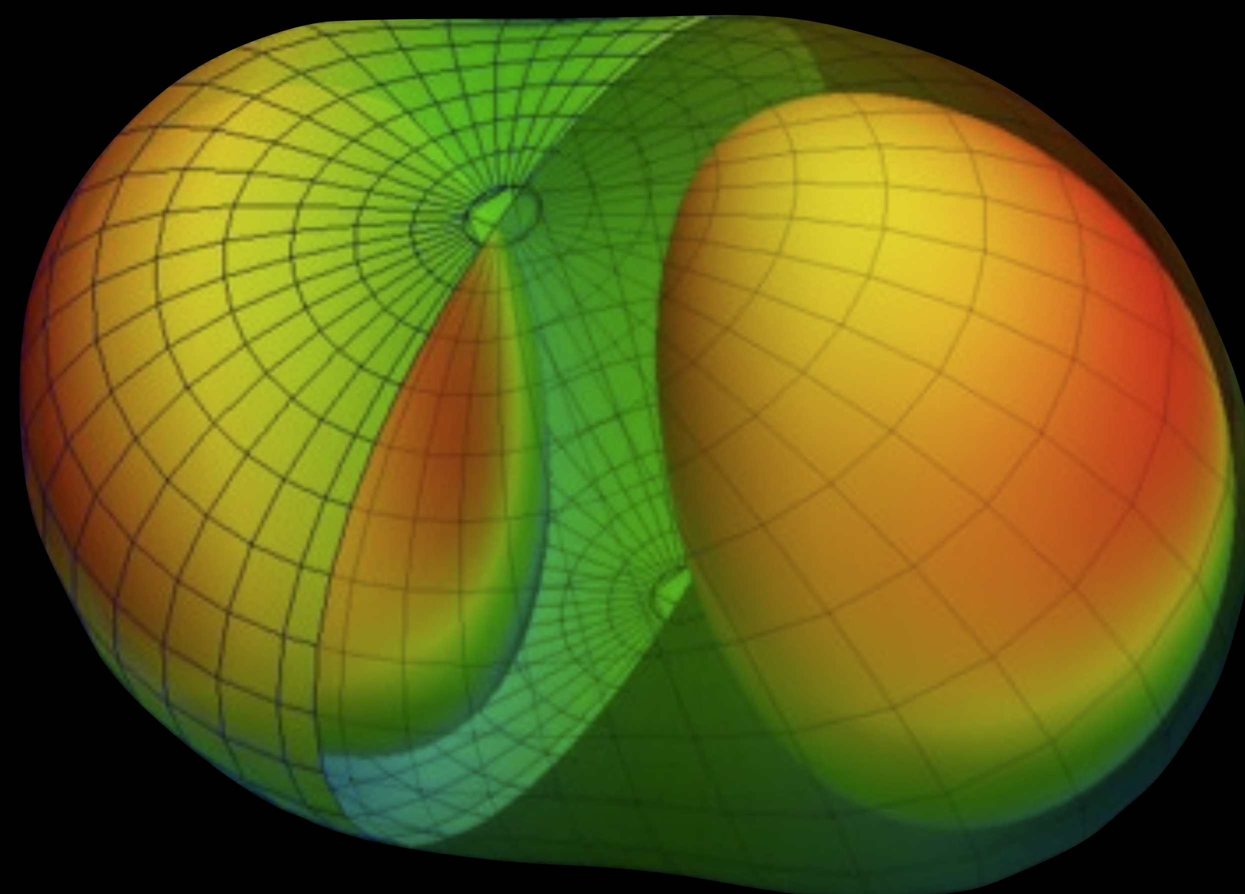
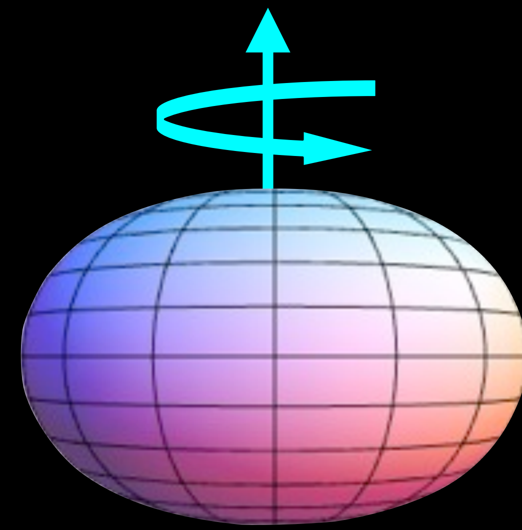
Simulating merging black holes with spins beyond the Bowen-York limit

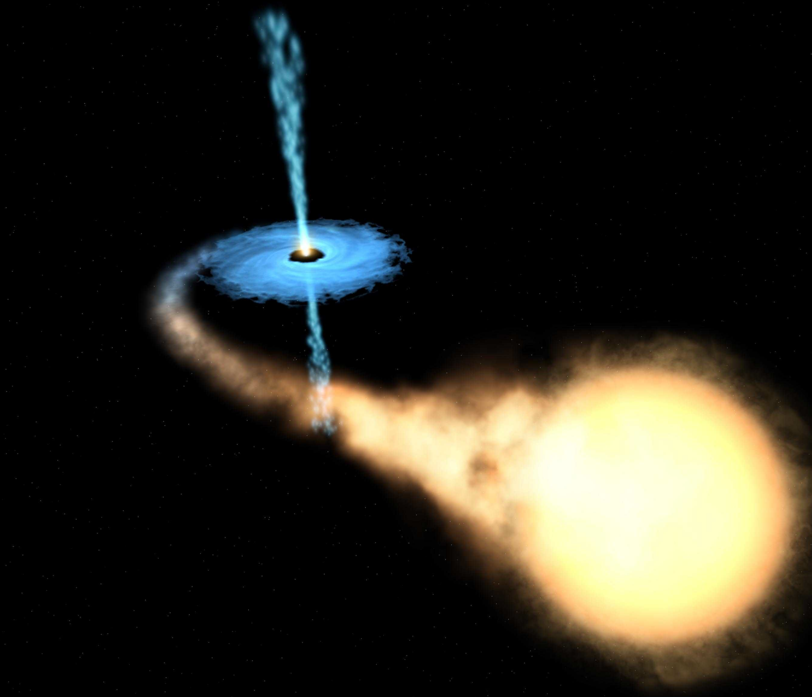


Geoffrey Lovelace (Cornell)
in collaboration with
Mark A. Scheel & Béla Szilágyi (Caltech)
see also arXiv:1010.2771

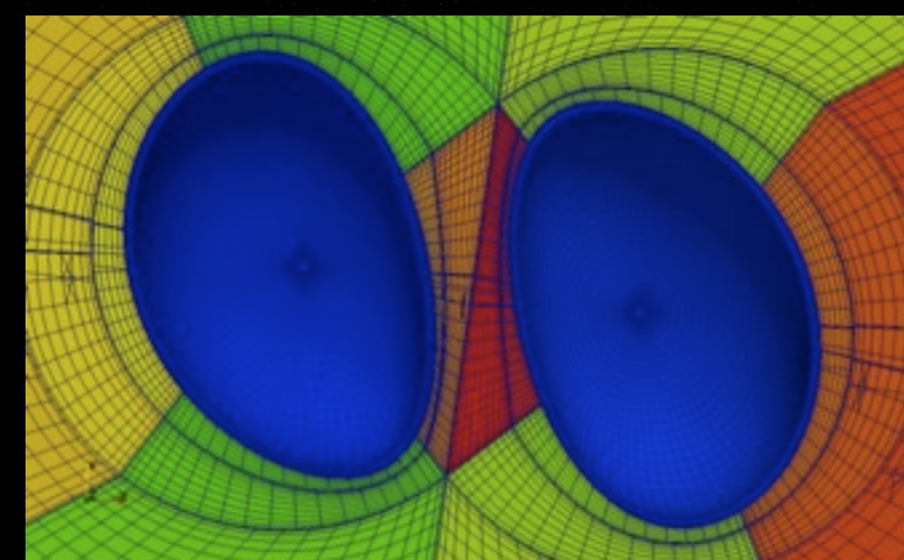
May 21, 2011

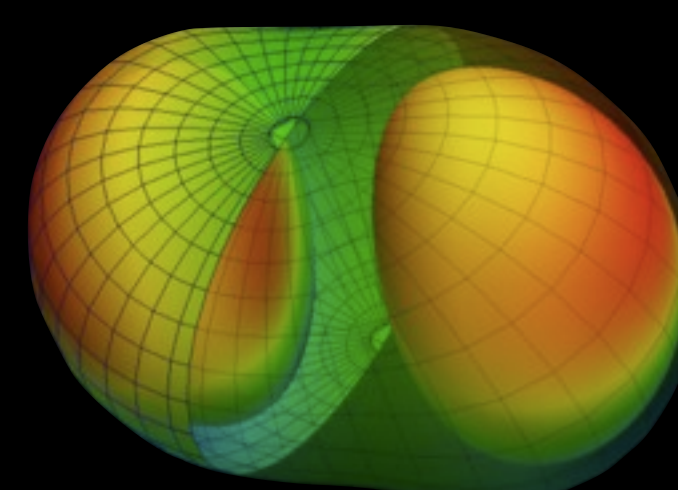
Outline

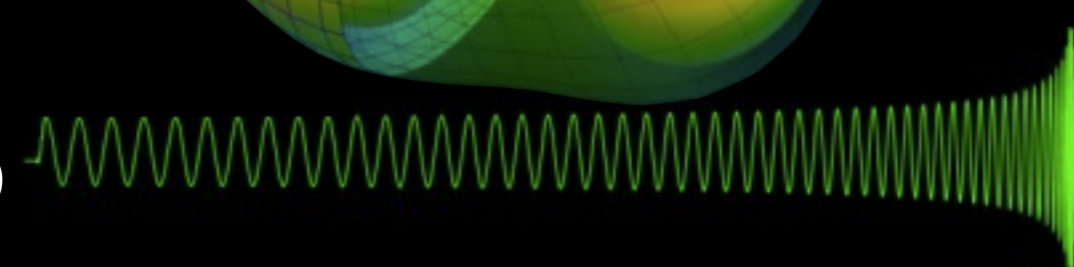




- Black hole spin
- Motivation
  - Astrophysical
  - Physical
- Challenges
  - Initial data
  - Evolution
- Results
  - Black-hole eccentricity, spin
  - Gravitational waveforms
  - Horizon vorticity
  - Extremality & cosmic censorship







Black hole spin

- Dimensionless spin

$$\chi := \frac{S}{M^2}$$

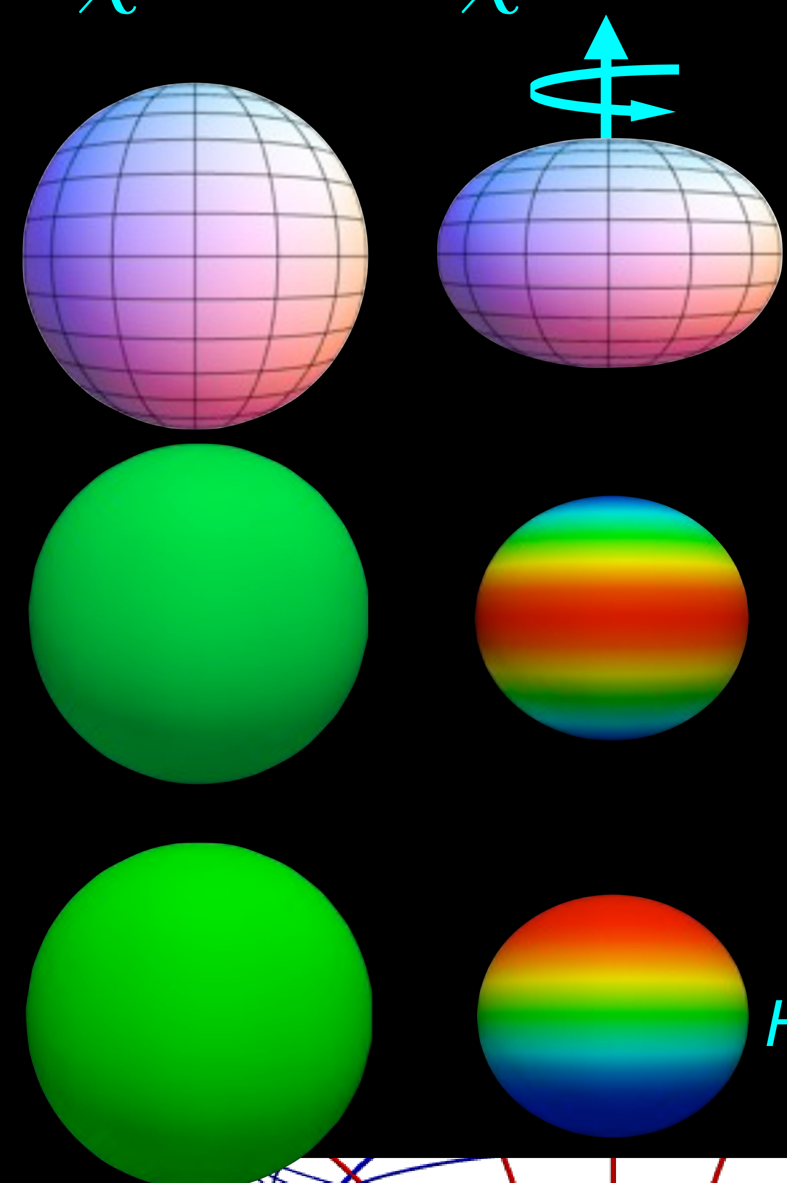
S = spin angular momentum
M = mass

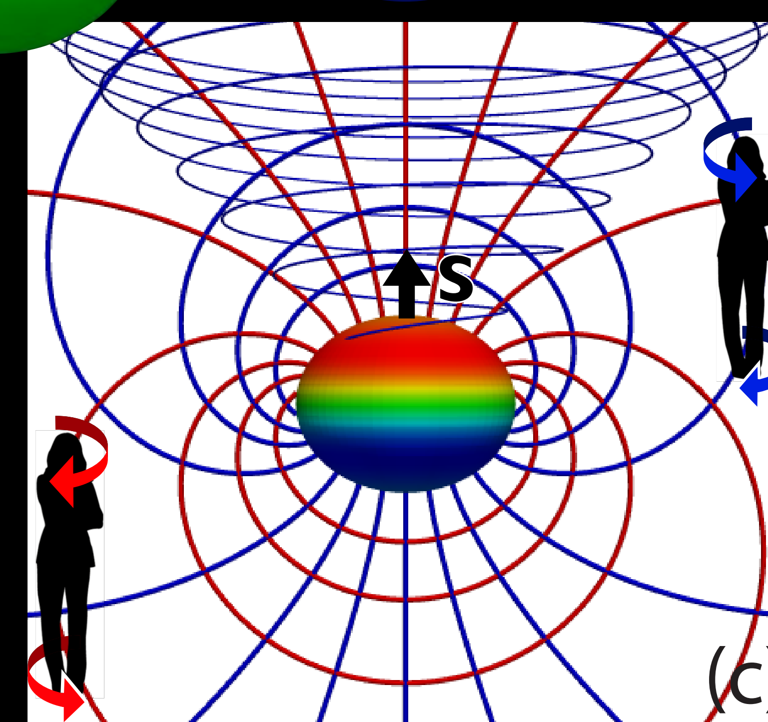
  - Geometrized units: $G = c = 1$
  - Stationary black hole:

$$0 \leq \chi < 1$$

    - Naked singularity if $\chi \geq 1$

- Spacetime geometry
  - Nonspherical horizon
  - Spacetime rotates: gyroscopes precess ("frame dragging")





Introduction

- Astrophysical motivation
  - Black holes could have spins $\chi := \frac{S}{M^2} \sim 1$
    - Accretion models
      e.g. χ ~ 0.998: neglect magnetohydrodynamics - K. S. Thorne (1974)
      χ ~ 0.95: include magnetohydrodynamics - S. L. Shapiro (2005)
    - Observational evidence (uncertain)
      e.g. microquasar GRS 1915+105
      χ > 0.98 - J.E. McClintock et al (2006)
      χ ~ 0.7 - M. Middleton et al (2006)
      see also J. Blum et al (2009) & refs. therein

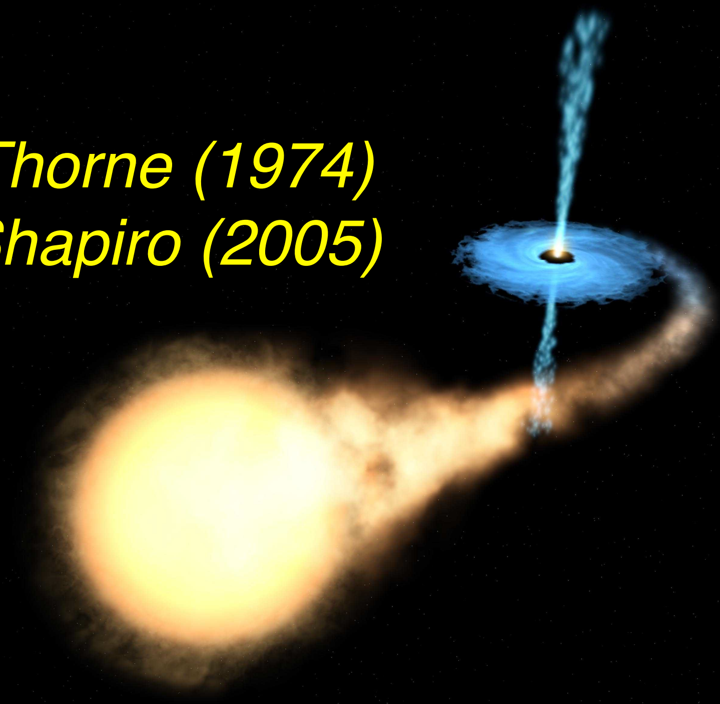
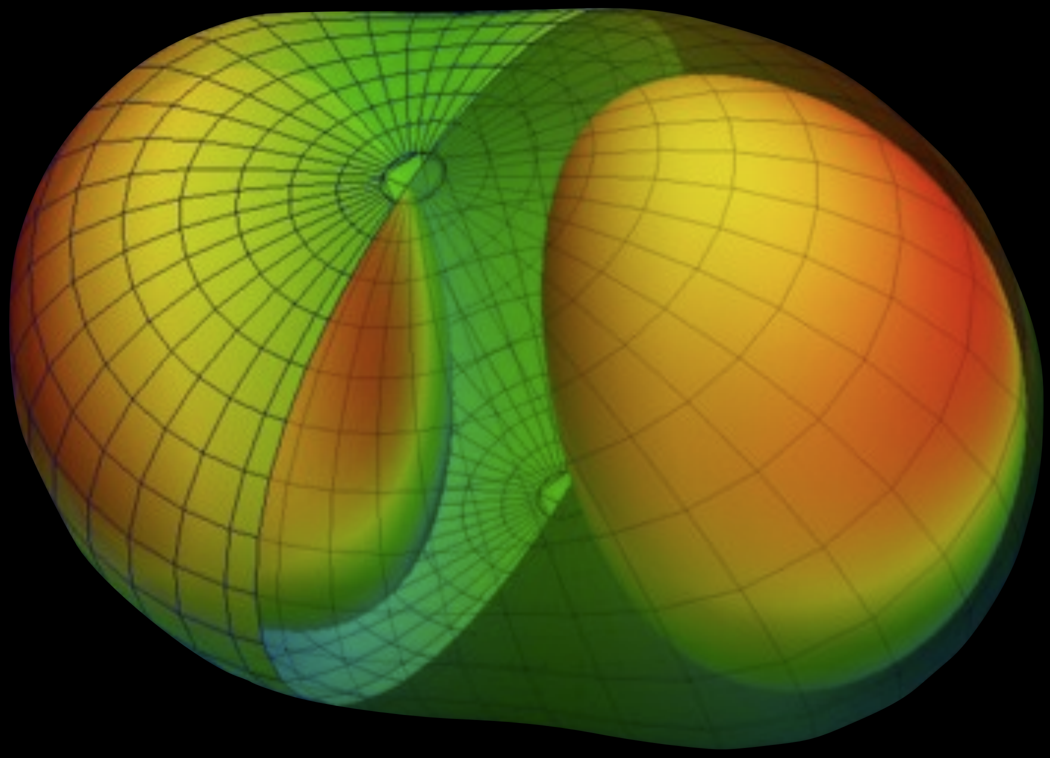


Image courtesy wikipedia

  - Predict gravitational waveforms from binary black holes (BBHs)
    - Calibrate analytic waveform models
      - Stellar-mass (ground detectors)
      - Supermassive (space detectors)
  - Final hole's mass, spin, recoil

Image courtesy www.ligo.caltech.edu

Introduction



- Physical motivation
  - Explore general relativity at its most extreme
    - Nonlinear behavior of strongly-warped spacetime
      For details, see R. Owen et al (2011), cf. M. Scheel's talk this morning
      - E.g. vorticity ("twisting") and tendicity ("stretching/squeezing") on and above horizon
  - Extremality & cosmic censorship
    - Stationary holes: naked singularity if $\chi \geq 1$
    - Superextremal dynamical black holes?

Initial data

- Must satisfy constraints

Maxwell

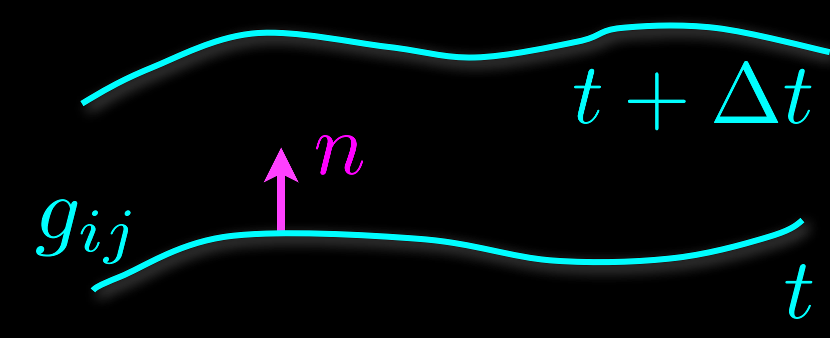
$\nabla \cdot E = 0$

$\nabla \cdot B = 0$

Einstein

$G_{nn} = 0$

$G_{nj} = 0$



  – Conformally flat: $g_{ij} \propto f_{ij}$

    - E.g. Bowen-York data: solve analytically $G_{nj} = 0$

      J. M. Bowen (1979), J. M. Bowen & J. W. York, Jr. (1980)

    - Can't make equilibrium spinning black holes

      Garat & Price (2000)

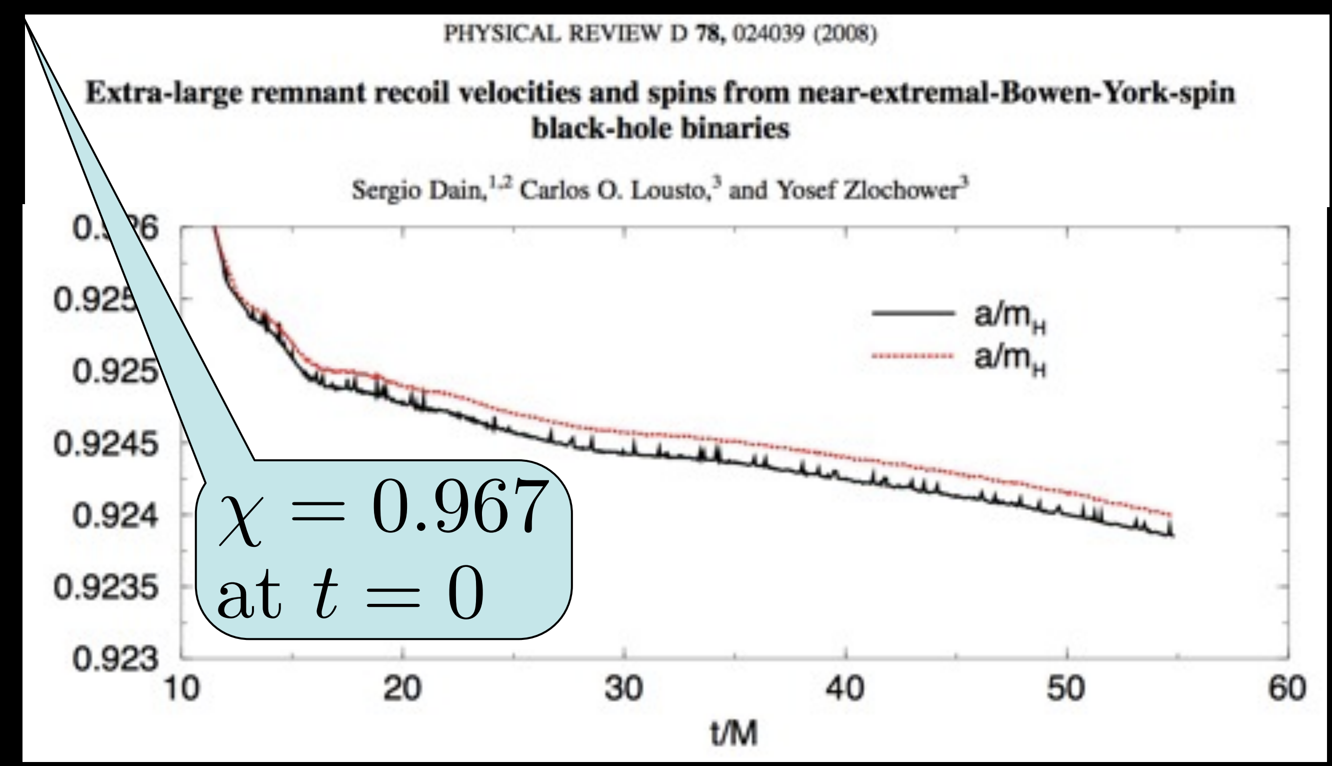
    - Binaries: Spins $\chi < 0.93$

$\chi = 0.8$ *L. Rezzolla et al (2008)*

$\chi = 0.9$ *P. Marronetti et al (2008)*

$\chi = 0.925$ *S. Dain, C. O. Lousto, & Y. Zlochower (2008)* →

$\chi = 0.85$ *M. Hannam et al (2010)*


PHYSICAL REVIEW D **78,** 024039 (2008)

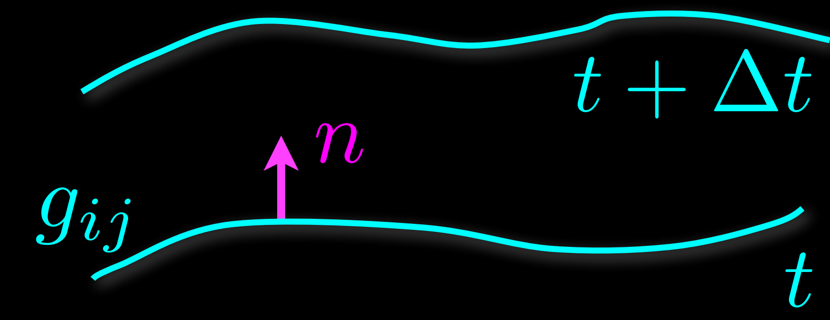
Extra-large remnant recoil velocities and spins from near-extremal-Bowen-York-spin black-hole binaries

Sergio Dain,[1,2] Carlos O. Lousto,[3] and Yosef Zlochower[3]

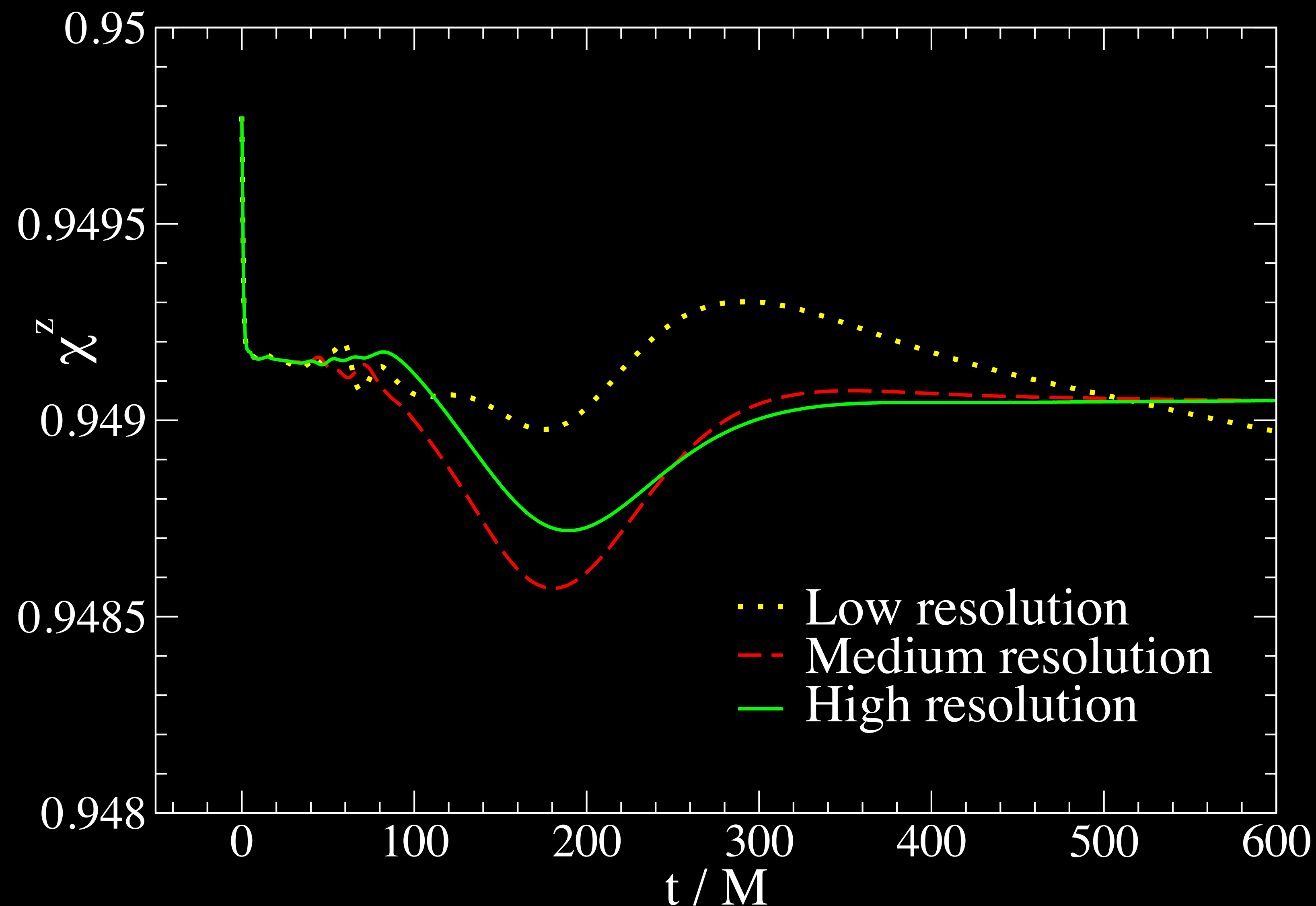
Initial data

- Must satisfy constraints

Maxwell	*Einstein*
$\nabla \cdot E = 0$	$G_{nn} = 0$
$\nabla \cdot B = 0$	$G_{nj} = 0$



  – Superposed-Kerr-Schild
    GL, R. Owen, H. P. Pfeiffer, & T. Chu (2008)
    - Must solve all (coupled) constraint equations

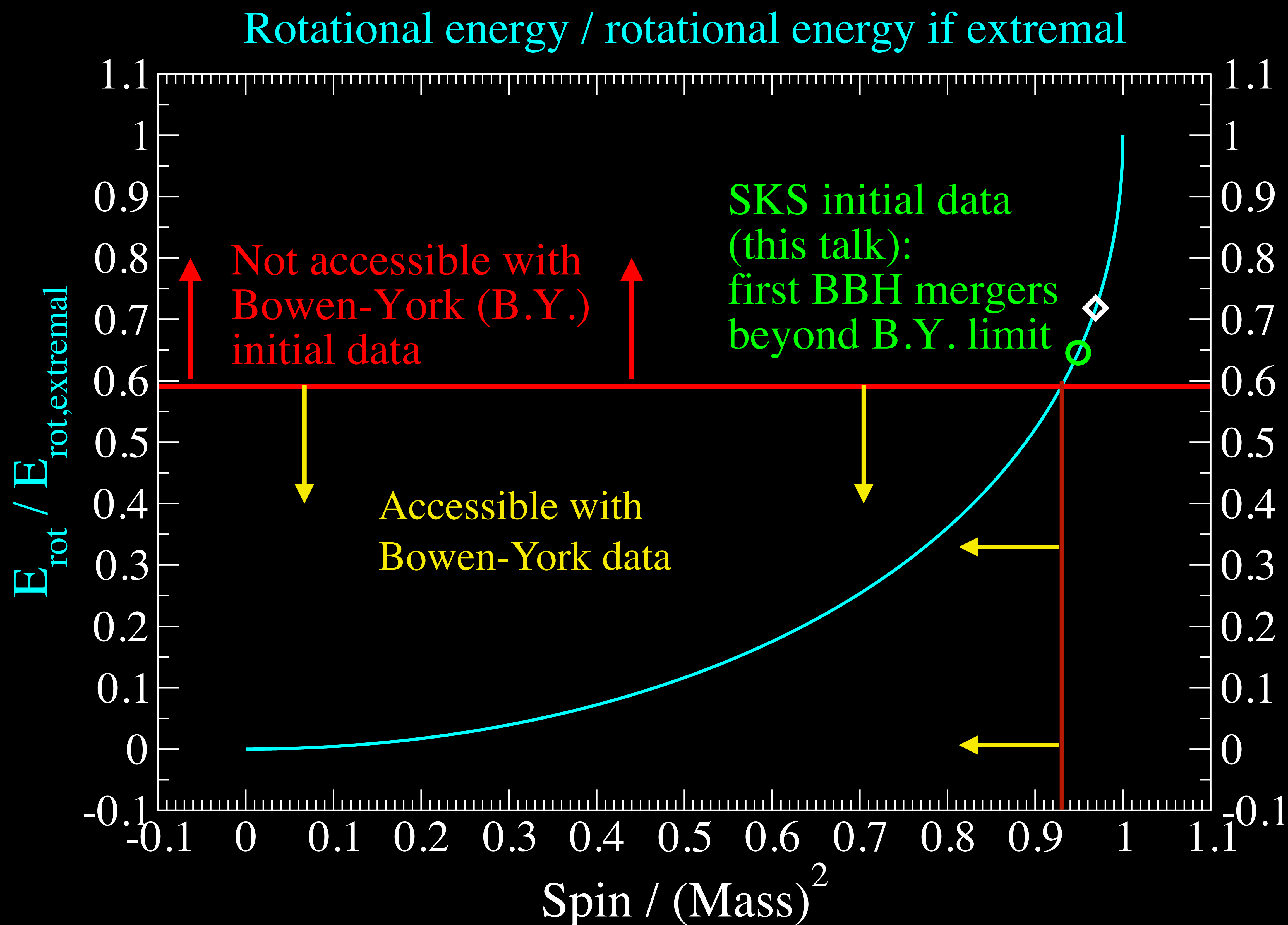


$$g_{ij} \propto f_{ij} + \sum_{n=1}^{2} \left(h^n_{ij} - f_{ij}\right) e^{-r_n^2/w_n^2}$$

Metric of a boosted, spinning hole

Conformally flat except near horizons

Initial data



Evolution

- For high accuracy: spectral methods
  - Require more resolution near merger

    use spectral adaptive mesh refinement

    For details, cf. talk yesterday by B. Szilágyi
    - Adjust resolution as needed
  - Need smooth, finite solution
    - Excise singularity
    - Grid coords. comove with holes
    - Map between grid & asymptotically inertial coords.

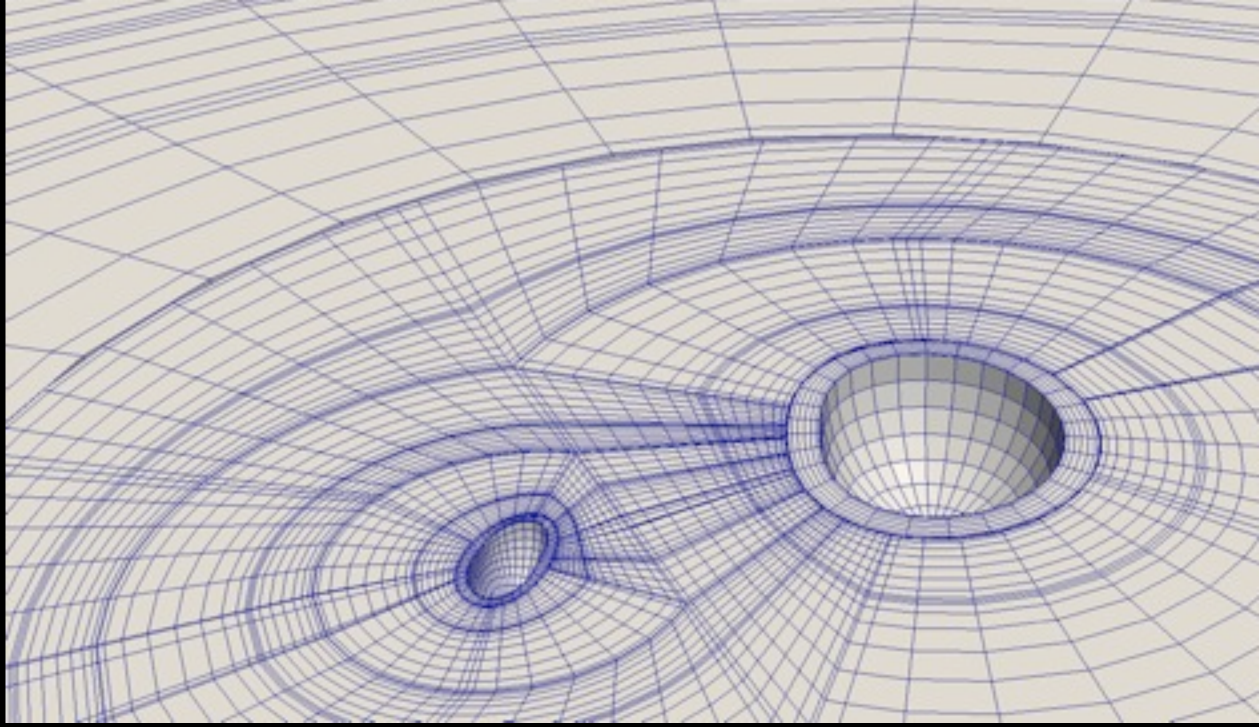
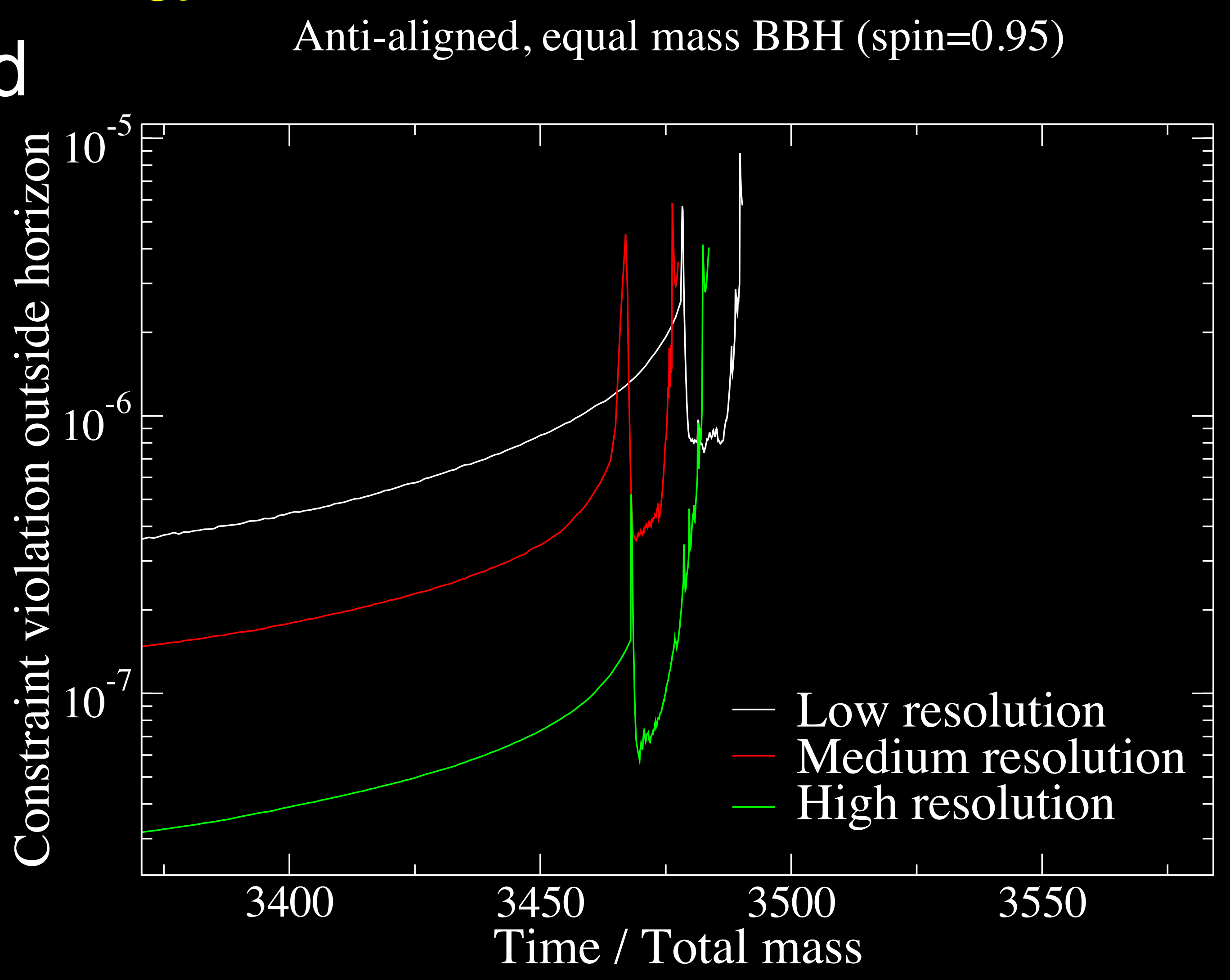
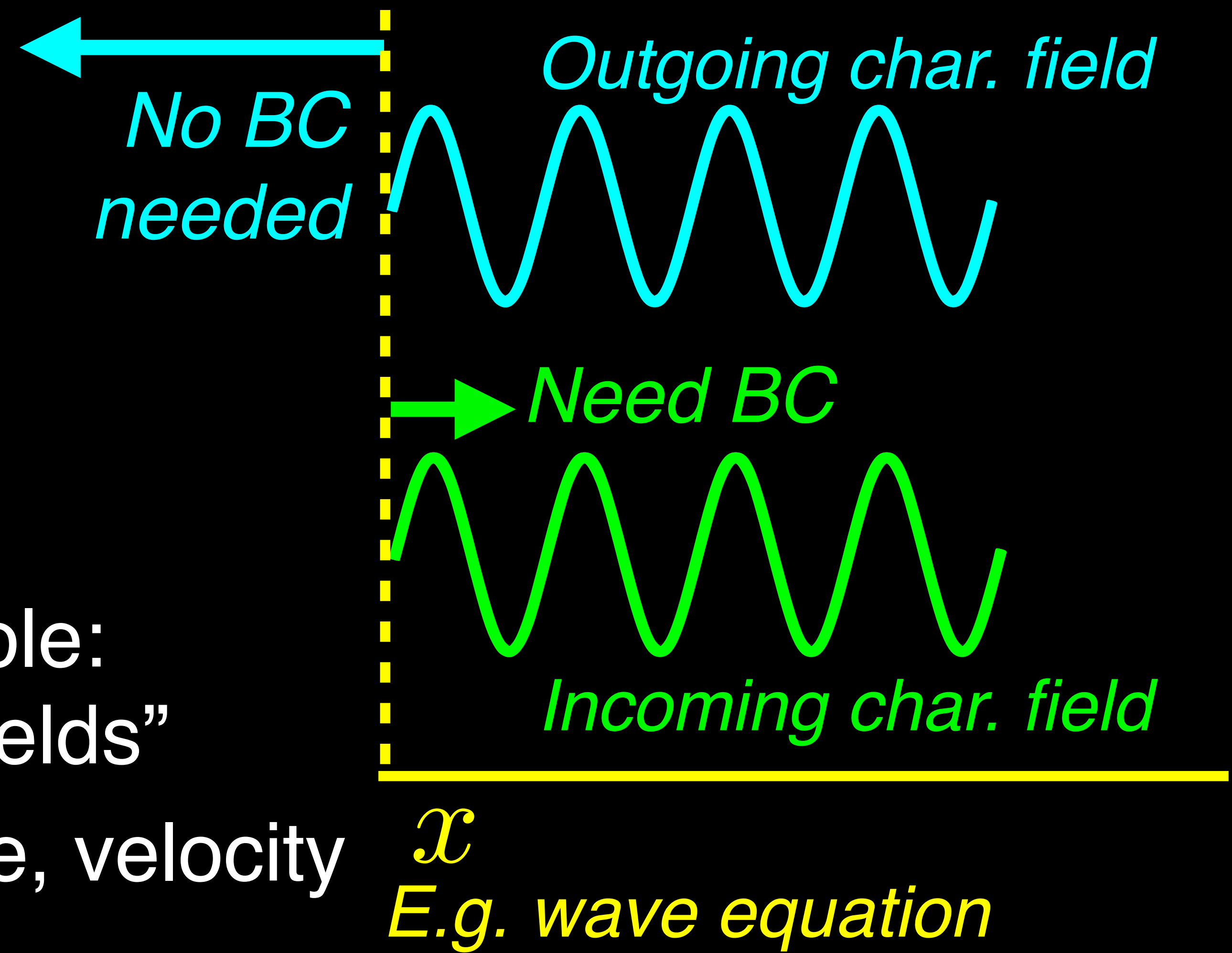


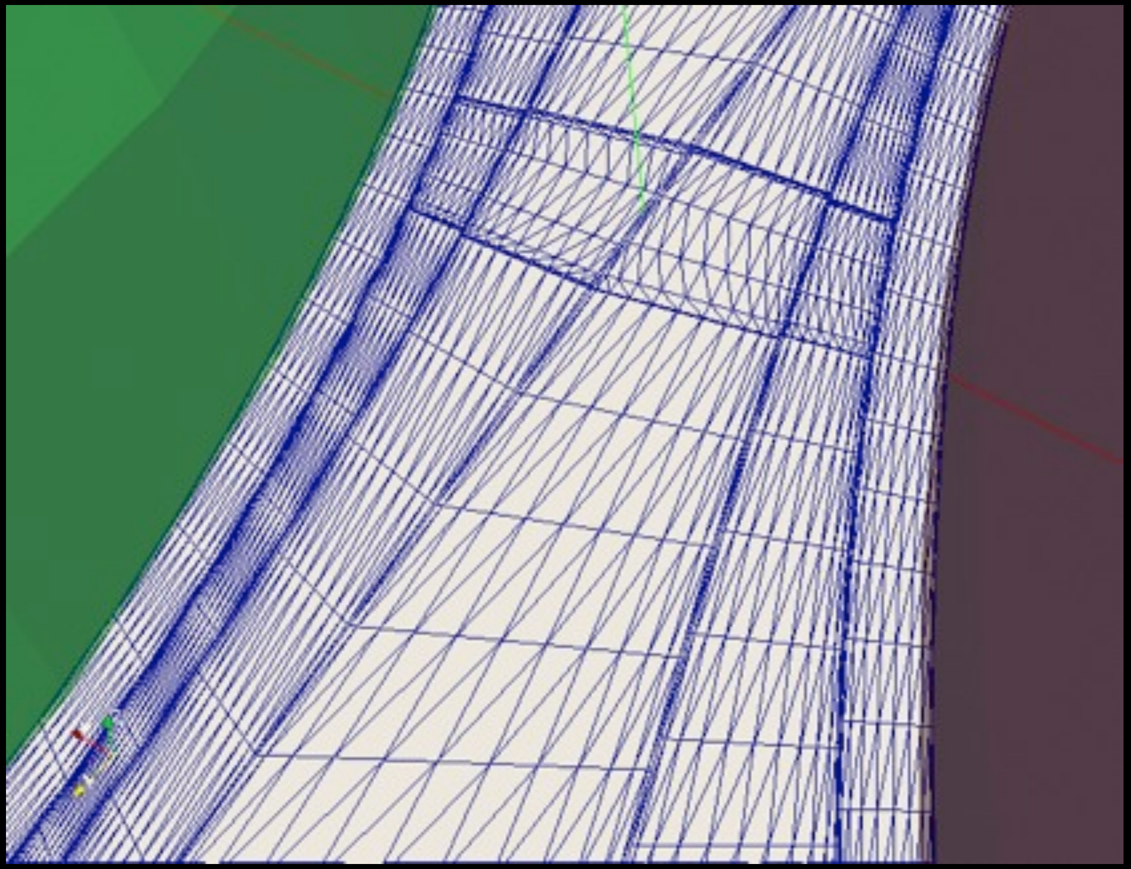
Figure courtesy Béla Szilágyi

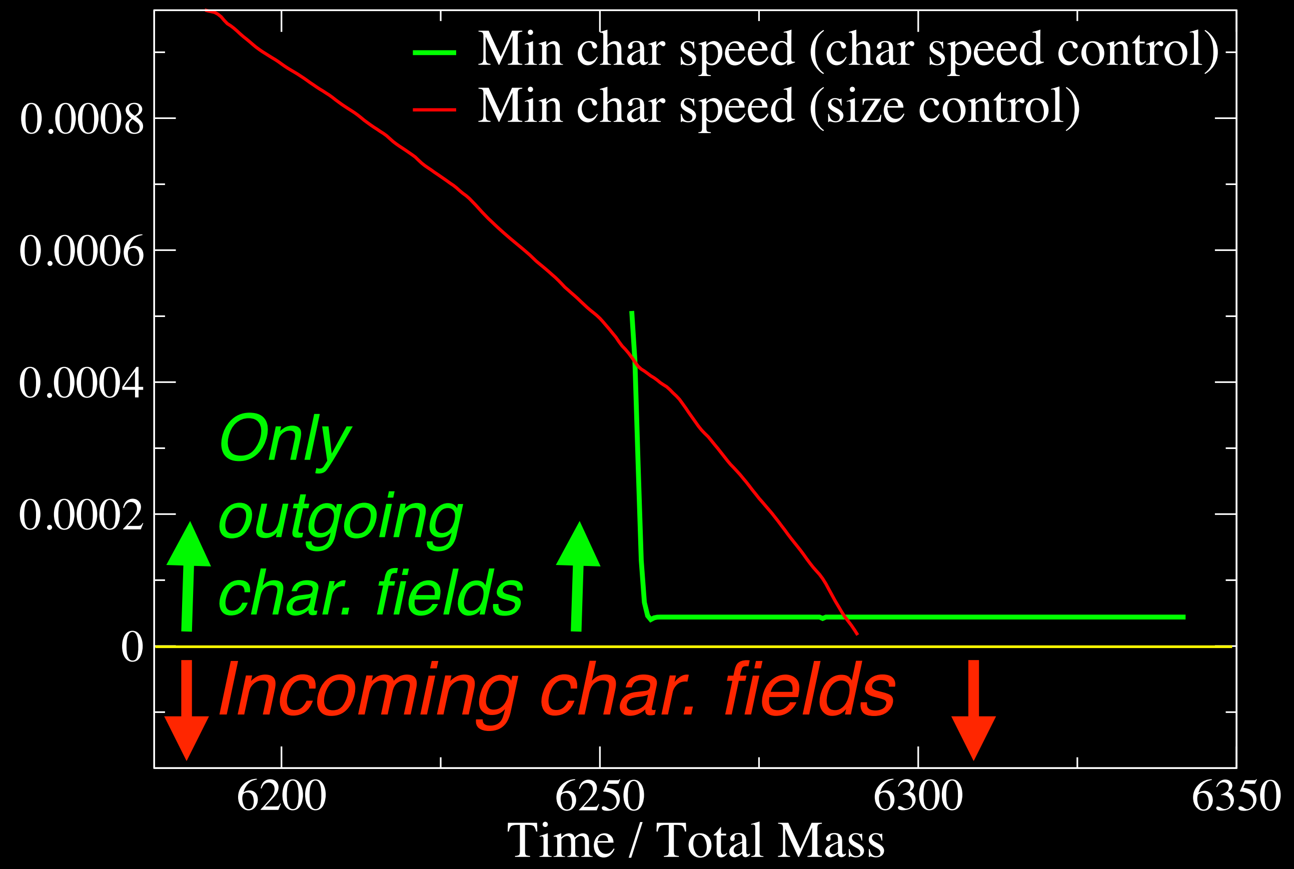


Excision with high spins

- Excision surface
  - Must be inside horizon
  - No boundary condition (BC)
    - OK if all info goes down the hole: “only outgoing characteristic fields”
    - Control excision surface shape, velocity







Results

$\chi_A = \chi_B = -0.95\mathbf{e}_z$

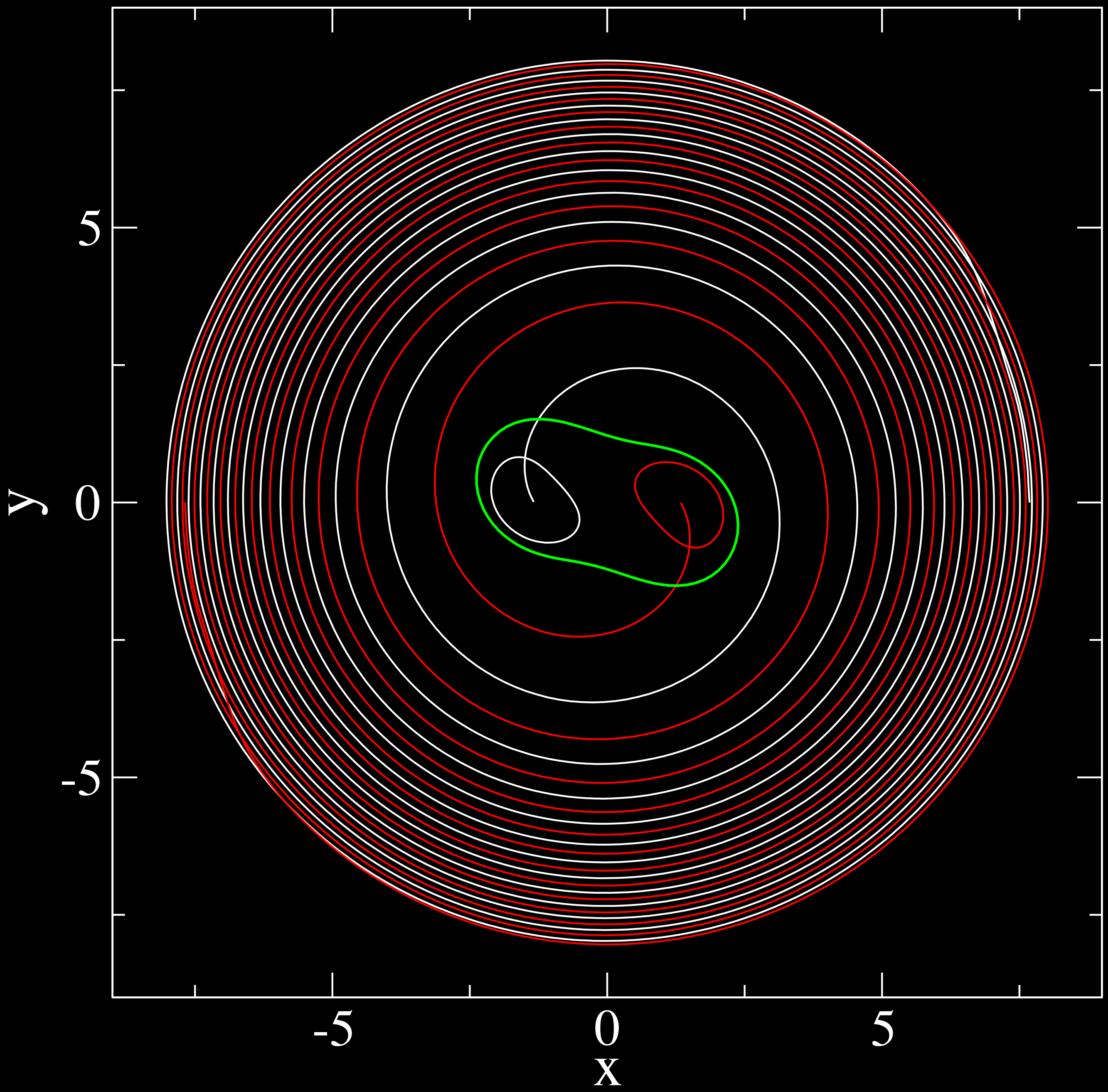
12.5 orbits

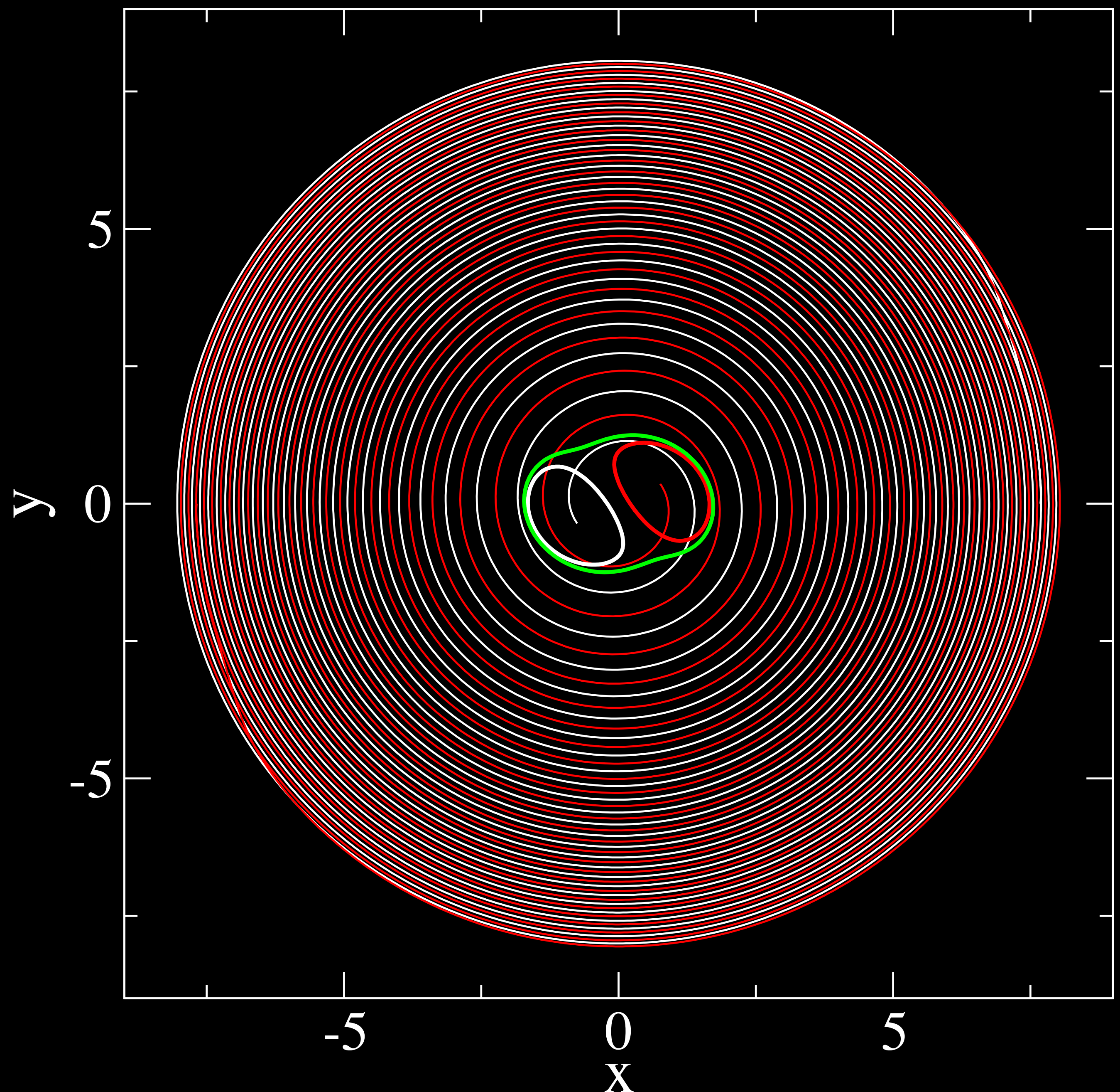
$\chi_{\text{final}} = +0.3757$

$\chi_A = \chi_B = +0.97\mathbf{e}_z$

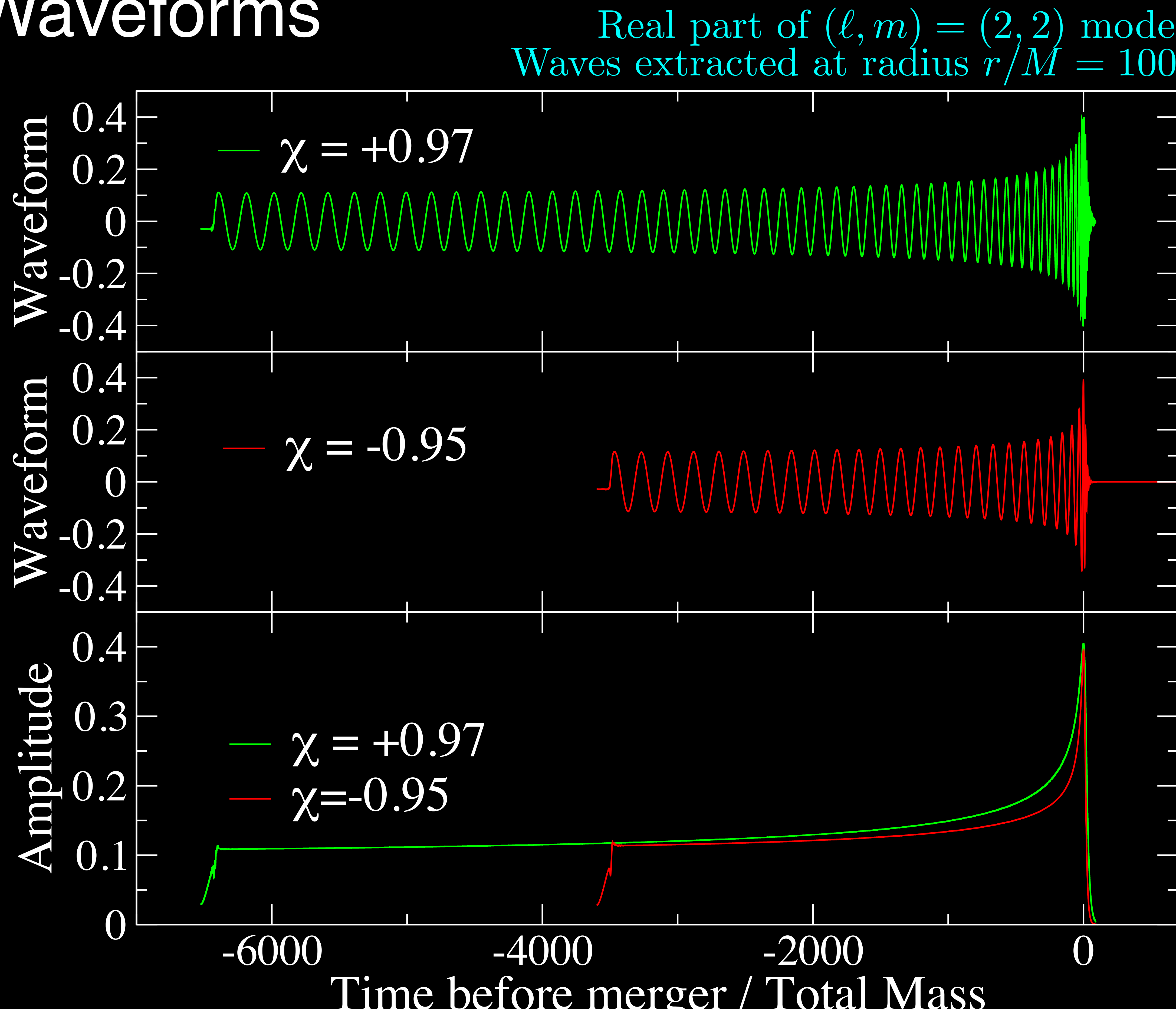
25.5 orbits

$\chi_{\text{final}} \approx +0.945$



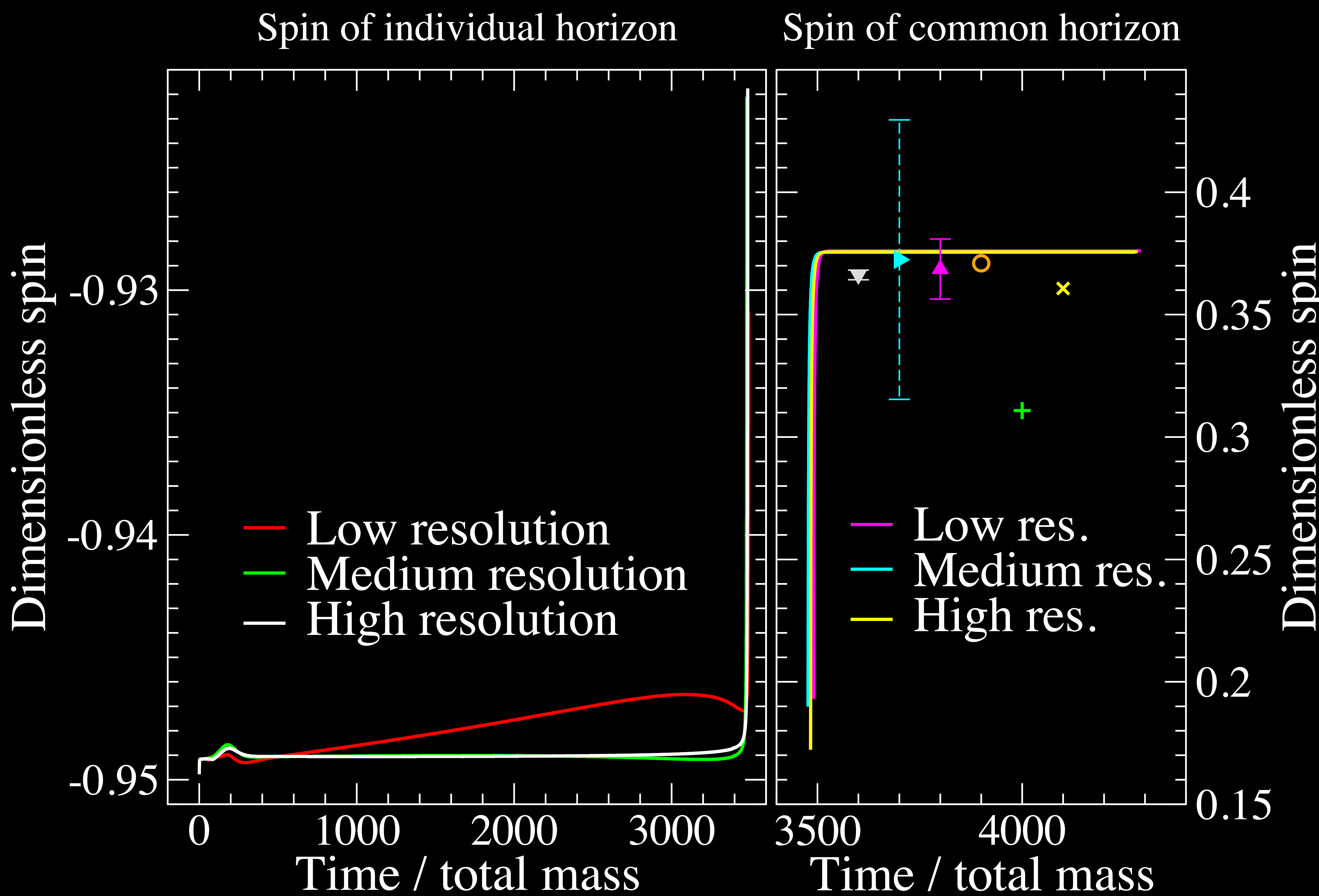


Waveforms



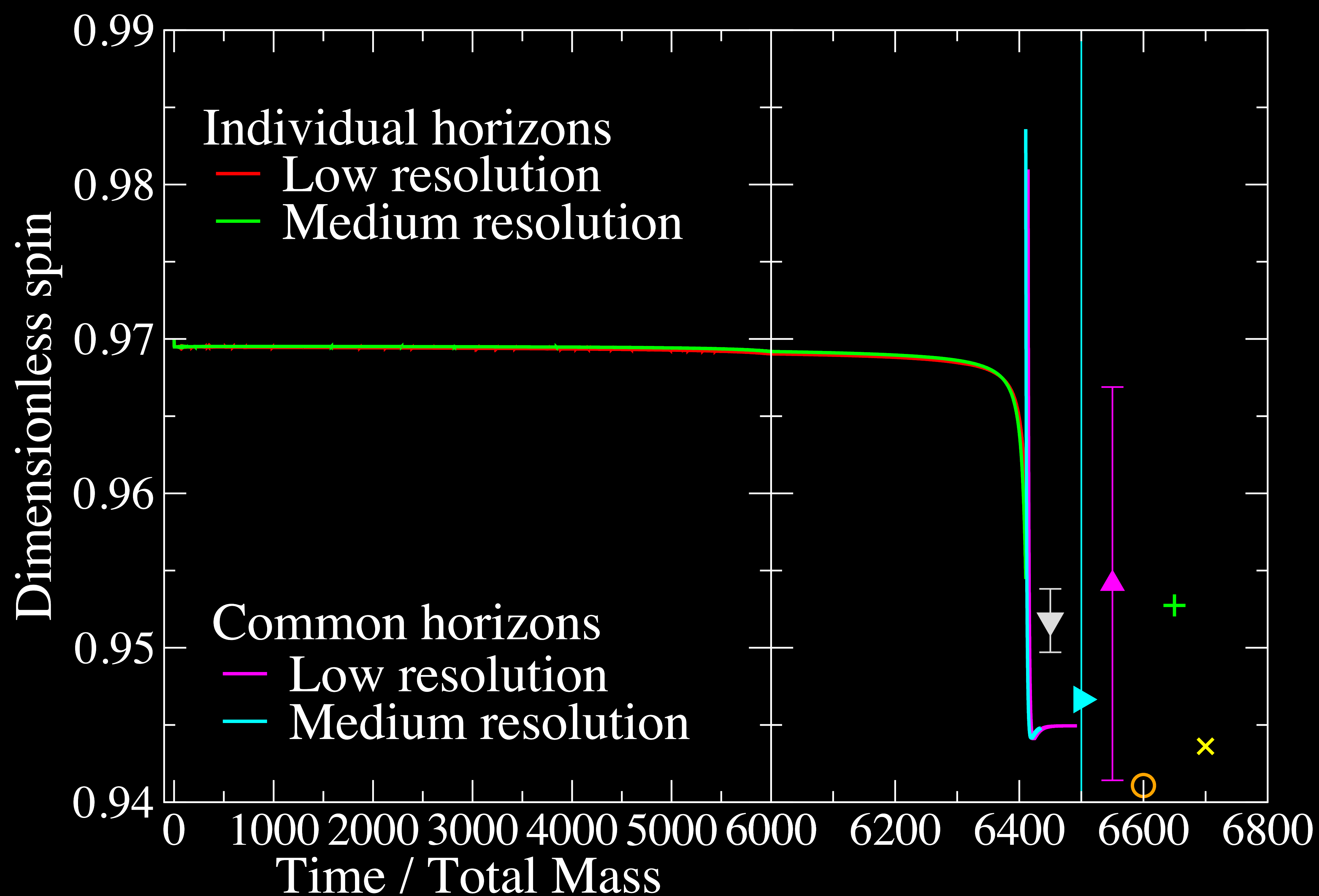
Real part of $(\ell, m) = (2, 2)$ mode
Waves extracted at radius $r/M = 100$
Waveform
$\chi = +0.97$
0.4
0.2
0
-0.2
-0.4
Waveform
$\chi = -0.95$
Amplitude
$\chi = +0.97$
$\chi = -0.95$
0.3
0.1
-6000
-4000
-2000
Time before merger / Total Mass

Spin vs. time



- ○ Campanelli, Lousto, and Zlochower (2006)
- ▶ Tichy and Marronetti (2008)
- × Boyle and Kesden (2008)
- ▲ Barausse and Rezzolla (2009)
- ▼ Rezzolla *et al* (2008)
- + Buonanno, Kidder, and Lehner (2008)

Spin vs. time



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Extremality

- Initial data

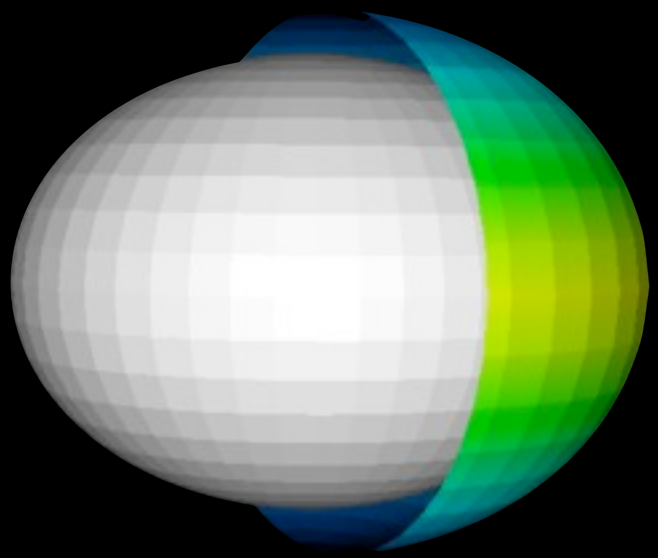
$$\chi = S/M^2$$

$$0 \le \chi \le 1$$

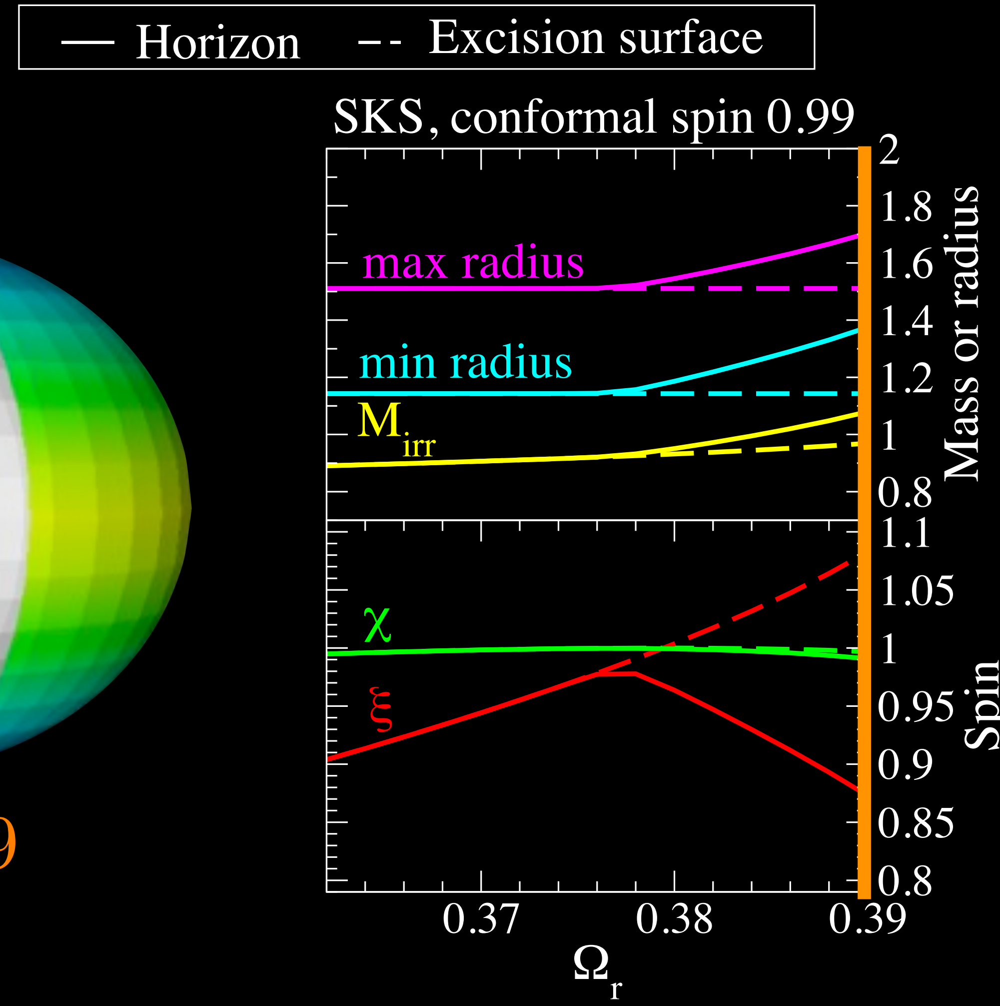
$$\xi = S/2M_{\mathrm{irr}}^2$$

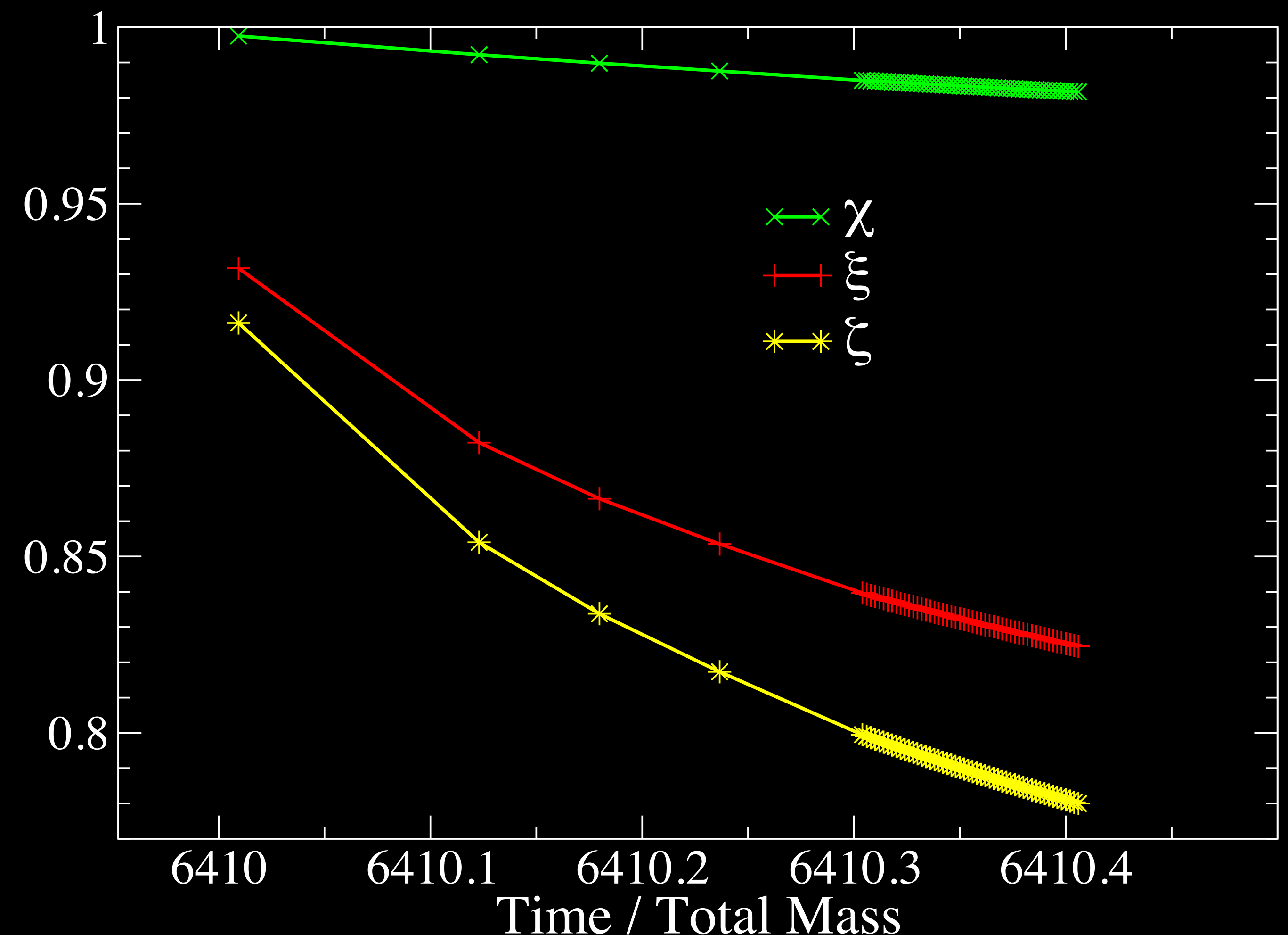
- Evolution

$$\zeta = \frac{M_{\mathrm{rot}}}{M_{\mathrm{rot}}(\chi=1)} = \frac{1-\sqrt{\left(1+\sqrt{1-\chi^2}\right)/2}}{1-1/\sqrt{2}}$$



$\Omega_r = 0.39$

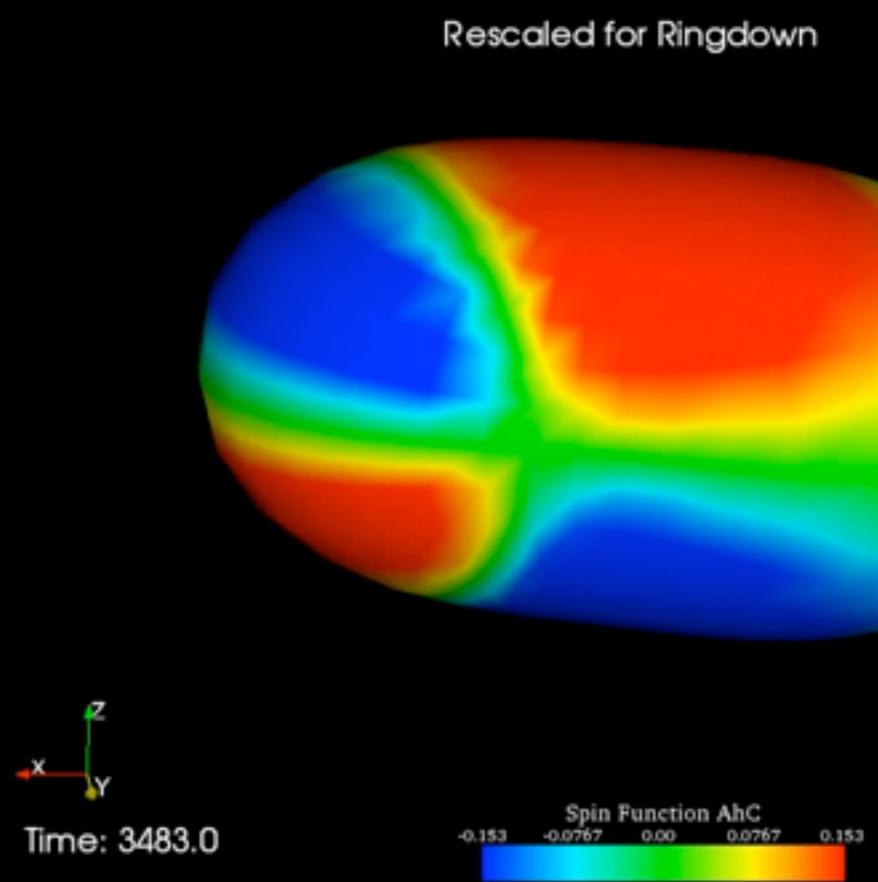


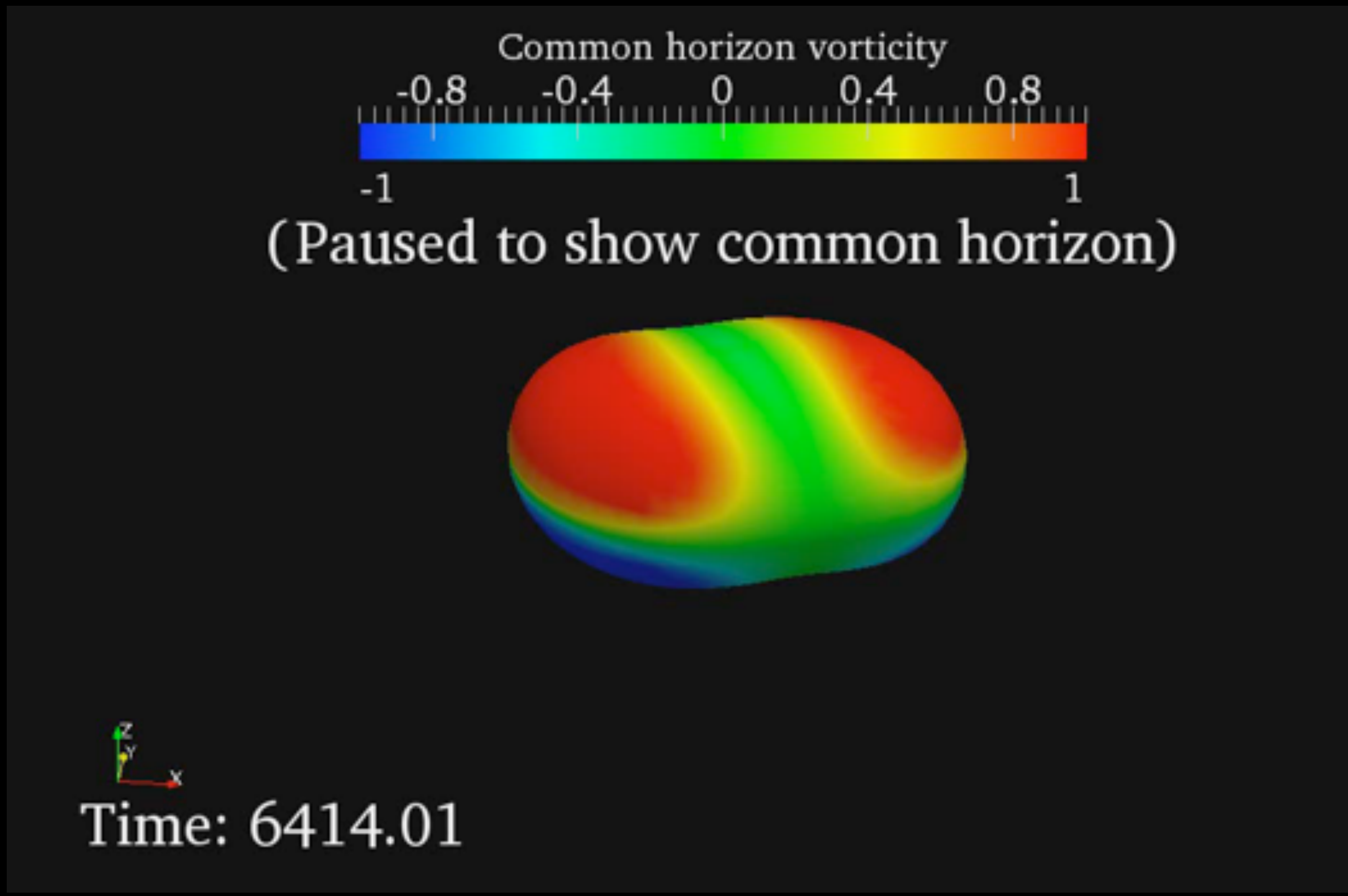


Horizon vorticity

$$\chi_A = \chi_B = -0.95\mathbf{e}_z$$

$$\chi_A = \chi_B = +0.97\mathbf{e}_z$$





Movie courtesy Dave Kotfis

Conclusion

- Nearly extremal spins
  - Astrophysical black holes may have spins ~ 1
  - Improved initial data: can simulate BBH with spins beyond the Bowen-York limit of $\chi \lesssim 0.93$
    - This talk: spins up to $\chi = 0.97$
- Future work
  - More simulations
    - Unequal masses, generic spin direction
    - Even higher spins
  - Extract science from high-spin simulations