Understanding Neutron Stars from Gravitational Wave **Observations**

Binary Neutron Star Coalescence as a Fundamental Physics Laboratory: INT, Seattle, 30 June 2014

B.S. Sathyaprakash

School of Physics and Astronomy, Cardiff University

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- Focus here on **binary** neutron star mergers

Outline ³

& Upcoming gravitational wave detectors

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Advanced detectors, Einstein Telescope

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	- Dark energy equation of state

Between 2006-2010 larger detectors took 2 years worth of data at unprecedented sensitivity levels

 \cdot \cdot No detections so far but beginning to impact astrophysics $\qquad \qquad \cdot$ $\qquad \qquad \cdot$

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American LIGO Hanford and Livingston detectors

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Advanced Detectors: Ca 2015-2025

Detector Networks 2015-

Baselines in light travel $time_{(}ms_{)}$ 6

Detector Networks 2016-

Baselines in light travel $time_{(}ms_{)}$ 7

Detector Networks 2018-

Baselines in light travel $time_{(}ms_{)}$

Detector Networks 2022-

Baselines in light travel time (ms) 9

Detector Beam Pattern Function

- \cdot Gives the sensitivity of a detector to sources at different parts of the sky
- $\cdot \epsilon$ For a single detector the beam is a quadrupole
- \cdot For a network of 5 or more globally distributed detectors the pattern can essentially become isotropic

Challenge of Gravitational Wave Searches

- A network of \cdot \cdot gravitational wave detectors is always on and sensitive to most of the sky
- Signals can be \cdot . milliseconds long or last for years
- Multiple signals could \cdot . be in band but with different amplitudes
- **We can integrate and** build SNR by coherently tracking signals in phase

Advanced LIGO Sensitivity

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Beyond Advanced Detectors: 2G+ and Einstein Telescope

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2008 -2011 European Conceptual Design Study

2013 -2016 ET R & D

Underground detectors should have Significant reduction in

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Sources in Advanced Detectors

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Sources in ET

Amplitude from a source of size R at a distance *D* is $\cdot \epsilon$.

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 $L = (Asymmetry factor) \times (GM/Rc^2)^5$

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- **Source Location** can be determined with a network of three or more \cdot . detectors
- **Source Distance** can be inferred if the signal model is accurate \cdot .

Sky Localization Error Ellipses :

Binary Neutron Stars at 160 Mpc; Uses only Timing Information

Red crosses denote regions where the network has blind spots

Fairhurst 2011

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Sky Localization Error Ellipses :

Binary Neutron Stars at 160 Mpc; Uses only Timing Information

Fairhurst 2011

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Comparison of Gravitational Wave Detector Network Sky Localization Approximations

K. Grover,¹ S. Fairhurst,² B. F. Farr,^{3,1} I. Mandel,¹ C. Rodriguez,³ T. Sidery,¹ and A. Vecchio¹

Sky Localization

about 2.5 Sq Degrees with LIGO-Virgo network $\frac{1}{10}$ by assumented of $\frac{1}{6}$

Neutron star (NS) and black hole (BH) binaries will

pointing telescopes, but the sky location can be reconstructure through through the time of arrival of G radiation \overline{G}

(a) Typical posterior density function $\mathcal{P}_{\mathcal{A}}$ and $\mathcal{P}_{\mathcal{A}}$ posterior density function $\mathcal{P}_{\mathcal{A}}$

How long do BNS signals last in our detectors?

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ing discoveries between now and 2028 will be the ones we

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NS Equation-of-State

Maximum Mass of a Neutron Star and Mass Gap

- \cdot Heaviest known neutron star has a mass of 2 solar masses
	- although many equations of state are ruled out by this model many more remain
- \cdot Finding heavier neutron stars is not likely to fix the problem
	- Many EoS predict heavier neutron stars with exotic cores
- **....** Measuring both NS mass and Radius is the key
	- \cdot \cdot If radius can be measured to within a few km then EoS will be very tightly constrained

Advanced detectors would go someway but ET will be critical to resolving the issues

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Effect of tides in BNS inspiral Effect of tides in PNC inspiral **delta in the contribution is in the contribution of the contribution in the contribution of the contribution of** \mathbf{z} \overline{a} and \overline{a} and \overline{a} , $\overline{$ arxiv:1101.4298 [astro-phone of the E. E. E. E. E. E. E. E. E. D, 19, 1994, 265 \overline{r} and \overline{r} the property is unknown. Effect of tides in divs inspiral

K. G. Arun, B. R. Iyer, B. S. Sathyaprakash, *N* oundaratajan, Thys. Rev. D, 71, 00+000 (2005), arxiv.gr-
gc/0411146. \boldsymbol{V} \boldsymbol{C} Arun **D D** Iver **D** S Sethvenreleach and **D** A Sundararajan, Phys. Rev. D, 71, 084008 (2005), arXiv:gr-K. G. Arun, B. R. Iyer, B. S. Sathyaprakash, and P. A. $qc/0411146.$

[23] L. Rezzolla, B. Giacomazzo, L. Baiotti, J. Granot, C. Kouve-

 $\overline{\mathcal{L}}$, $\overline{\mathcal{L}}$

$$
\Psi_{PP}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\eta x^{5/2}} \sum_{k=0}^{N} \alpha_k x^{k/2}
$$

T. Hinderer, B. D. Lackev, R. N. Lang. and J. S. Read. Phys.

post-Newtonian point-particle frequency domain phase can be

Rev. D, 81, 123016 (2010), arXiv:0911.3535 [astro-ph.HE]. T. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read, Phys.
Rev. D. 81, 122016 (2010), exVive0011, 2525 Latre ph UEL 1. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read, Ph
Rev. D, **81**, 123016 (2010), arXiv:0911.3535 [astro-ph.HE]. and J.
3535 [a 0 -ph.

x = (π*M f*) ²/³ and the corresponding coefficients α*^k* given in [25]. Throughout this work we use *N* = 7 corresponding to a 3.5 PN phase expansion (the highest known at the time of publication). The parameters *tc* and φ*^c* are the time of coalescence and phase at coalescence and we use *f* to represent the GW frequency in the rest frame of the source. Note that if the signal is modeled using the point-particle phase such Ψtidal(*f*) = " *a*=1,2 3λ*^a* 128η # −24 χ*a* \$ 1 + 11η χ*a* % *x*⁵/² *^M*⁵ (3) [−] ⁵ 28χ*^a* & ³¹⁷⁹ [−] ⁹¹⁹χ*^a* [−] ²²⁸⁶χ² *^a* + 260χ³ *a* ' *^x*⁷/² *M*⁵ (where we sum over the contributions from each NS (indexed by *a*). The parameter λ = (2/3)*R*⁵ ns*k*² characterizes the ^Ψ*PP*(*f*) ⁼ ²^π *f tc* [−] ^φ*^c* [−] ^π + *k*=0 α*^k x^k*/² (2) where we use the post-Newtonian dimensionless parameter *x* = (π*M f*) ²/³ and the corresponding coefficients α*^k* given in [25]. Throughout this work we use *N* = 7 corresponding [29] T. Hinderer, Astrophys. J., 677, 1216 (2008), arXiv:0711.2420. [30] A. W. Steiner, J. M. Lattimer, and E. F. Brown, Astrophys. J., 722, 33 (2010), arXiv:1005.0811 [astro-ph.HE]. [31] F. Ozel, G. Baym, and T. G ¨ uver, Phys. Rev. D, ¨ 82, 101301 (2010), arXiv:1002.3153 [astro-ph.HE]. [32] T. Damour and A. Nagar, Phys. Rev. D, 80, 084035 (2009), arXiv:0906.0096 [gr-qc]. [33] K. D. Kokkotas and G. Schafer, Mon. Not. R. Astron. Soc., 275, 301 (1995), arXiv:gr-qc/9502034. [34] L. Baiotti, T. Damour, B. Giacomazzo, A. Nagar, and L. Rezzolla, Physical Review Letters, 105, 261101 (2010), [18] F. Pannarale, L. Rezzolla, F. Ohme, and J. S. Read, ArXiv eprints (2011), arXiv:1103.3526 [astro-ph.HE]. [19] E. E. Flanagan and T. Hinderer, Phys. Rev. D, 77, 021502 uchi, Phys. Rev. D, 83, 124008 (2011), arXiv:1105.4370 [astroph.HE]. [45] C. K. Mishra, K. G. Arun, B. R. Iyer, and B. S. Sathyaprakash, Phys. Rev. D, 82, 064010 (2010), arXiv:1005.0304 [gr-qc]. In our analysis we use a Fisher matrix approach applied to a PN frequency domain waveform to estimate the accuracy to which the redshift can be measured. We also assume nonspinning component masses and treat the waveform as valid up to the innermost-stable-circular orbit (ISCO) frequency, *The signal model*—We follow the approach of [24, 25] in *a*=1,2 128η χ*a* χ*a ^M*⁵ (3) [−] ⁵ 28χ*^a* & ³¹⁷⁹ [−] ⁹¹⁹χ*^a* [−] ²²⁸⁶χ² *^a* + 260χ³ where we sum over the contributions from each NS (indexed by *a*). The parameter λ = (2/3)*R*⁵ ns*k*² characterizes the strength of the induced quadrupole given an external tidal

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distance multiplied by a geometric factor accounting for the

orientation of the binary relative to the detector) within given

redshift intervals will allow the accurate determination of ac-

tual luminosity distance and consequently of cosmological pa-

rameters including those governing the dark energy equation

of state. Such a scenario significantly increases the potential

for 3rd generation GW detectors to perform precision cosmol-

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ity distance and redshift simultaneously for individual BNS

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 (201)

151 (2001), arXiv:astro-ph/0111092.

arXiv:nucl-th/9603037.

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 $\mathcal{A}^{\mathcal{A}}_{\mathcal{A}}$ K. Hotokezaka, M. Shibata, and K. Shibata, and K. Ki-Shibata, and

Rev. C, 58, 1804 (1998), arXiv:hep-ph/9804388.

 q_0

BNS mergers and equation of state of NS

- \cdot Spectrum of gravitational radiation from black hole binaries is featureless
- \cdot . Radiation from binary neutron star mergers carries an imprint of the star's mass and equation of state

Tuesday, 1 July 2014

NS EoS with a population of BNS mergers: Advanced detectors, ~25 merger events hie Eag with

Dark Energy Equation-of-State

Why are BNS signals standard sirens? 31

- **Example 2** Luminosity distance *D* can be inferred if one can measure:
	- the flux of radiation *F* and
	- absolute luminosity *L*

 $D_L =$ \sqrt{L} $4\pi F$

Schutz Nature1986

- \cdot . Flux of gravitational waves determined by amplitude of gravitational waves measured by our detectors
- Absolute luminosity can be inferred from the rate \dot{f} at which the frequency of a source changes
	- Not unlike Cephied variables except that \dot{f} is completely determined by general relativity
- \cdot . Therefore, compact binaries are self-calibrating standard sirens

Advanced LIGO Distance Reach to Binary Coalescences

$\ddot{}$ $\overline{}$ \mathbf{S} bursts as standard sine \mathbf{S} Suming short hard CRRs are hinary neutron star this rate. It is not contained to the rate of the r
The rate of the rate of th Hubble Constant from Advanced Detectors Assuming short-hard-GRBs are binary neutron stars 33

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allows

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inated by beamed NS-BH binaries using the "full" netis further augustion by a factor of 1.12. The stim face? we find that one year of observation should be enough to measure H_0 to an accuracy of $\sim 1\%$ if SHBs are domwork of LIGO, Virgo, AIGO, and LCGT—admittedly,

 $\frac{1 \text{ hV}}{2014}$

 \log_{10} \leq \log_{10} Tuesday, 1 July 2014

Hubble Constant from Advanced Detectors Conclusion EM counterparts

25 events:

 H_0 = 69 ± 3 km s⁻¹ Mpc⁻¹ (~4% at 95% confidence)

■ 50 events:

- H_0 = 69 ± 2 km s⁻¹ Mpc⁻¹ (~3% at 95% confidence)
- ! WMAP7+BAO+SnIa (Komatsu et al.,2011):

 \blacksquare H₀ = 70.2 ± 1.4 km s⁻¹ Mpc⁻¹ (~2% at 68%) confidence)

$P_{\text{S}} = 0.011$ Del Pozzo, 2011

ET Distance Reach to Coalescing Binaries

ET Distance Reach to Coalescing Binaries

ET Distance Reach to Coalescing Binaries

Visibility of Binary Inspirals in **Einstein** Telescope 10 20 20 30 40 50 60 70 80 1 10³ 10³ 1 $10²$ 10² 10^3 M_1/M _{\odot} *M₂/M* ETB, $z=1$

ET: Measuring Dark Energy and Dark Matter 37

- \cdot . ET will observe 100's of binary neutron stars and GRB associations each year
- \cdot . GRBs could give the host location and red-shift, GW observation provides $D_{\rm L}$

Class. Quantum Grav. **27** (2010) 215006

Sathyaprakash et al 2010

Measuring *w* and its variation with z \sim The equation-of-state (EOS) of the data energy component w dominates the evolution of recent expansion of \sim the Universe observations. In this paper, we show the observation \mathbf{z}

38

Baskaran, Van Den Broeck, Zhao, Li, 2011

as a function of redshift z:

Hubble without the Hubble: Cosmology using advanced gravitational-wave detectors alone

Stephen R. Taylor[∗]

Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK

Jonathan R. Gair†

Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK

Ilya Mandel‡

NSF Astronomy and Astrophysics Postdoctoral Fellow, MIT Kavli Institute, Cambridge, MA 02139; and School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT (Dated: January 31, 2012)

Cosmology with the lights off: Standard sirens in the Einstein Telescope era

Stephen R. Taylor[∗] and Jonathan R. Gair[†] Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK (Dated: July 6, 2012) (Dated: July 6, 2012)

$Coseo a$ ansatz for the relationship between $Coseo b$ Cosmology without Livi Coul ⁴⁰ distribution is model as not on **2 Cosmology without EM Counterpart** for local studies due to the divergence at high redshift. COSHOLOGY WILHOUL EM COUTTER PAIL Cosmology without EM Counterparts

Distribution of Chirp Mass Γ neutron star mass distribution. The chirp mass distribution of Γ ∙ ⊱Distribution of Chirp Mass
Normal, Distribution of Chirp Mass Evolve that "the "tank" form that ensures w = −1. The ensures w = +1. The ensures w = +1. The ensures w = +1. T
That ensures w = +1. The ensu $\frac{1}{2}$

The maximum binary system mass could conceivably system mass could conceivably conceivably conceivably conceivably \mathcal{L}

$$
\mathcal{M} \sim N(\mu_c, \sigma_c^2),
$$

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$$
\mu_c \approx 2(0.25)^{3/5} \mu_{\text{NS}}, \quad \sigma_c \approx \sqrt{2}(0.25)^{3/5} \sigma_{\text{NS}},
$$

\n
$$
\mu_{\text{NS}} \in [1.0, 1.5] M_{\odot}, \sigma_{\text{NS}} \in [0, 0.3] M_{\odot}
$$

$$
w(a) = w_0 + w_a(1 - a),
$$

$$
w(z) = w_0 + w_a\left(\frac{z}{1 + z}\right).
$$

Taylor Cai $\frac{1}{2}$ Tuesday, 1 July 2014 \overline{a} $\overline{2}$ Taylor, Gair 2012

 $\mathcal{L}(\mathcal{L})$

distribution is modeled as normal,

The two system properties we will use in our analysis

are the redshifted chirp mass, Mz, and the luminosity

distance, DL. We assume that only systems with an SNR

 $\mathcal{G}(\mathcal{G})$

write down the distribution of the distribution of the number of events per second per se

unit time in the observer's frame with M, z and effective

with mean and standard deviation

Measuring dark energy EoS and its variation with redshift

41

Measuring red-shift from GW observations alone

Messenger-Read method to measure redshift makes use of the post-Newtonian tidal term Messenger Read method to measure redshift makes use of the nest Newtonian tidal term post-Newtonian post-Newtonian tradition Messenger_Read method to measure redshift makes use of the post_Newtonian tidal term gle the mass parameters and the mass parameters and the redshift from the waveform the waveform the waveform the waveform of t makes use of the post_Newtonian tidal term $\ddot{}$ Aessenger_Read method to measure redshift 43 $\frac{3}{2}$ M. O, $\frac{3}{2}$ qc/0703086. [39] S. Hild *et al.*, Classical and Quantum Gravity, 28, 094013

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x = (π*M f*) ²/³ and the corresponding coefficients α*^k* given in [25]. Throughout this work we use *N* = 7 corresponding to a 3.5 PN phase expansion (the highest known at the time of publication). The parameters *tc* and φ*^c* are the time of coalescence and phase at coalescence and we use *f* to represent the GW frequency in the rest frame of the source. Note that if the signal is modeled using the point-particle phase such Ψtidal(*f*) = " *a*=1,2 3λ*^a* 128η # −24 χ*a* \$ 1 + 11η χ*a* % *x*⁵/² *^M*⁵ (3) [−] ⁵ 28χ*^a* & ³¹⁷⁹ [−] ⁹¹⁹χ*^a* [−] ²²⁸⁶χ² *^a* + 260χ³ *a* ' *^x*⁷/² *M*⁵ (where we sum over the contributions from each NS (indexed by *a*). The parameter λ = (2/3)*R*⁵ ns*k*² characterizes the ^Ψ*PP*(*f*) ⁼ ²^π *f tc* [−] ^φ*^c* [−] ^π + *k*=0 α*^k x^k*/² (2) where we use the post-Newtonian dimensionless parameter *x* = (π*M f*) ²/³ and the corresponding coefficients α*^k* given in [25]. Throughout this work we use *N* = 7 corresponding [29] T. Hinderer, Astrophys. J., 677, 1216 (2008), arXiv:0711.2420. [30] A. W. Steiner, J. M. Lattimer, and E. F. Brown, Astrophys. J., 722, 33 (2010), arXiv:1005.0811 [astro-ph.HE]. [31] F. Ozel, G. Baym, and T. G ¨ uver, Phys. Rev. D, ¨ 82, 101301 (2010), arXiv:1002.3153 [astro-ph.HE]. [32] T. Damour and A. Nagar, Phys. Rev. D, 80, 084035 (2009), arXiv:0906.0096 [gr-qc]. [33] K. D. Kokkotas and G. Schafer, Mon. Not. R. Astron. Soc., 275, 301 (1995), arXiv:gr-qc/9502034. [34] L. Baiotti, T. Damour, B. Giacomazzo, A. Nagar, and L. Rezzolla, Physical Review Letters, 105, 261101 (2010), [18] F. Pannarale, L. Rezzolla, F. Ohme, and J. S. Read, ArXiv eprints (2011), arXiv:1103.3526 [astro-ph.HE]. [19] E. E. Flanagan and T. Hinderer, Phys. Rev. D, 77, 021502 uchi, Phys. Rev. D, 83, 124008 (2011), arXiv:1105.4370 [astroph.HE]. [45] C. K. Mishra, K. G. Arun, B. R. Iyer, and B. S. Sathyaprakash, Phys. Rev. D, 82, 064010 (2010), arXiv:1005.0304 [gr-qc]. In our analysis we use a Fisher matrix approach applied to a PN frequency domain waveform to estimate the accuracy to which the redshift can be measured. We also assume nonspinning component masses and treat the waveform as valid up to the innermost-stable-circular orbit (ISCO) frequency, *The signal model*—We follow the approach of [24, 25] in *a*=1,2 128η χ*a* χ*a ^M*⁵ (3) [−] ⁵ 28χ*^a* & ³¹⁷⁹ [−] ⁹¹⁹χ*^a* [−] ²²⁸⁶χ² *^a* + 260χ³ where we sum over the contributions from each NS (indexed by *a*). The parameter λ = (2/3)*R*⁵ ns*k*² characterizes the strength of the induced quadrupole given an external tidal

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distance multiplied by a geometric factor accounting for the

orientation of the binary relative to the detector) within given

redshift intervals will allow the accurate determination of ac-

tual luminosity distance and consequently of cosmological pa-

rameters including those governing the dark energy equation

of state. Such a scenario significantly increases the potential

for 3rd generation GW detectors to perform precision cosmol-

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ity distance and redshift simultaneously for individual BNS

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Host redshifts from gravitational wave observations ⁴⁵

Host-galaxy redshifts from gravitational-wave observations of binary neutron star mergers

C. Messenger,¹ Kentaro Takami,^{2, 3} Sarah Gossan,⁴ Luciano Rezzolla,^{3, 2} and B. S. Sathyaprakash⁵

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Topics for discussion

- Missing post Newtonian terms
	- Tidal terms are at 5 and 5.5 PN order; unknown terms at 4 and 4.5 PN severely bias the estimation of parameters
	- What progress can be made in computing 4 and 4.5 PN terms?
	- Are there other ways of mitigating the e!ect of unknown PN terms?
- \cdot . Signal from the merger phase and bar mode instability
	- Would it be possible to build a complete analytic model for the signal emitted during and post-merger?
- \cdot . Effect of strong magnetic fields, high spins, multicomponent fluid, ...
	- How far away are we from "realistic" BNS simulations?
	- How good are these simulations: stability and convergence?