Dr. Jocelyn Read
Department of Physics and Astronomy
University of Mississippi
108 Lewis Hall
University, MS 38677

17 October 2011

Dr. Greg Childers, Search Committee Chair
Department of Physics
California State University, Fullerton
PO Box 6850
Fullerton, California 92834-6850

Dear Dr. Childers, and members of the Search Committee,

I am writing to apply for the position of Assistant Professor in Theoretical Gravitational-Wave Astronomy and Astrophysics at California State University, Fullerton. I believe my current research, in theoretical gravitational-wave astrophysics, would make a strong contribution to the new Gravitational-Wave Physics and Astronomy Center at CSUF. I look forward to building the new Center together with Dr. Josh Smith, as well as to the opportunity to engage with new students at CSUF as they discover physics.

I received my PhD from the University of Wisconsin–Milwaukee in 2008 with the thesis "Neutron stars in compact binary systems: from the equation of state to gravitational radiation." Since then, I have developed a strong research program that bridges the theoretical modelling of neutron-star binaries with the data analysis tools required to measure new astrophysics using LIGO signals. This program has attracted interest from the international physics community resulting in nineteen invited talks in the last three years.

I have also connected the source modelling to high-energy electromagnetic astrophysics and cosmology, developing new collaborations and research areas. This year I submitted a NASA Research Opportunities in Space and Earth Sciences proposal to study the combination of gamma-ray burst and gravitational-wave signals resulting from the dynamic response of inspiralling neutron stars, with Co-Is D. Tsang (Caltech), C. Ott (Caltech), and E. Berti (University of Mississippi).

While my focus as a post-doc has been on research, I have also been working to stay active in teaching and to develop new outreach tools. I have contributed guest lectures in Introductory Physics, Astrophysics, and Mathematical Methods while at the University of Mississippi. In 2009, at the 3rd International Summer School on Astroparticle Physics in Nijmegen, The Netherlands, I gave lectures in "Gravitational waves: modelling sources." I enjoy the opportunity to introduce my field of research to a broad audience, and continuously experiment with new ways to explain both motivations and results.

Over the last year I have been working out ways to construct accurate models of curved spacetimes from printed patterns, which could then be used as teaching tools, and helping to develop a new "Science Café" general-audience program in Oxford, Mississippi.

I have attached teaching and research statements to expand on the qualifications discussed above, along with a C.V. including publications. I thank you very much for your consideration, and look forward to hearing from you.

Sincerely,

Jocelyn Read

Jocelyn S. Read — Curriculum Vitae

CONTACT INFORMATION

Department of Physics and Astronomy
University of Mississippi
108 Lewis Hall
University, MS USA 38677

Citizenship: Canadian
Phone: 1-662-380-3984
Fax: 1-662-915-5045
E-mail: jocelyn.read@gmail.com

EDUCATION

Doctor of Philosophy in Physics August 2008
Neutron stars in compact binary systems: from the equation of state to gravitational radiation.
University of Wisconsin–Milwaukee, Milwaukee, WI, USA
Advisors: John Friedman & Jolien Creighton

Bachelor of Science May 2002
Combined Honours in Physics and Mathematics
University of British Columbia, Vancouver, BC, Canada

POSITIONS HELD

University of Mississippi, USA 2010-Present
Postdoctoral research, with Emanuele Berti. Redshift measurements and cosmology with gravitational-wave detectors. Resonant neutron star crust shattering as a model of Short Gamma Ray Burst precursors. Testing alternative theories of gravity with neutron star observations.

MPIGP (Albert Einstein Institute), Potsdam, Germany 2008-2010
Postdoctoral research, Astrophysical Relativity group. Tidal effects on binary neutron stars and mixed binaries in perturbative/post-Newtonian and numerical frameworks. Gravitational wave astrophysics with advanced ground based detectors.

University of Wisconsin–Milwaukee, USA 2003-2008
Doctoral research, with John Friedman and Jolien Creighton. Relativistic astrophysics of neutron stars—parameterizing the nuclear equation of state and astrophysical constraints, constructing binary neutron star initial data, data analysis estimates from numerical gravitational waves.

University of Wisconsin–Milwaukee, USA 2003
Center for Gravitation and Cosmology, LSC Group. Template spacing for cosmic string signal searches in LIGO data with Jolien Creighton and Xavier Siemens.

University of British Columbia, Vancouver, Canada Summer 2002
Mathematica code for Bayesian analysis of period variation in binary star system, with Phil Gregory.

University of California–Los Angeles, USA Summer 2001
Research in Industrial Projects for Students, Institute for Pure and Applied Mathematics. Metropolis Monte Carlo simulation of Indium Arsenide surface reconstruction.

Shell Canada, Calgary, AB, Canada Summer 1999
Internal publication: "Model-based analysis to resolve sub-tuning level detail in Devonian reef." Developed method of analysing seismic data in an area with complex overlaying geology.

Canadian Hunter, Calgary, AB, Canada Summer 1997
Database compilation and analysis for statistically significant correlations between sub-ground temperature and hydrocarbon locations.

RESEARCH INTERESTS

Gravitational wave astronomy and data analysis, numerical relativity, perturbative and post-Newtonian methods in gravity, neutron star equations of state and phenomenology.

PUBLICATIONS

Online at: `http://bit.ly/jsread-inspire`

"Resonant Shattering of Neutron Star Crusts." David Tsang, Jocelyn S. Read, Tanja Hinderer, Anthony L. Piro, Ruxandra Bondarescu. arXiv:1110.0467, submitted to Phys. Rev. Lett.

"Compact stars in alternative theories of gravity: Einstein-Dilaton-Gauss-Bonnet gravity." Paolo Pani, Emanuele Berti, Vitor Cardoso, Jocelyn Read. arXiv:1109.0928, submitted to Phys. Rev. D.

"Measuring a cosmological distance-redshift relationship using only gravitational wave observations of binary neutron star coalescences." Chris Messenger, Jocelyn Read. arXiv:1107.5725, submitted to Phys. Rev. Lett.

"Will black hole-neutron star binary inspirals tell us about the neutron star equation of state?" Francesco Pannarale, Luciano Rezzolla, Frank Ohme, Jocelyn S. Read. arXiv:1103.3526, accepted to Phys. Rev. D.

"Data formats for numerical relativity waves." P. Ajith et al. 24 Feb 2011 revision of arXiv:0709.0093.

"The vacuum revealed: the final state of vacuum instabilities in compact stars." Paolo Pani, Vitor Cardoso, Emanuele Berti, Jocelyn Read, Marcelo Salgado. Phys. Rev. D 83 (2011) 081501.

"Sensitivity Studies for Third-Generation Gravitational Wave Observatories." S. Hild et al. Class. Quant. Grav. 28 (2011) 094013.

"Gravitational waves from neutron stars: Promises and challenges." N. Andersson, V. Ferrari, D.I. Jones, K.D. Kokkotas, B. Krishnan, J. Read, L. Rezzolla, B. Zink. Gen. Rel. Grav. 43 (2011) 409-436.

"Tidal deformability of neutron stars with realistic equations of state." Tanja Hinderer, Benjamin D. Lackey, Ryan N. Lang, Jocelyn S. Read. Phys. Rev. D 81 (2010) 123016.

"The third generation of gravitational wave observatories and their science reach." M. Punturo *et al.* Class. Quantum Grav. 27 (2010) 084007.

"Measuring the neutron star equation of state with gravitational wave observations." Jocelyn S. Read, Charalampos Markakis, Masaru Shibata, Koji Uryu, Jolien D. Creighton, John L. Friedman. Phys. Rev. D 79 (2009) 124033.

"Constraints on a phenomenologically parameterized neutron-star equation of state." Jocelyn S. Read, Benjamin DĹackey, John L. Friedman, Benjamin J. Owen. Phys. Rev. D 79 (2009) 124032.

PUBLICATIONS *(cont'd)*

"Models of helically symmetric binary systems." Shin'ichirou Yoshida, Benjamin C. Bromley, Jocelyn S. Read, Koji Uryu, John L. Friedman. Class. Quantum Grav. 23 (2006) S599-S613.

"Gravitational wave bursts from cosmic (super)strings: Quantitative analysis and constraints." Xavier Siemens, Jolien Creighton, Irit Maor, Saikat Ray Majumder, Kipp Cannon, Jocelyn Read. Phys. Rev. D 73 (2006) 105001.

IN PREPARATION

"Matter effects on double neutron star binary waveforms." Jocelyn S. Read, Luca Baiotti, Jolien Creighton, John L. Friedman, Koutarou Kyutoku, Charalampos Markakis, Luciano Rezzolla, Masaru Shibata, Keisuke Taniguchi.

"Neutron stars, equations of state, and gravitational waves." Jocelyn S. Read. *Invited Topical Review*, Class. Quantum Grav.

INVITED TALKS AND SEMINARS

8 invited talks in 2011 including APS, GWPAW, MICRA

"Extreme tides: the dynamic response of neutron stars in coalescing binaries." Astrophysics Seminar, University of Florida, Gainesville, FL, USA. Scheduled for 28 October 2011.

"Learning about dense matter from gravitational-wave observations." Institute for Theoretical Science Seminar, University of Oregon, Eugene, OR, USA. 11 October 2011.

"Neutron stars: from nuclear physics to gravitational-wave astronomy." LSST Science Lunch, University of Washington, Seattle, WA, USA. 10 October 2011.

"Measuring a cosmological distance-redshift relationship using only gravitational wave observations of binary neutron star coalescences." With C. Messenger. LSC-Virgo wide Data Analysis Council meeting (telecon). 12 August 2011.

"EOS/Parameter choices for NSNS/NSBH simulations." Microphysics in Computational Relativistic Astrophysics, Perimeter Institute, Waterloo, Canada. 23 June 2011.

"Measuring the neutron-star equation of state using gravitational waves from binary observations." April Meeting of the American Phsyics Society *(Invited)*, Anaheim, CA, USA. 30 April 2011.

"Constraining the equation of state using advanced gravitational-wave detectors." Gravitational Wave Physics and Astronomy Workshop (GWPAW). Milwaukee, WI, USA. 26 January 2011.

"Measuring waveforms of binary neutron stars." Caltech-JPL Association for Gravitational Wave Research Seminar. Pasadena, CA, USA. 4 January 2011.

6 invited talks in 2010

"Measuring the equation of state using gravitational waves from binary observations." Exploring Physics with Neutron Stars, a celebration of Fred Lamb's 65th Birthday. Tucson, Arizona. 19 November 2010.

INVITED TALKS AND SEMINARS *(cont'd)*

"What can we learn about neutron stars from binary neutron star coalescences?" Einstein Telescope Working Group 4 meeting. Nice, France. 1 September 2010.

"Modelling waveforms from binary neutron stars." NRDA/CAPRA 2010: Theory Meets Data Analysis at Comparable and Extreme Mass Ratios. Perimeter Institute, Waterloo, Canada. 25 June 2010.
`http://pirsa.org/index.php?p=speaker&name=Jocelyn_Read`

"Measuring tidal deformation from binary neutron star inspiral." Yukawa Institute for Theoretical Physics, Kyoto, Japan. 14 May 2010.

"Dense matter and gravitational waves." Montana State University, Bozeman, MT, USA. 5 March 2010.

"Tidal deformation in binary neutron star inspiral." GR Seminar Series, Eberhard-Karls-Universität Tübingen, Germany. 11 Feb 2010.

5 invited talks in 2009

"Tidal deformation in binary neutron star inspiral." University of Southampton Relativity Seminars, Southampton, UK. 4 Dec 2009.

"Science goals for NINJA 2 - a NR-Matter Perspective," J. Faber, I. Hawke, C. Ott, and J. Read. NRDA 2009: Numerical Relativity and Data Analysis Meeeting, AEI, Potsdam, Germany. 9 July 2009.

"Binary neutron star inspiral and the equation of state." University of Wisconsin–Milwaukee, Milwaukee, WI, USA. 5 June 2009.

"Physics from binary neutron star coalescences." Einstein Telescope Working Group 4 Meeting, Cardiff University (via telephone). 25 March 2009.

"Measuring the size of neutron stars using gravitational waves." Cardiff University, Wales. 6 March 2009.

CONTRIBUTED TALKS

"Hybrid waveforms for binary neutron stars." Numerical Relativity meets Data Analysis Meeting. Cardiff, UK. 10 July 2011.

"Finite size (tidal) effects on gravitational waves." Gravitational Wave Bursts Meeting. Chichen-Itza, Yucatan, Mexico. 9 Dec 2010.

"Numerical and post-Newtonian estimates of tidal deformation in binary neutron stars." Marcel Grossman Meeting 12, Paris, France. 16 July 2009.

"Tidal deformation in binary neutron star inspiral." NSDN meeting: Neutron stars as gravitational wave sources, Rome, Italy. 23 April 2009.

"Constraints on a phenomenological equation of state for neutron star cores." Compstar 2009, Coimbra, Portugal. 13 February 2009.

"BNS-NRDA: Numerical Relativity meets Data Analysis for Binary Neutron Stars." KITP Miniprogram: Interplay between Numerical Relativity and Data Analysis. Santa Barbara, CA, USA. 11 January 2008.

CONTRIBUTED TALKS *(cont'd)*

"BNS-NRDA: Numerical Relativity meets Data Analysis for Binary Neutron Stars." 17th Midwest Relativity Meeting. St. Louis, MO, USA. 2 November 2007. *Received Blue Apple Award for best student presentation.*

"Parameterized equations of state for neutron stars." Workshop B1, 18th General Relativity and Gravitation Conference, Sydney, Australia. 12 July 2007.

"Models of helically symmetric binary systems." Workshop B2, 18th General Relativity and Gravitation Conference, Sydney, Australia. 12 July 2007.

"Parameterized equations of state for neutron stars." APS April Meeting, Jacksonville, FL, USA. 16 April 2007.

"Comparing numerical methods for nonlinear toy models with helical symmetry." Workshop on Helically Symmetric Systems, Albert Einstein Institute, Potsdam, Germany. 10 January 2007.

"Models of helically symmetric binary systems." APS April Meeting. Dallas, TX, USA. 23 April 2006.

"Constructing helically symmetric spacetimes." APS April Meeting. Tampa, FL, USA. 16 April 2005.

TEACHING INTERESTS

Mechanics, electromagnetism, mathematical methods, software engineering for scientists, modern physics, classical and quantum field theory, general relativity, astrophysics, gravitational waves, compact objects.

TEACHING AND OUTREACH

"The Intense Life of Stars after Death." Public lecture. Oxford Science Café, Oxford, MS, USA. Scheduled for Nov 15 2011.

"Build your own embedded spacetime: A theoretical outreach talk" Outreach and Public Engagement Session, Amaldi 9, Cardiff, UK, July 12 2011.
`http://bit.ly/PapercraftSpacetime`

Lecturer, 3rd International Summer School on Astroparticle Physics. "Gravitational waves: modelling sources." Radboud University Nijmegen, Nijmegen, the Netherlands. August 19-28, 2009.

Guest lectures:
Physics 212 (Physics for Science and Engineering II): Wave superposition
Physics 552 (Mathematical Methods of Physics II): Bayesian probability and MCMC
Astronomy 325 (Astrophysics): Observing neutron stars
University of Mississippi, Oxford, MS, USA 2010-2011

Teaching Assistant:
Physics 209 (Electricity and Magnetism)
Physics 120 (Introductory Physics)
University of Wisconsin–Milwaukee, Milwaukee, WI, USA 2003-2004

Volunteer ESL teaching assistant. Krabi, Thailand & Nam Bak, Laos Fall 2000

Volunteer ESL science tutoring. University of British Columbia 1997-1998

Professional activities

Principal Investigator, NASA ROSES, "The Dynamic Response and Multi-messenger Signatures of Inspiraling and Coalescing Neutron Stars"
Co-Is David Tsang, Christian Ott, Emanuele Berti. Submitted 2011, pending

Scientific Organizing Committee, Numerical Relativity Meets Data Analysis (NRDA), Cardiff, Wales July 10-15 2011

Member of:
the LIGO Scientific Collaboration 2010-
the American Physical Socety, the Division of Astrophysics, and the Topical Group on Gravitation 2005-
the Einstein Telescope Astrophysics Working Group 2009-

External reviewer, Phys. Rev. D 2010-

Proofreader, Free High School Science Texts (`http://www.fhsst.org`) 2010

Seminar Coordinator, Numerical Relativity Group, AEI 2009-2010

UWM Academic Policy Committee 2007-2008

UWM Physics Graduate Student "Lunch Chats" seminar coordinator 2005-2006

Other Skills

12 years UNIX/Linux/BSD experience.
Proficient in BASH, C/C++, FORTRAN, Python, Maple, Mathematica, LaTeX.

References

John Friedman
University of Wisconsin–Milwaukee
P.O. Box 413, Milwaukee, WI
USA 53201
friedman@uwm.edu
1-414-229-4476

Jolien Creighton
University of Wisconsin–Milwaukee
P.O. Box 413, Milwaukee, WI
USA 53201
jolien@gravity.phys.uwm.edu
1-414-229-2907

Emanuele Berti
University of Mississippi
P.O. Box 1848, University, Mississippi
USA 38677
berti@phy.olemiss.edu
1-662-915-1941

Patrick Brady
University of Wisconsin–Milwaukee
P.O. Box 413, Milwaukee, WI
USA 53201
patrick@gravity.phys.uwm.edu
1-414-229-6508

Badri Krishnan
Albert Einstein Institute
Callinstr. 38, Hannover
D-30167 Germany
badri.krishnan@aei.mpg.de
+49-331-567-7323

Christian D. Ott
California Institute of Technology
1200 E. California Blvd., Pasadena, CA
USA 91125
cott@tapir.caltech.edu
1-626-395-8410

Anna Watts
University of Amsterdam
P.O. Box 94249
1090 GE Amsterdam, the Netherlands
a.l.watts@uva.nl
+31-20-525-8495

B. S. Sathyaprakash
Cardiff University
5, The Parade, Cardiff
CF24 3YB, UK
B.Sathyaprakash@astro.cf.ac.uk
+44-029-208-76962

TEACHING STATEMENT

As a teacher, I strive to show students the beauty I find in physics. The drive for clear presentation of physics concepts in my research talks and seminars also extends to teaching students.

As an undergraduate, I volunteered at the English as a Second Language Science Resource center at the University of British Columbia. However, my first formal teaching experience was as a teaching assistant for introductory courses at the University of Wisconsin–Milwaukee. With these first experiences, I developed teaching goals for myself that still apply. I try to develop multiple perspectives, to accommodate students with different learning styles and backgrounds—if students are frustrated, repeating the same explanation is rarely helpful. I tell interesting stories related to the material I'm presenting. I also emphasize the physical meaning behind the equations we use.

I found that incorporating concept maps and sketches was particularly helpful for students whose understanding of physics is less intuitive. For a Mechanics course at UWM, I had a student who was having trouble getting started with problems create a map of the different equations available. In a tutorial session on Introductory Electromagnetism, I constructed a review diagram showing how fields and potentials were linked by each of the equations we had covered. One student in that class concluded their teaching evaluation with "I can't think of a single way to make a physics discussion any better."

I find it useful to read articles and research about teaching methods for ideas about how to effectively convey information. Resources like the Force Concept Inventory show how students are likely to misinterpret ideas in introductory physics. I try to encourage active learning on the part of students, with quizzes and problems that connect concepts in new ways. One of my best moments as a TA was when a quiz I'd written, about work done by friction, led to a student telling me excitedly as he handed it in that he'd gained a new understanding of energy.

I think it is also important for students' understanding for the teacher to simply get things right. While some errors are inevitable, I try to make sure that the things I write and say are accurate or appropriately qualified, showing clear logical structure in the solving of complex equations and making assumptions explicit. This also sets a good example for the development of students' own problem solving skills. Teaching students how to clearly lay out a mathematical argument on paper can improve their problem-solving skills—as well as making grading easier.

In 2010, I stepped in to lecture on "Gravitational Waves: modelling sources" at an Astroparticle Physics summer school in Nijmegan, the Netherlands, with three days notice. Working from existing course outlines and finding good pedagogical and review articles allowed for efficient preparation. I enjoyed the opportunity to introduce my field of research to a broad audience of graduate students and postdocs, as well as attending faculty, and my lectures were well received.

More recently, I lectured as a substitute for faculty at the University of Mississippi, taking over undergraduate classes in Astrophysics and introductory Physics. The small class size of the Astrophysics class allowed me to experiment with a class outline entirely driven by student questions, which was a lot of fun, and I am interested in working on scaling higher levels of participation to larger classes. In an introductory physics on Wave Superposition, I attempted to give the undergraduate students a feel for the mathematical concepts beyond just plugging in equations, and got them participating with questions and answers by the end of the class. I also gave a week of guest lectures for the graduate physics course in Mathematical Methods, giving a quick overview of Bayesian probability and Markov Chain Monte Carlo methods for parameter estimation, and gained experience in making appropriately challenging problem sets.

I have also involved myself in outreach activities while at the University of Mississippi. I worked out how to produce patterns for accurate but easily constructed paper models of the spacetime around black holes and neutron stars. These tactile props help explain to a general audience what curvature means, and I presented them in the outreach session at the 9th Amaldi conference in Cardiff last summer. I have also contributed to the development of a Science Café in Oxford, MS, which involves short general-audience talks and discussion in a local bakery, making flyers to advertise the event and developing an outreach presentation that I will give in November.

I value the renewed depth of understanding that teaching a subject brings me, and the chance to review topics of interest in a broader context. I am always delighted to explain my field of research to new people.

TEACHING INTERESTS: Mechanics, electromagnetism, mathematical methods, software engineering for scientists, modern physics, classical and quantum field theory, general relativity, astrophysics, gravitational waves, compact objects.

Jocelyn S. Read

Research Statement

My scientific interests cover a range of topics in neutron-star astrophysics and gravitational-wave astronomy. I use a combination of analytic and numerical methods to link the theoretical properties of neutron stars to their observable characteristics, investigating the physics of dense matter in extreme conditions through both electromagnetic and gravitational-wave observations.

Key results from my research include a widely-used phenomenological equation of state (EOS) parameterization for neutron stars [1], a generalized stability criterion for rotating neutron stars used to efficiently find maximal spins [1], the first quantitative estimates of neutron star EOS measurability in the second-generation Laser Interferometer Gravitational-Wave Observatory (LIGO), using the results of fully relativistic hydrodynamic simulations [2], and the calculation of early-inspiral tidal effects on gravitational waves for a full range of realistic EOSs, using a post-Newtonian/perturbative framework [3]. My work on tidal interactions in binaries of neutron stars has led to a new model for precursor flares before Short Gamma Ray Bursts [4] and revealed the possibility of using gravitational-wave observations alone to measure both redshift and luminosity distance [5].

My research also includes combining post-Newtonian/perturbative orbital dynamics with tidal disruption estimates in black-hole-neutron-star binaries[6], exploring the effects of modified gravity on neutron star observations [7, 8], and contributing to the science case for the third-generation "Einstein Telescope" gravitational-wave detector [9, 10, 11, 12]. Past research included exploring methods to construct relativistic binary initial data [13] and searching for cosmic string signals in LIGO[14].

As an assistant professor at California State Fullerton, I will develop a program which allows students to develop broadly-applicable computational, mathematical, and numerical modelling skills, while continuing to advance the state-of-the art in neutron star astrophysics, EOS exploration, and gravitational-wave astronomy. I will build a research program accessible to undergraduates as well as graduate students—for example, several of the perturbative approaches reduce to understanding and solving particular ODEs for a range of parameters. Developing resources for outreach can also yield tangible results from short-term projects. To build such a program, an effective startup package will require an initial period of support for students and sufficient travel funds to maintain engagement with the international scientific community while sources of external funding are secured. Computational resources will also be required to support comprehensive studies of astrophysical scenarios.

Understanding the neutron star EOS brings together the interests of diverse areas in physics, and gravitational-wave astrophysics is an emerging field; many interesting problems remain unexplored. Below I outline several topics of research in these areas where I and my research group will address currently outstanding issues, and find important new questions.

MATTER PROPERTIES FROM OBSERVATIONS OF NEUTRON STARS

There is substantial uncertainty about the behaviour of matter in the cores of neutron stars, which reach densities of up to ten times nuclear density. Various EOSs have been proposed based on different composition and interaction models for matter at these densities. I am interested in developing methods to systematically explore the effects of EOS differences.

In collaboration with John Friedman, Ben Lackey, and Ben Owen, I developed a way to write a phenomenological EOS which can approximate many different candidates by the choice of a few parameters, independently of the details of the underlying model. This allows us to use observations to constrain a parameter space, rather than individually allowing or ruling out an ever-changing set of proposed candidates [1]. Since our work, this type of parameterization has been incorporated and built upon by several groups working on neutron star EOS [15, 16, 17].

I am interested in extending the phenomenological description beyond strictly ground-state equilibrium matter, to allow the inclusion of composition and temperature-dependent effects. These are required to describe dynamic behaviour in certain oscillation modes, and become important in neutron-star mergers. While EOS tables which include these effects are available (e.g. [18, 19, 20]), they do not currently cover the full range of possible ground-state EOS. A simplified but systematic approach may be powerful in this regime as well.

Understanding of the range of realistic EOSs is also key for realistic numerical simulation of systems with neutron stars.

TIDAL INTERACTIONS IN COMPACT BINARIES

Neutron stars in compact binaries lose energy to gravitational waves, spiralling towards their companion. As they orbit, the EOS determines the deformation of a neutron star, and of the surrounding spacetime, due to interaction with the companion's tidal field. Perturbative calculations of the strength of this deformation can be used to calculate corrections to the binding energy of orbits and to the gravitational-wave luminosity. These are incorporated into post-Newtonian orbital dynamics and waveforms that describe the inspiral of the two stars.

The results can be used directly to estimate detectability and parameter extraction from binary neutron-star inspiral with gravitational wave detectors. With Tanja Hinderer, Benjamin Lackey, and Ryan Lang, I explored the possible constraint of realistic neutron-star EOSs from binary neutron stars [3]. Even restricted to the low-frequency regime, Advanced LIGO/VIRGO can constrain extreme EOS. Later work with Francesco Pannarale, Luciano Rezzolla, and Frank

Ohme considered mixed black-hole/neutron-star binaries with tidal disruption cutoffs [6], showing that inspiral alone would not be sufficient to distinguish them from binary black holes.

The post-Newtonian/perturbative description of matter effects continues to impact current research in gravitational-wave signals and data analysis. It is being used in investigations of the impact of matter on current gravitational-wave searches, and is required to accurately connect with the high-frequency regime where numerical simulations come into play (next section). Recently, in collaboration with Chris Messenger, I also showed that the matter effects could allow redshift to be determined from gravitational-wave observations, leading to potentially significant cosmological constraints [5].

Studying the tidal interactions of neutron-stars in this framework has also led to new explorations of dense matter. Precursor flares were recently observed before Short Gamma-Ray Bursts [21], which are generally thought to result from the merger of a compact binary which includes a neutron star. With collaborators David Tsang, Tanja Hinderer, Tony Piro, and Ruxandra Bondarescu, I developed a new model for these precursor flares: the periodic tidal deformation can excite a resonant mode, shattering the neutron-star crust [4]. Especially when combined with gravitational-wave observations, measurement of precursors constrains the frequencies of these resonant modes, placing restrictions on the EOS of the neutron-star crust.

Current research involves developing more sophisticated models for the precursor flares, including a more detailed description of deformation of various surfaces, a detailed study of mode dynamics, the verification of analytic models by comparison with numerical simulations, and the exploration of state-of-the-art crust EOS with collaborator Andrew Steiner. I am principal investigator on a currently-submitted NASA proposal, "The Dynamic Response and Multi-messenger Signatures of Inspiraling and Coalescing Neutron Stars," to study these systems.

Gravitational waves from simulations of binary coalescence

The EOS affects the dynamics of neutron-star binary inspiral even more strongly close to merger. Numerical simulations with systematically varying EOS trace these effects on the system through the final orbits, the coalescence of the two stars, and the prompt or delayed collapse to a black hole.

First results using numerical simulations of double neutron-star inspiral [2] showed that different EOSs produce noticeably different late-inspiral signals in advanced detectors, for relatively close binary neutron star mergers (occurring roughly yearly). These merger difference are significant in a broadband detector configuration or in one tuned to be especially sensitive at high frequencies.

To do the best gravitational-wave astrophysics, it is imperative to develop a thorough understanding of matter effects on binary coalescence waveforms by the time Advanced LIGO measures such signals. Looking to the future, a third-generation detector such as the Einstein Telescope would be able to track binary neutron-star waveforms accurately through inspiral and merger [9]—probing dense matter somewhat like an astrophysical-scale version of the Relativistic Heavy Ion Collider.

A large portion of my current work involves the analysis of new numerical waveforms in a broad collaboration (with L. Baiotti, J. Creighton, J. Friedman, K. Kyutoku, C. Markakis, M. Shibata, K. Taniguchi), involving numerical relativity groups based both in AEI–Potsdam and the YITP in Kyoto [22]. The length of inspirals simulated and the numerical resolution continue to improve, and the comparison of waveforms from different codes strengthens our understanding of numerical error. We have substantially decreased the uncertainty in numerical-only estimates. The new results agree with the previous estimates [2] and re-emphasize the potential of Advanced LIGO to constrain the neutron-star EOS.

Going further, to learn the most about the EOS, the high-frequency regime of numerical simulation must be joined to lower-frequency post-Newtonian models. Constructing such hybrid waveforms requires long numerical inspirals at high resolution, the inclusion of perturbative/post-Newtonian matter effects, and careful analysis of the systematic errors potentially induced by matching the two together[22]. Based on this work, the future development of a phenomenological inspiral/merger/post-merger description for binary neutron-star waveforms, analogous to those developed for binary black holes (e.g. [23, 24]), is likely to be key to efficient data analysis.

An final interesting prospect for investigating the detectability of this type of signal is the extension of the Numerical INJection Analysis (NINJA) project [25] to encompass waveforms from numerical simulations incorporating matter. I have already contributed to extending the data formats used in NINJA to apply to data from systems with matter [26]. With James Clark (UMass Amherst), I am working to coordinate a project which will test inspiral- and burst-search pipelines with simulation data from systems including double neutron-star binaries and mixed black-hole/neutron-star binaries; more information is available on the Matter NINJA wiki [27].

References

[1] Jocelyn S Read, Benjamin Lackey, Benjamin Owen, and John Friedman. Constraints on a phenomenologically parametrized neutron-star equation of state. *Physical Review D*, 79(12), June 2009.

[2] Jocelyn S Read, Charalampos Markakis, Masaru Shibata, Kōji Uryū, Jolien Creighton, and John Friedman. Measuring the neutron star equation of state with gravitational wave observations. *Physical Review D*, 79(12):1–12, June 2009.

[3] Tanja Hinderer, Benjamin Lackey, Ryan Lang, and Jocelyn S Read. Tidal deformability of neutron stars with realistic equations of state and their gravitational wave signatures in binary inspiral. *Physical Review D*, 81(12):1–12, June 2010.

[4] David Tsang, Jocelyn S. Read, Tanja Hinderer, Anthony L. Piro, and Ruxandra Bondarescu. Resonant Shattering of Neutron Star Crusts. *arXiv:1110.0467, submitted to Phys Rev Lett*, 2011.

[5] Chris Messenger and Jocelyn Read. Measuring a cosmological distance-redshift relationship using only gravitational wave observations of binary neutron star coalescences. *arXiv:1107.5725, submitted to Phys Rev Lett*, 2011.

[6] Francesco Pannarale, Luciano Rezzolla, Frank Ohme, and Jocelyn S. Read. Will black hole-neutron star binary inspirals tell us about the neutron star equation of state? *arXiv:1103.3526, accepted to Phys Rev D*, 2011.

[7] Paolo Pani, Vitor Cardoso, Emanuele Berti, Jocelyn Read, and Marcelo Salgado. The vacuum revealed: the final state of vacuum instabilities in compact stars. *Phys.Rev.*, D83:081501, 2011.

[8] Paolo Pani, Emanuele Berti, Vitor Cardoso, and Jocelyn Read. Compact stars in alternative theories of gravity. Einstein-Dilaton-Gauss-Bonnet gravity. *arXiv:1109.0928, submitted to Phys Rev D*, 2011.

[9] N. Andersson, V. Ferrari, D. I. Jones, K. D. Kokkotas, B. Krishnan, Jocelyn S Read, L. Rezzolla, and B. Zink. Gravitational waves from neutron stars: promises and challenges. *General Relativity and Gravitation*, August 2010.

[10] S. Hild, M. Abernathy, F. Acernese, P. Amaro-Seoane, N. Andersson, et al. Sensitivity Studies for Third-Generation Gravitational Wave Observatories. *Class.Quant.Grav.*, 28:094013, 2011.

[11] M. Punturo, M. Abernathy, F. Acernese, B. Allen, N. Andersson, et al. The Einstein Telescope: A third-generation gravitational wave observatory. *Class.Quant.Grav.*, 27:194002, 2010.

[12] M. Punturo, M. Abernathy, F. Acernese, B. Allen, N. Andersson, et al. The third generation of gravitational wave observatories and their science reach. *Class.Quant.Grav.*, 27:084007, 2010.

[13] Shin'ichirou Yoshida, Benjamin C Bromley, Jocelyn S Read, Kōji Uryū, and John L Friedman. Models of helically symmetric binary systems. *Classical and Quantum Gravity*, 23(16):S599–S613, August 2006.

[14] Xavier Siemens, Jolien Creighton, Irit Maor, Saikat Majumder, Kipp Cannon, and Jocelyn S Read. Gravitational wave bursts from cosmic (super)strings: Quantitative analysis and constraints. *Physical Review D*, 73(10), May 2006.

[15] K. Hebeler, J. Lattimer, C. Pethick, and A. Schwenk. Constraints on Neutron Star Radii Based on Chiral Effective Field Theory Interactions. *Physical Review Letters*, 105(16):161102, October 2010.

[16] Feryal Ozel, Gordon Baym, and Tolga Guver. Astrophysical Measurement of the Equation of State of Neutron Star Matter. *Phys. Rev.*, D82:101301, 2010.

[17] Andrew W Steiner, James M Lattimer, and Edward F Brown. The Equation of State from Observed Masses and Radii of Neutron Stars. *The Astrophysical Journal*, 722(1):33–54, October 2010.

[18] H. Shen, H. Toki, K. Oyamatsu, and K. Sumiyoshi. Relativistic equation of state of nuclear matter for supernova and neutron star. *Nucl.Phys.*, A637:435–450, 1998.

[19] G. Shen, C. J. Horowitz, and S. Teige. Equation of State of nuclear matter in a Virial expansion of nucleons and nuclei. *Phys. Rev.*, C82:045802, 2010.

[20] James M. Lattimer and F.Douglas Swesty. A Generalized equation of state for hot, dense matter. *Nucl.Phys.*, A535:331–376, 1991.

[21] Eleonora Troja, Stephan Rosswog, and Neil Gehrels. Precursors of short gamma-ray bursts. *Astrophys.J.*, 723:1711–1717, 2010.

[22] Jocelyn S Read, Luca Baiotti, Jolien Creighton, John L. Friedman, Koutarou Kyutoku, Charalampos Markakis, Luciano Rezzolla, Masaru Shibata, and Keisuke Taniguchi. Matter effects on double neutron star binary waveforms. *In preparation.*

[23] Parameswaran Ajith, S. Babak, Y. Chen, M. Hewitson, B. Krishnan, et al. Phenomenological template family for black-hole coalescence waveforms. *Class.Quant.Grav.*, 24:S689–S700, 2007.

[24] L. Santamaria et al. Matching post-Newtonian and numerical relativity waveforms: systematic errors and a new phenomenological model for non-precessing black hole binaries. *Phys. Rev.*, D82:064016, 2010.

[25] B Aylott and Others. Testing gravitational-wave searches with numerical relativity waveforms: Results from the first Numerical INJection Analysis (NINJA) project. January 2009.

[26] P. Ajith, M. Boyle, D. A. Brown, S. Fairhurst, M. Hannam, I. Hinder, S. Husa, B. Krishnan, R. A. Mercer, F. Ohme, C. D. Ott, J. S. Read, L. Santamaria, and J. T. Whelan. Data formats for numerical relativity waves. *arXiv:0709.0093, updated 24 Feb 2011*.

[27] Matter NINJA home page. `https://www.ninja-project.org/doku.php?id=matter:home`.