High-energy grazing collisions of Black-hole binaries

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Overview

- Motivation
- Computational framework
- Summary of head-on collisions
- Grazing collisions
- Discussion…

Motivation

- Cosmic censorship

  Can we generate naked singularities?

- Universal Dyson limit on luminosity

  Dyson ‘63

- Zoom-whirl behaviour

  Pretorius & Khuranna ‘07

- Test analytical techniques

  Penrose ’74, D’Eath & Payne ’93, Eardley & Giddings ’02, Cardoso & Lemos ’02,…

- BH generation in collision experiments

  Critical impact parameter, cross sections

  BH parameters after GW emission?

Modeling of dynamic BHs

In full GR only possible using numerical relativity!

- Moving puncture framework

  UT Brownsville '06, NASA Goddard '06

- BSSN formulation

- Γ- driver shift condition

  $1+\log$ slicing

- Puncture initial data   Brandt & Brügmann '97

  Bowen-York '80   parameters

- Finite differencing

  Carpet Mesh refinement   Schnetter

Modeling of dynamic BHs

Diagnostics

- Newman-Penrose scalar Ψ_4
- Apparent horizon

  Thornburg
- Ringdown analysis

  Berti, Cardoso & Starinets '09
- Consistency check $M^2 = M_0^2 + \dfrac{S^2}{4M_0^2}$

  Christodoulou '72

Uncertainties

- Discretization error
- Extraction radius (scattering cases)
- Junk radiation

Setup of the problem

- Take two black holes

  Total rest mass: $M_0 = M_{A,0} + M_{B,0}$

  Initial position: $\pm x_0$

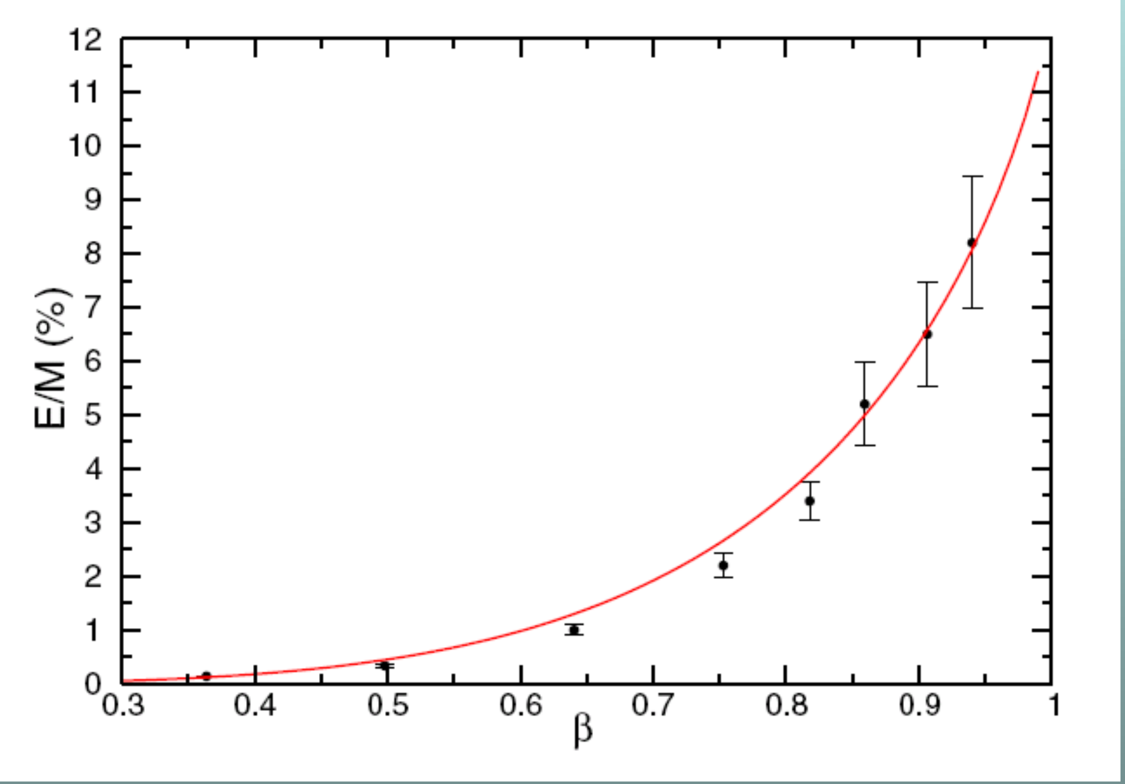
  Linear momentum: $P\,[\cos\alpha,\ \sin\alpha,\ 0]$

- For now: Equal-mass, non-spinning
- Impact parameter: $b = \dfrac{L}{P}$
- Head-on: $b = 0$
- Grazing: $b = 2.0\ \ldots\ 3.6\,M$

Head-on collision: $b = 0$

- Total radiated energy: $14 \pm 3\,\%$ for $v \to 1$

  About half of Penrose '74

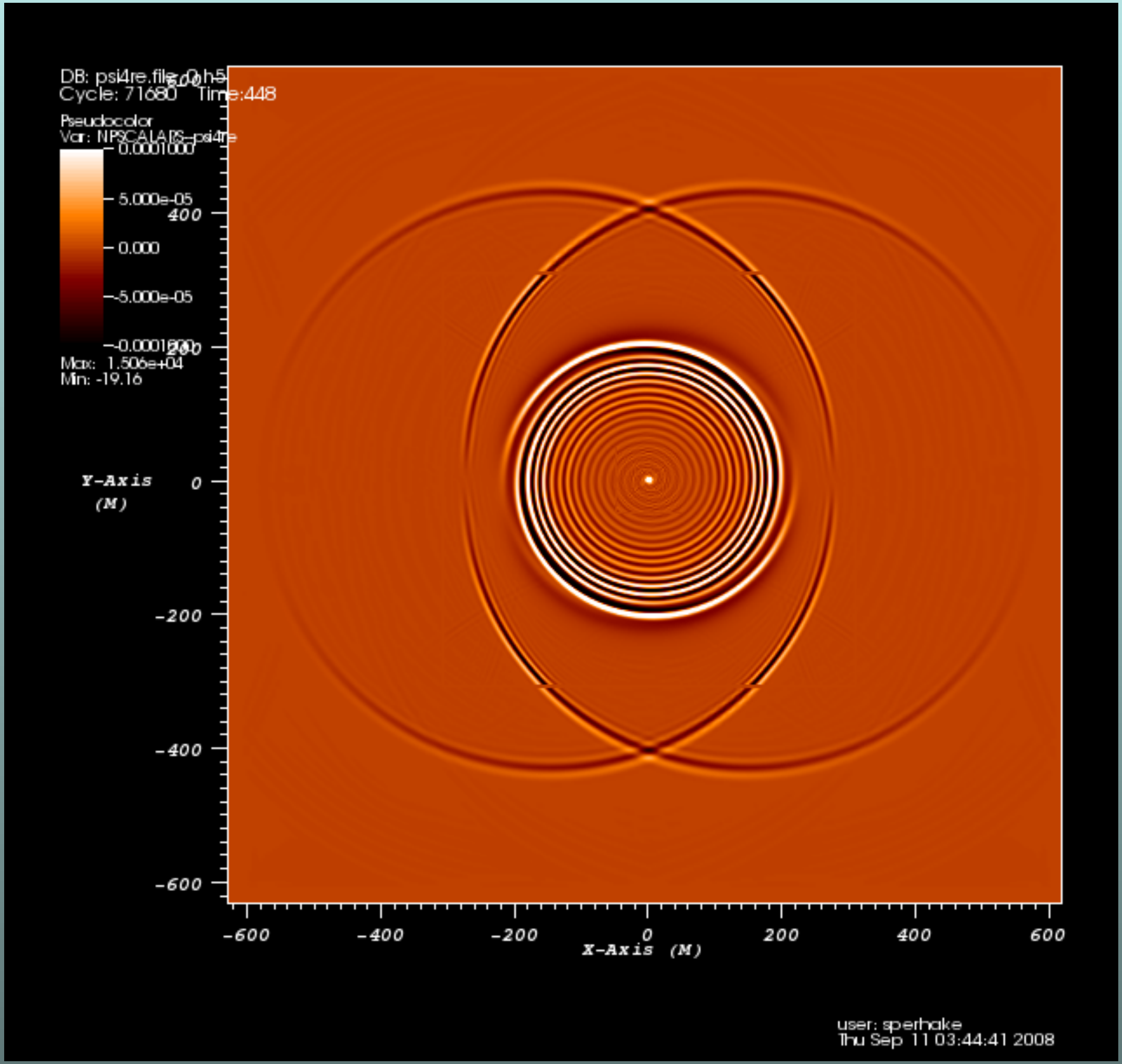


- Agreement with approximative methods

  Flat spectrum, multipolar GW structure

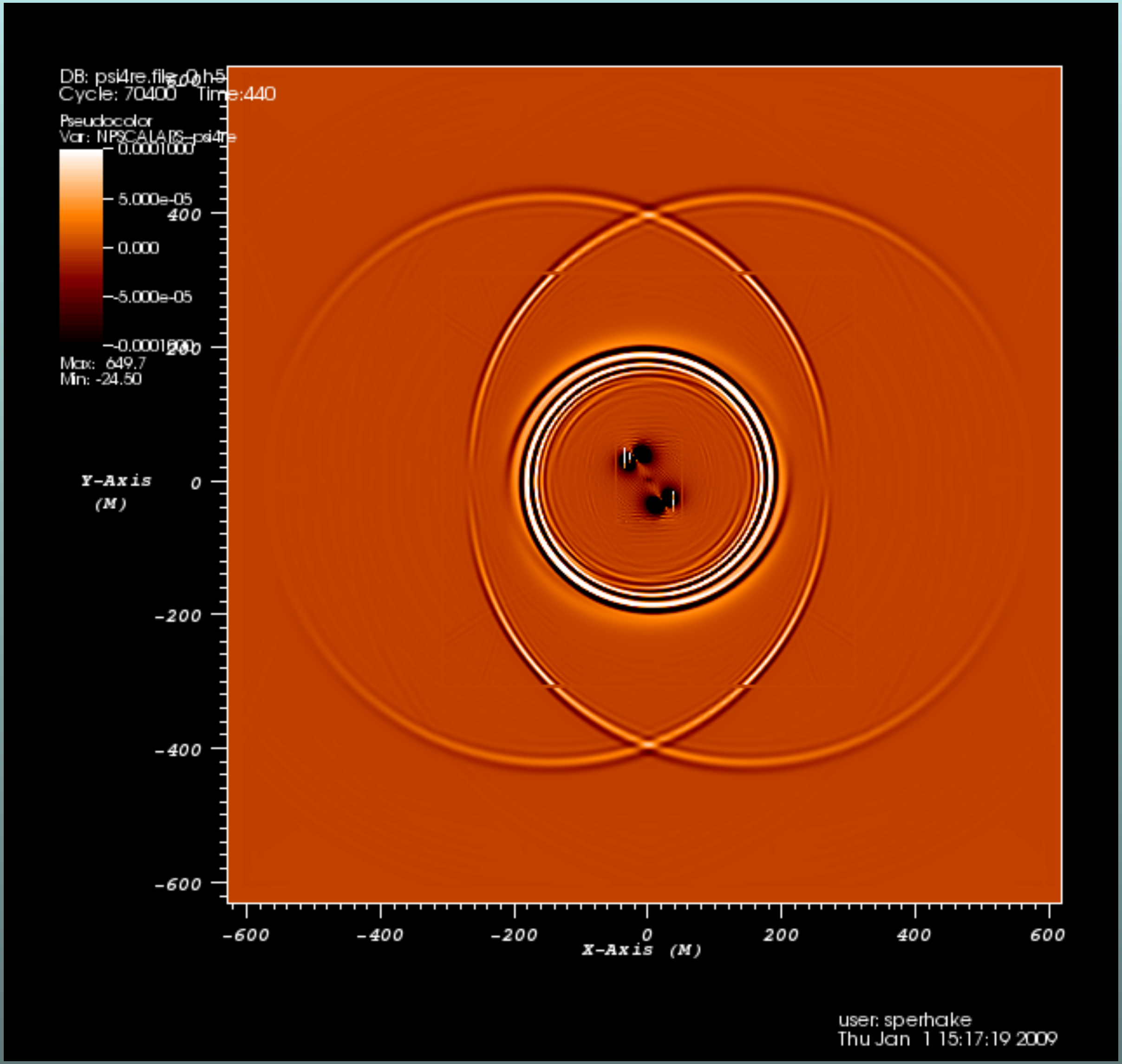
Grazing collisions: $b \neq 0, \quad \gamma = 1.52$

Possible outcome: Merger



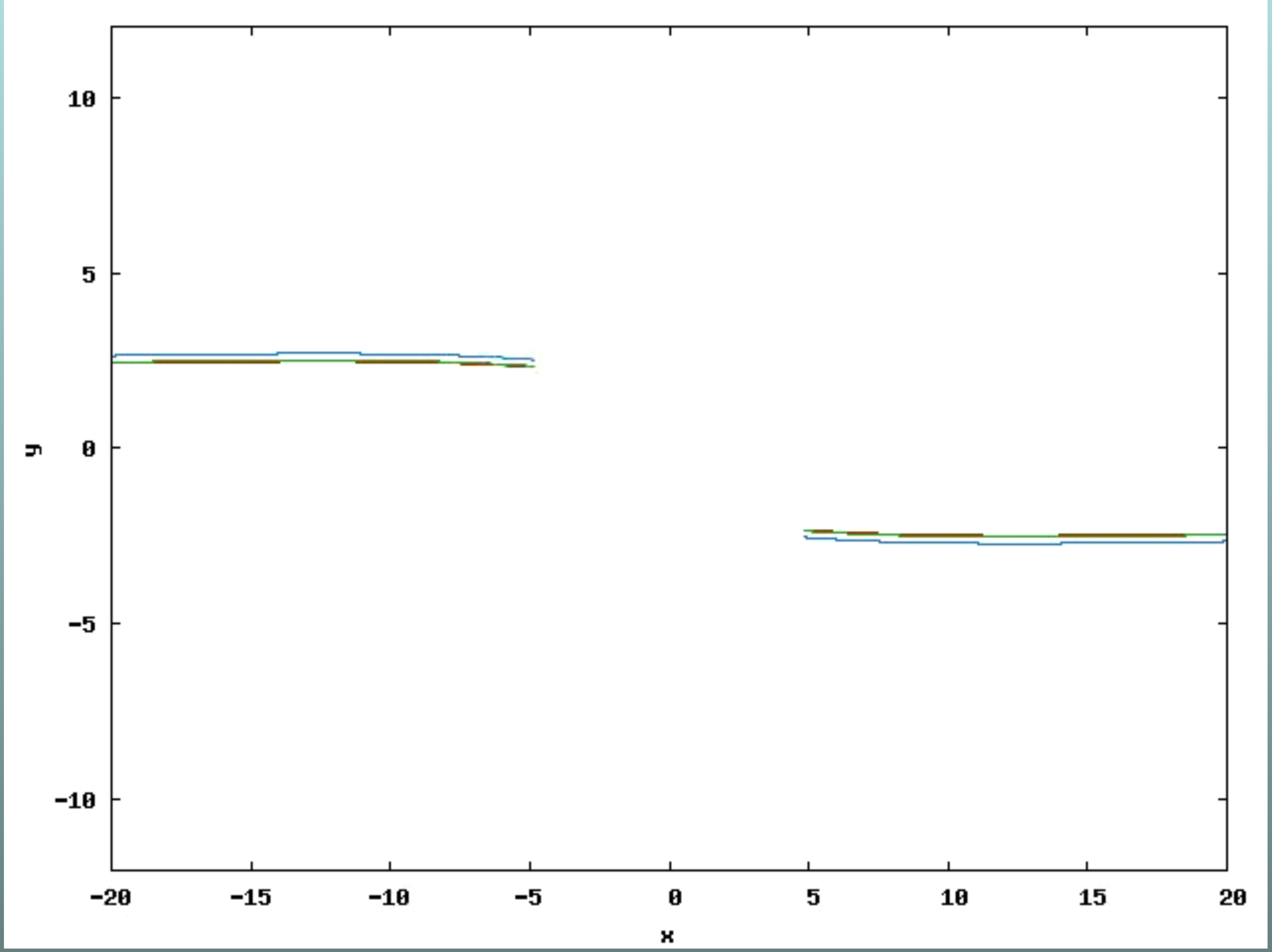
Grazing collisions: $b \neq 0, \quad \gamma = 1.52$

Possible outcome: Scattering



Grazing collisions: $b \neq 0, \quad \gamma = 1.52$

Immediate vs. Delayed vs. No merger



Critical impact parameter

$b < b_{\text{crit}} \quad \Rightarrow \quad$ Merger

$b > b_{\text{crit}} \quad \Rightarrow \quad$ Scattering

- Numerical study: $b_{\text{crit}} = \dfrac{2.5 \pm 0.05}{v} M$

  Shibata et al. '08

- Good agreement for $\gamma = 1.52$: $3.39 < b_{\text{crit}} < 3.4$
- Overestimate for $\gamma = 2.93$: $2.3 < b_{\text{crit}} < 2.4$
- $v \rightarrow 1$ limit still needs to be determined

  Yoshino & Rychkov '05 use Penrose construction

  $\Rightarrow b_{\text{crit}} = 1.685\, M$

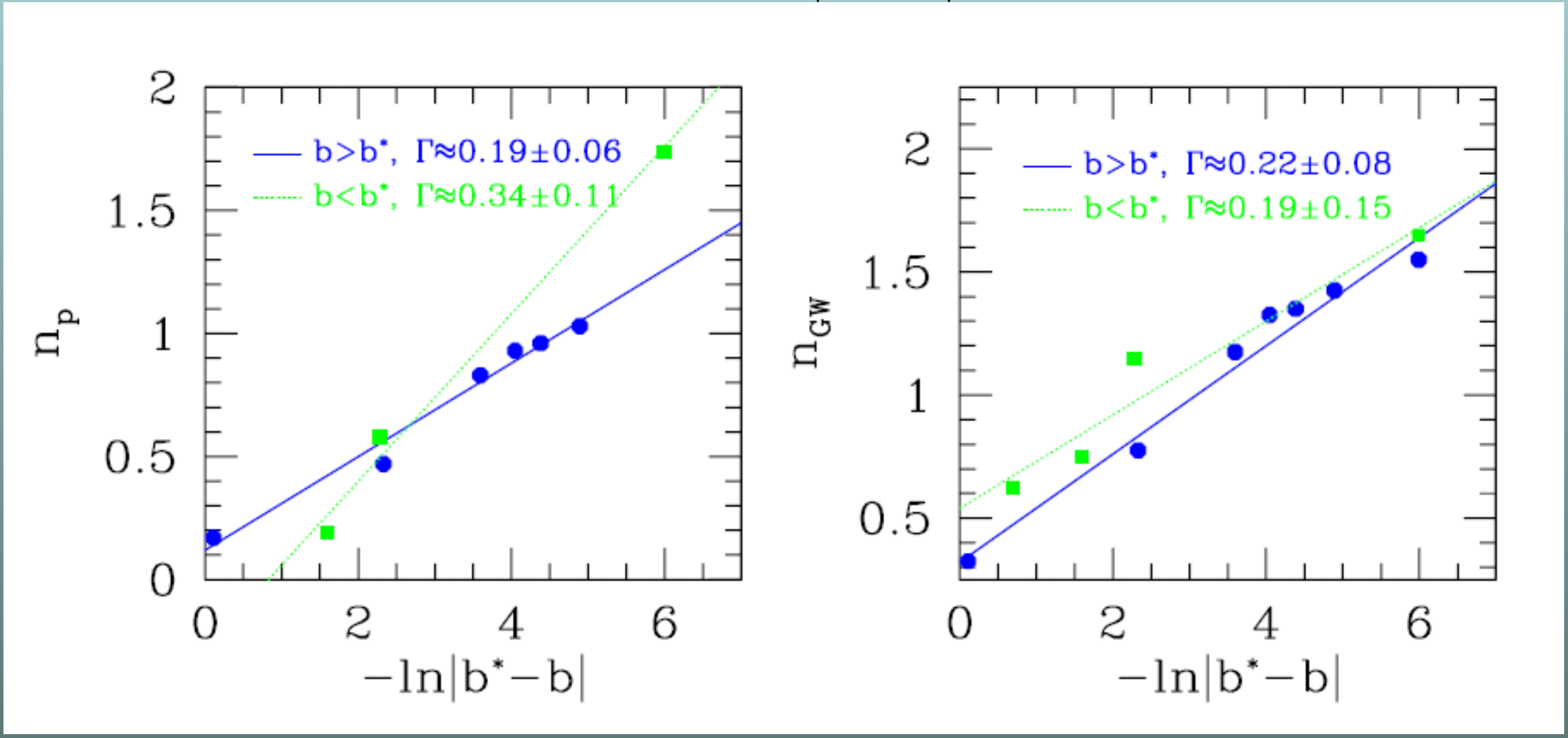
Threshold of immediate merger: Zoom-whirl

- Geodesic limit: Perts. of unstable Schwarzschild orbit

  $\Rightarrow$ Orbits zoom out or plunge   Pretorius, Levin,…

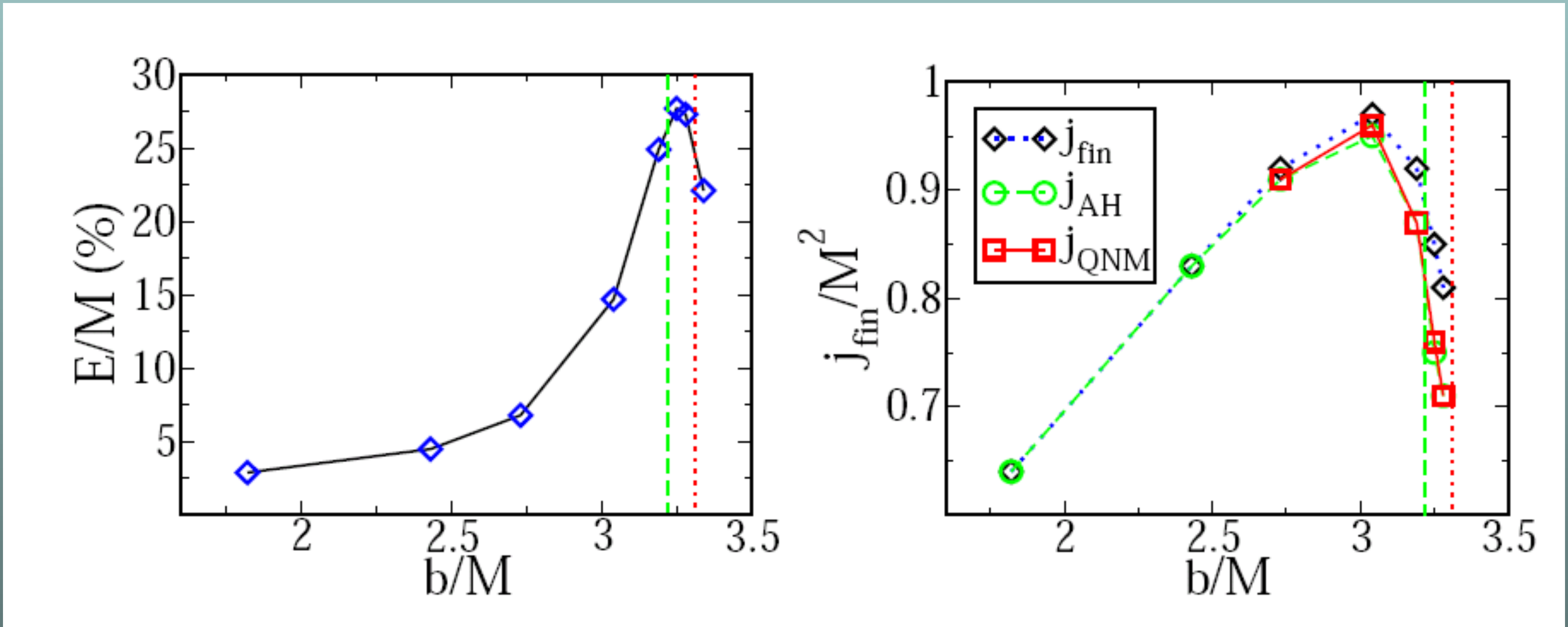
- 1-par family of geodesics approaches orbit for $b \to b^*$

$$n = C - \Gamma \ln\left|b - b^*\right|$$

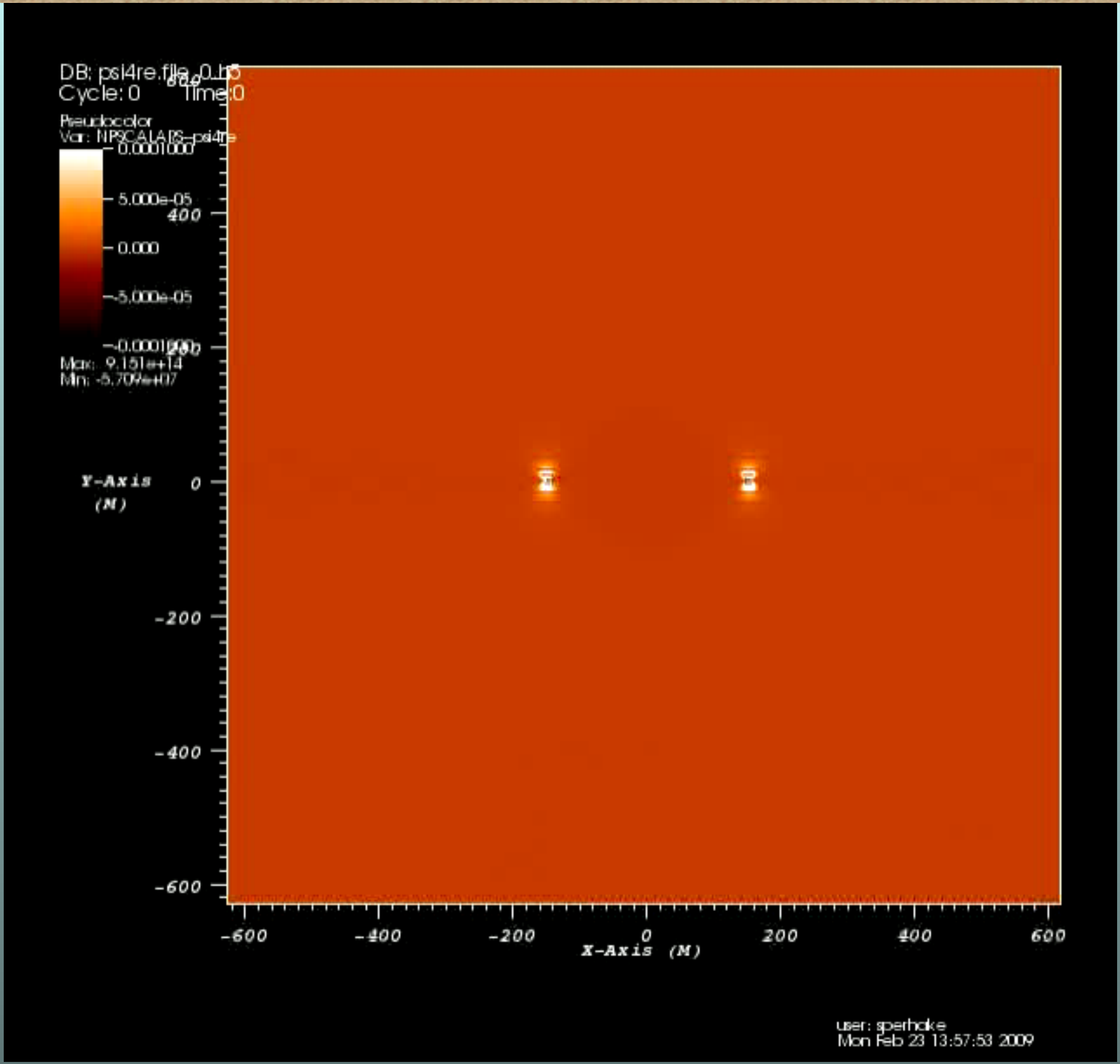


BH parameters

- b - Sequence with $\gamma = 1.52$
- $j_{\rm fin}$ from (i) radiation, (ii) horizon, (iii) ringdown
- $j_{\rm fin}$ larger than in Shibata et al. '08
- $E_{\rm rad} \approx 35\,\%$ for $\gamma = 2.93$; about $10\,\%$ of Dyson luminosity



Gravitational radiation: Delayed merger



Summary

- Head-on collisions: E_{rad} about half of Penrose limit

  Good agreement with approx. methods

- Grazing collisions:

  Enormous radiation of GWs $E_{\mathrm{rad}} \approx 35\,\%$

  Luminosity close to Dyson limit

  Final spins up to Kerr limit (within uncertainties)

  No violation of cosmic censorship

  Zoom-whirl behaviour