$



Kick distributions with and without PN inspiral