

Vañó-Viñuales, Alex; Husa, Sascha

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- 83C05 Einstein's equations (general structure, canonical formalism, Cauchy problems)
- 83-08 Computational methods for problems pertaining to relativity and gravitational theory
- 83C25 Approximation procedures, weak fields in general relativity and gravitational theory
- 83C57 Black holes
- 83C10 Equations of motion in general relativity and gravitational theory

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References:

- [1] Barack L 1999 Late time dynamics of scalar perturbations outside black holes. 1. A Shell toy model *\textit{Phys. Rev.} D* 59 044016 · [Zbl 0949.83044](#)
- [2] Leaver E W 1986 Solutions to a generalized spheroidal wave equation *\textit{J. Math. Phys.}* 27 1238 · [Zbl 0612.34041](#)
- [3] Leaver E W 1986 Spectral decomposition of the perturbation response of the Schwarzschild geometry *\textit{Phys. Rev.} D* 34 384-408 · [Zbl 1222.83053](#)
- [4] Penrose R 1963 Asymptotic properties of fields and space-times *\textit{Phys. Rev. Lett.}* 10 66-8
- [5] Penrose R 1965 Zero rest mass fields including gravitation: asymptotic behavior *\textit{Proc. R. Soc.} A* 284 159
- [6] Friedrich H 1983 Cauchy problems for the conformal vacuum field equations in general relativity *\textit{Commun. Math. Phys.}* 91 445-72 · [Zbl 0555.35116](#)
- [7] Frauendiener J 2004 Conformal infinity *\textit{Living Rev. Relativ.}* 7 1 (pages 21-22 and 25-35)
- [8] Friedrich H 2002 *\textit{Conformal Einstein Evolution}* pp 1-50 · [Zbl 1054.83006](#)
- [9] Husa S 2003 *\textit{Numerical Relativity with the Conformal Field Equations}* pp 159-92
- [10] Husa S, Schneemann C, Vogel T and Zenginoğlu A 2006 Hyperboloidal data and evolution *\textit{AIP Conf. Proc.}* 841 306-13
- [11] Frauendiener J and Vogel T 2005 Algebraic stability analysis of constraint propagation *\textit{Class. Quantum Grav.}* 22 1769-93 · [Zbl 1073.83012](#)
- [12] Abbott B P *\textit{et al}* 2016 Observation of gravitational waves from a binary black hole merger *\textit{Phys. Rev. Lett.}* 116 061102
- [13] Abbott B P *\textit{et al}* 2016 GW151226: observation of gravitational waves from a 22-solar-mass binary black hole coalescence *\textit{Phys. Rev. Lett.}* 116 241103
- [14] Abbott B P *\textit{et al}* 2016 Properties of the binary black hole merger GW150914 *\textit{Phys. Rev. Lett.}* 116 241102
- [15] Abbott B P *\textit{et al}* 2016 Binary black hole mergers in the first advanced LIGO observing run *\textit{Phys. Rev.} X* 6 041015
- [16] Boyle M and Mroue A H 2009 Extrapolating gravitational-wave data from numerical simulations *\textit{Phys. Rev.} D* 80 124045
- [17] Reisswig C, Bishop N, Pollney D and Szilagyi B 2009 Unambiguous determination of gravitational waveforms from binary black hole mergers *\textit{Phys. Rev. Lett.}* 103 221101 · [Zbl 1187.83026](#)
- [18] Pretorius F 2005 Evolution of binary black hole spacetimes *\textit{Phys. Rev. Lett.}* 95 121101 · [Zbl 1191.83026](#)
- [19] Campanelli M, Lousto C, Marronetti P and Zlochower Y 2006 Accurate evolutions of orbiting black-hole binaries without

- excision \textit{Phys. Rev. Lett.}96 111101
- [20] Baker J G, Centrella J, Choi D-I, Koppitz M and van Meter J 2006 Gravitational wave extraction from an inspiraling configuration of merging black holes \textit{Phys. Rev. Lett.}96 111102
- [21] Shibata M and Nakamura T 1995 Evolution of three-dimensional gravitational waves: harmonic slicing case \textit{Phys. Rev.} D 52 5428-44 · [Zbl 1250.83027](#)
- [22] Baumgarte T W and Shapiro S L 1999 On the numerical integration of Einstein's field equations \textit{Phys. Rev.} D 59 024007 · [Zbl 1250.83004](#)
- [23] Bona C, Ledvinka T, Palenzuela C and Zacek M 2003 General-covariant evolution formalism for numerical relativity \textit{Phys. Rev.} D 67 104005 · [Zbl 1074.83003](#)
- [24] Hannam M, Husa S, Pollney D, Brüggmann B and O'Murchadha N 2007 Geometry and regularity of moving punctures \textit{Phys. Rev. Lett.}99 241102 · [Zbl 1228.83070](#)
- [25] Hannam M, Husa S, Ohme F, Brüggmann B and O'Murchadha N 2008 Wormholes and trumpets: the Schwarzschild spacetime for the moving-puncture generation \textit{Phys. Rev.} D 78 064020
- [26] Choptuik M W 1993 Universality and scaling in gravitational collapse of a massless scalar field \textit{Phys. Rev. Lett.}70 9-12
- [27] Tamburino L A and Winicour J H 1966 Gravitational fields in finite and conformal Bondi frames \textit{Phys. Rev.}150 1039-53
- [28] Penrose R and Rindler W 1984-1986 \textit{(Spinors and Space-Time vol 1 and 2)} (Cambridge: Cambridge University Press) (Vol 1: <https://doi.org/10.1017/CBO9780511564048> Vol 2: <https://doi.org/10.1017/CBO9780511524486>)
- [29] Stewart J 1997 \textit{Advanced General Relativity} (Cambridge: Cambridge University Press) · [Zbl 0752.53048](#)
- [30] Andersson L 2002 Construction of hyperboloidal initial data \textit{The Conformal Structure of Space-Time}\textit{(Lecture Notes in Physics vol 604)} ed L Frauendiener and H Friedrich pp 183-94 · [Zbl 1043.83004](#)
- [31] Rinne O 2010 An axisymmetric evolution code for the Einstein equations on hyperboloidal slices \textit{Class. Quantum Grav.}27 035014
- [32] Rinne O and Moncrief V 2013 Hyperboloidal Einstein-matter evolution and tails for scalar and Yang-Mills fields \textit{Class. Quantum Grav.}30 095009
- [33] Bardeen J M, Sarbach O and Buchman L T 2011 Tetrad formalism for numerical relativity on conformally compactified constant mean curvature hypersurfaces \textit{Phys. Rev.} D 83 104045
- [34] Morales M D and Sarbach O 2017 Evolution of scalar fields surrounding black holes on compactified constant mean curvature hypersurfaces \textit{Phys. Rev.} D 95 044001
- [35] Zenginoğlu A 2008 Hyperboloidal foliations and scri-fixing \textit{Class. Quantum Grav.}25 145002
- [36] Zenginoğlu A 2008 Hyperboloidal evolution with the Einstein equations \textit{Class. Quantum Grav.}25 195025
- [37] Zenginoğlu A 2008 A Hyperboloidal study of tail decay rates for scalar and Yang-Mills fields \textit{Class. Quantum Grav.}25 175013
- [38] Zenginoğlu A 2007 A conformal approach to numerical calculations of asymptotically flat spacetimes \textit{PhD Thesis} Max Planck Institute for Gravitational Physics (AEI) and University of Potsdam, Institute of Physics and Astronomy, Potsdam
- [39] Vañó-Viñuales A, Husa S and Hilditch D 2015 Spherical symmetry as a test case for unconstrained hyperboloidal evolution \textit{Class. Quantum Grav.}32 175010
- [40] Bona C, Palenzuela-Luque C and Bona-Casas C 2009 \textit{Elements of Numerical Relativity and Relativistic Hydrodynamics} 2nd edn (New York: Springer) (<https://doi.org/10.1007/978-3-642-01164-1>) · [Zbl 1176.85001](#)
- [41] Bona C, Massó J, Seidel E and Stela J 1995 A new formalism for numerical relativity \textit{Phys. Rev. Lett.}75 600-3
- [42] Alcubierre M \textit{et al} 2003 Gauge conditions for long term numerical black hole evolutions without excision \textit{Phys. Rev.} D 67 084023
- [43] Friedrich H and Rendall A D 2000 \textit{The Cauchy Problem for the Einstein Equations} pp 127-224 · [Zbl 1006.83003](#)
- [44] Ohme F, Hannam M, Husa S and O'Murchadha N 2009 Stationary hyperboloidal slicings with evolved gauge conditions \textit{Class. Quantum Grav.}26 175014 · [Zbl 1176.83022](#)
- [45] Vañó-Viñuales A and Husa S 2017 Spherical symmetry as a test case for unconstrained hyperboloidal evolution III: black holes (in preparation)
- [46] Buchman L T, Pfeiffer H P and Bardeen J M 2009 Black hole initial data on hyperboloidal slices \textit{Phys. Rev.} D 80 084024
- [47] Hilditch D 2015 Dual foliation formulations of general relativity (arXiv:1509.02071[gr-qc])
- [48] Hilditch D, Harms E, Bugner M, Rueter H and Brüggmann B 2016 The evolution of hyperboloidal data with the dual foliation formalism: mathematical analysis and wave equation tests (arXiv:1609.08949[gr-qc])
- [49] Schneemann C 2006 Numerische Berechnung von hyperboloidalen Anfangsdaten für die Einstein-Gleichungen \textit{Master's Thesis} Max Planck Institute for Gravitational Physics (AEI), Potsdam
- [50] Zenginoğlu A and Husa S 2006 Hyperboloidal foliations with scri-fixing in spherical symmetry \textit{Recent Developments in Theoretical and Experimental General Relativity, Gravitation, Relativistic Field Theories. Proc., 11th Marcel Grossmann Meeting, MG11}\textit{(Berlin, Germany, 23-29 July 2006)} pp 1624-6
- [51] Zenginoğlu A, Nunez D and Husa S 2009 Gravitational perturbations of Schwarzschild spacetime at null infinity and the

- hyperboloidal initial value problem \textit{Class. Quantum Grav.}26 035009
- [52] Frauendiener J 1998 Numerical treatment of the hyperboloidal initial value problem for the vacuum Einstein equations. 2. The Evolution equations \textit{Phys. Rev.} D 58 064003 · [Zbl 0959.83003](#)
- [53] Wald R M 1984 \textit{General Relativity} (Chicago: University of Chicago Press) (<https://doi.org/10.7208/chicago/9780226870373.001.0001>) · [Zbl 0549.53001](#)
- [54] Vañó-Viñuales A 2015 Free evolution of the hyperboloidal initial value problem in spherical symmetry \textit{PhD Thesis} U. Illes Balears, Palma
- [55] Newman E and Penrose R 1962 An approach to gravitational radiation by a method of spin coefficients \textit{J. Math. Phys.}3 566-78 · [Zbl 0108.40905](#)
- [56] Gustafsson B, Kreiss H and Olinger J 1995 Time dependent problems and difference methods \textit{Pure and Applied Mathematics} 2nd edn (New York: Wiley) (<https://doi.org/10.1002/9781118548448>) · [Zbl 0843.65061](#)
- [57] Calabrese G, Hinder I and Husa S 2006 Numerical stability for finite difference approximations of Einstein's equations \textit{J. Comput. Phys.}218 607-34 · [Zbl 1106.65080](#)
- [58] Husa S 2007 Numerical modeling of black holes as sources of gravitational waves in a nutshell \textit{Eur. Phys. J.}152 183-207
- [59] Arbona A, Bona C, Massó J and Stela J 1999 Robust evolution system for numerical relativity \textit{Phys. Rev.} D 60 104014
- [60] Alcubierre M, Brügmann B, Pollney D, Seidel E and Takahashi R 2001 Black hole excision for dynamic black holes \textit{Phys. Rev.} D 64 061501
- [61] Vañó-Viñuales A and Husa S 2015 Unconstrained hyperboloidal evolution of black holes in spherical symmetry with GBSSN and Z4c \textit{J. Phys.: Conf. Ser.}600 012061
- [62] Alcubierre M 1997 The appearance of coordinate shocks in hyperbolic formalisms of general relativity \textit{Phys. Rev.} D 55 5981-91
- [63] Alcubierre M 2003 Hyperbolic slicings of space-time: singularity avoidance and gauge shocks \textit{Class. Quantum Grav.}20 607-24 · [Zbl 1137.83354](#)
- [64] Reimann B, Alcubierre M, Gonzalez J A and Nunez D 2005 Constraint and gauge shocks in one-dimensional numerical relativity \textit{Phys. Rev.} D 71 064021
- [65] Alcubierre M 2005 Are gauge shocks really shocks? \textit{Class. Quantum Grav.}22 4071-82 · [Zbl 1075.83532](#)
- [66] Garfinkle D, Gundlach C and Hilditch D 2008 Comments on Bona-Masso type slicing conditions in long-term black hole evolutions \textit{Class. Quantum Grav.}25 075007 · [Zbl 1138.83005](#)
- [67] Bernstein D H 1993 Physics, astronomy, and astrophysics: a numerical study of the black hole plus Brill wave spacetime \textit{PhD Thesis} Illinois Univ., Urbana-Champaign
- [68] Anninos P \textit{et al} 1995 Three-dimensional numerical relativity: The Evolution of black holes \textit{Phys. Rev.} D 52 2059-82
- [69] Brown J D 2009 Covariant formulations of BSSN and the standard gauge \textit{Phys. Rev.} D 79 104029
- [70] van Meter J R, Baker J G, Koppitz M and Choi D-I 2006 How to move a black hole without excision: gauge conditions for the numerical evolution of a moving puncture \textit{Phys. Rev.} D 73 124011
- [71] Gundlach C and Martin-Garcia J M 2006 Well-posedness of formulations of the Einstein equations with dynamical lapse and shift conditions \textit{Phys. Rev.} D 74 024016
- [72] Hilditch D and Richter R 2016 Hyperbolicity of physical theories with application to general relativity \textit{Phys. Rev.} D 94 044028
- [73] Alcubierre M \textit{et al} 2005 Generalized harmonic spatial coordinates and hyperbolic shift conditions \textit{Phys. Rev.} D 72 124018
- [74] Husa S, Gonzalez J A, Hannam M, Brügmann B and Sperhake U 2008 Reducing phase error in long numerical binary black hole evolutions with sixth order finite differencing \textit{Class. Quantum Grav.}25 105006
- [75] Kreiss H and Olinger J 1973 \textit{Methods for the Approximate Solution of time Dependent Problems} \textit{(GARP Publications Series vol 10)} (Geneva: International Council of Scientific Unions, World Meteorological Organization)
- [76] Babiuc M \textit{et al} 2008 Implementation of standard testbeds for numerical relativity \textit{Class. Quantum Grav.}25 125012 · [Zbl 1144.83002](#)
- [77] Brandt S and Brügmann B 1997 A Simple construction of initial data for multiple black holes \textit{Phys. Rev. Lett.}78 3606-9
- [78] Vañó-Viñuales A and Husa S 2015 Free hyperboloidal evolution in spherical symmetry (arXiv:1512.00776 [gr-qc])
- [79] Brügmann B 1999 Binary black hole mergers in 3d numerical relativity \textit{Int. J. Mod. Phys.} D 8 85
- [80] Brügmann B \textit{et al} 2008 Calibration of moving puncture simulations \textit{Phys. Rev.} D 77 024027
- [81] Martín-García J M xAct: efficient tensor computer algebra for \textit{Mathematica} www.xact.es/
- [82] Brown J D 2008 BSSN in spherical symmetry \textit{Class. Quantum Grav.}25 205004
- [83] Alic D, Bona-Casas C, Bona C, Rezzolla L and Palenzuela C 2012 Conformal and covariant formulation of the Z4 system with constraint-violation damping \textit{Phys. Rev.} D 85 064040

- [84] Sanchis-Gual N, Montero P J, Font J A, Müller E and Baumgarte T W 2014 Fully covariant and conformal formulation of the Z4 system in a reference-metric approach: comparison with the BSSN formulation in spherical symmetry \textit{Phys. Rev.} D 89 104033 · [Zbl 1329.83052](#)
- [85] Bernuzzi S and Hilditch D 2010 Constraint violation in free evolution schemes: comparing BSSNOK with a conformal decomposition of Z4 \textit{Phys. Rev.} D 81 084003
- [86] Weyhausen A, Bernuzzi S and Hilditch D 2012 Constraint damping for the Z4c formulation of general relativity \textit{Phys. Rev.} D 85 024038

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