Two Statistical Challenges in Gravitational-Wave Astronomy

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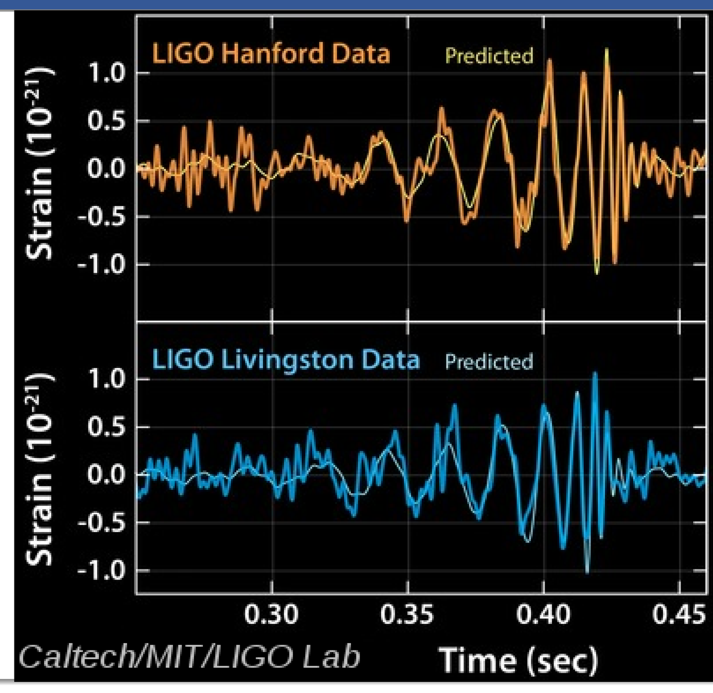
LIGO has opened the observational era of gravitational wave astronomy

Advanced LIGO has detected the first gravitational wave signal, GW150914, from the merger of two stellar-mass black holes [A1, 2]. With even higher-sensitivity observation runs in the near future, gravitational-wave data analysis is now joining the world of observational astronomy. Statistics and inference played an important role in the discovery of GW150914, and will be a key ingredient in meeting any of the challenges in this endeavor.

Many such challenges remain: confident detection and precise parameter estimation of an increasing number of signals; inference of merger rates and source population properties; detecting other types of GW sources; . . .

On this poster I discuss just two of them, related to my own work. But please feel invited to talk to me about any other LIGO- and GW-related topics!



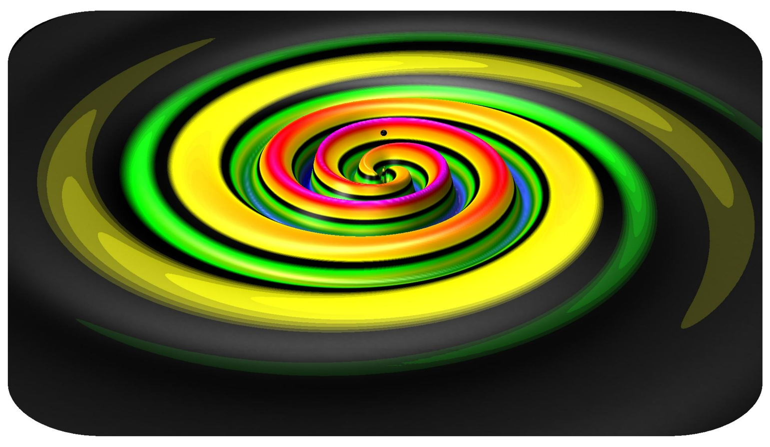
Challenge A: modelling binary black-hole (BBH) coalescence

current work with S. Husa, X. Jiménez Forteza et al. @UIB; collaborating with Cardiff Univ., ICTS Bengaluru, IUCAA Pune

How can the properties of gravitational-wave emission from BBH coalescences be inferred with fitting formulae calibrated to numerical-relativity simulations, and how can advanced statistical and machine learning methods improve this procedure? Simulations are computationally expensive and thus only sparsely cover the parameter space of binary masses and spins, so that we need to calibrate phenomenological models with fits to NR data. Model selection can improve fits of quantities such as the radiated energy and peak luminosity, and the full inspiral-merger-and-ringdown waveform models.

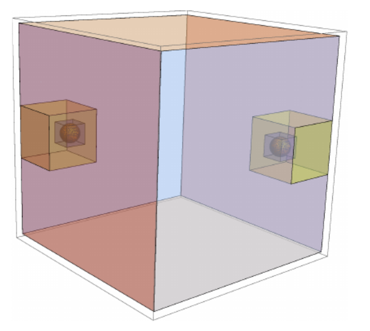
A.I binary black hole (BBH) coalescence

- BBHs are 'clean' gravity-only systems [A3]
- well described by general relativity [A4]
- strong-field dynamics near merger require numerical solutions of Einstein's equations ('Numerical Relativity', NR [A5, 6, 7])
- BBH parameter space: mass ratio, (total mass), two 3D spin vectors
- dominant spin dynamics captured by aligned spin
- full precesssional dynamics require all 6 components



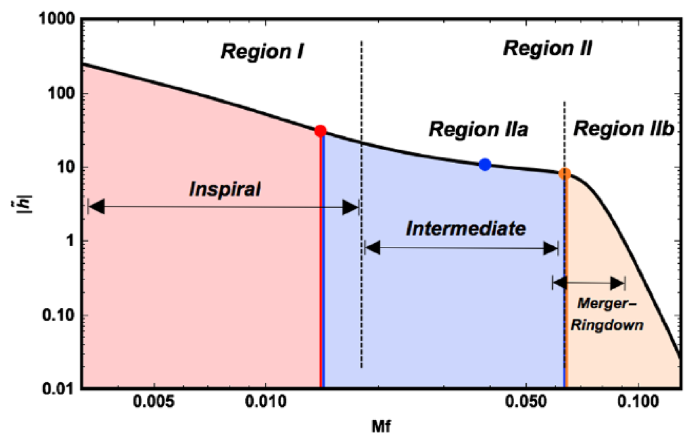
NR: ψ_4 from a BBH merger [S. Husa, R. Jaume @UIB]

A.II Fits and Models



'moving puncture' BBH simulation grids

- BBH waveform models calibrated to NR
- IMRPhenom approach [A9, 10, 11]: split phase evolution into 3 regimes (inspiral, merger, ringdown), fit phenomenological model for each
- successful in estimating the properties of GW150914 through LALInference [A1, 2, 4, 8]

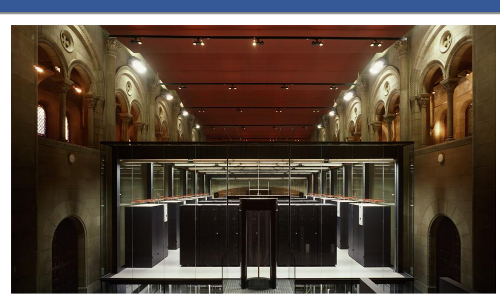


regimes of the PhenomD waveform model [A11]

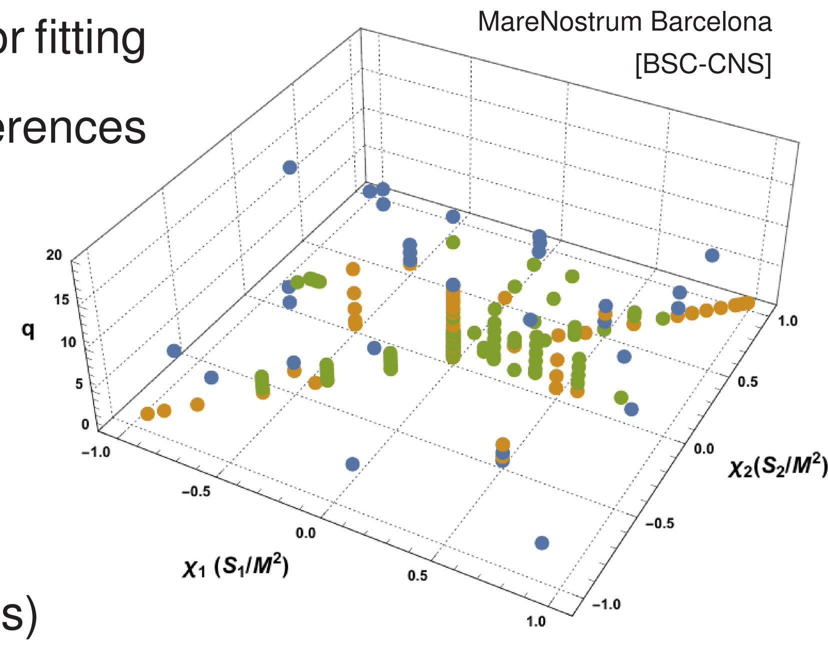
- interesting quantities: final mass, final spin, radiated energy and luminosity
- fun fact: though we can only 'see' them in GWs, BBH mergers are the most 'luminous' events since the Big Bang
- recent UIB fit [A12], GW150914 peak luminosity: $3.6^{+0.5}_{-0.4} \cdot 10^{56}$ erg/s

A.III Open Challenges

- *in principle*, we can generate arbitrary numbers of NR sims and fully cover the BBH parameter space
- *in practice*, each NR run takes days–months even on top computers, so . . .
- . . . place new sims where they matter most for fitting
- . . . carefully study numerical errors and differences between data sets from different codes
- . . . use effective model selection (currently: AIC, BIC, cross-validation; future: fully Bayesian, Neural Networks?) to ensure that we . . .
  - . . . neither under- nor overfit features in the mass-ratio – spin parameter space
  - . . . extrapolate robustly into undercovered difficult regions (high mass ratio, high spins)



MareNostrum Barcelona [BSC-CNS]



aligned-spin NR data set for [A12]

A.IV References

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- [A3] Sathyaprakash & Schutz, LRR 12 (2009), 2
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- [A9] Hannam et al., *PRL* **113**,151101 (2014)
- [A10] Husa et al., *PRD* **93**,044006 (2016)
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- [A12] Jiménez Forteza, Keitel, Husa et al., https://dcc.ligo.org/LIGO-T1600018/public

Challenge B: robust searches for Continuous Waves

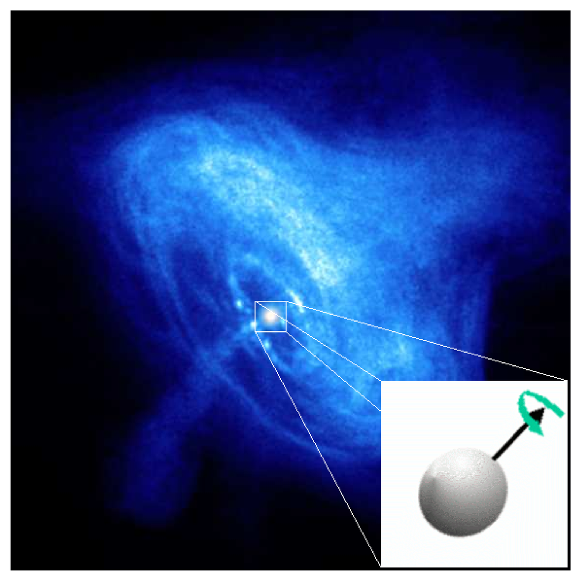
work with R. Prix, M. A. Papa, P. Leaci, M. Sidiqi, Y.-M. Hu (AEI Hannover, 2010–2015)

Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut)

How can Bayesian model selection improve the search for Continuous Gravitational Waves from rapidly-spinning neutron stars? Most search methods assume Gaussian noise and rely on data-cleaning, ad-hoc vetoes or manual post-processing to deal with non-Gaussian noise artifacts. With generalized noise models, we can derive more robust detection statistics. An additional challenge is to extend CW searches to cover transient gravitational-wave signals of similar frequency evolution, but limited duration.

B.I Neutron stars, Continuous Waves, and detector artifacts

- non-axisymmetric rotating neutron stars emit quasi-monochromatic gravitational waves
- long-duration Continuous Wave (CW) signals: one of the main LIGO/Virgo/KAGRA targets [B1]
- "lines" are (almost-)stationary instrumental artifacts, e.g. from electrical power, vibrating mirror suspensions, digital components
- most CW search methods assume Gaussian noise, susceptible to false alarms from instrumental artifacts
- usually treated with ad-hoc vetoes, and sometimes with expensive follow-up methods



Chandra/NASA, inset: R. Prix

B.II Line-robust statistics

- standard frequentist $\mathcal{F}$-statistic [B2, 3] rederived as a Bayes factor [B4] (under an unphysical amplitude prior):

$$B_{\mathrm{S/G}} = \frac{P(\text{ signal } \mid \text{data}, \mathcal{I})}{P(\text{Gaussian noise} \mid \text{data}, \mathcal{I})} \propto e^{\mathcal{F}}$$

- modeling line artifacts as perfect CW impostors limited to a single detector, obtain line-robust detection statistic [B5, 6]:

$$B_{\mathrm{S/GL}} = \frac{P(\text{ signal } \mid \text{data}, \mathcal{I})}{P(\text{Gaussian noise} \mid \text{data}, \mathcal{I}) + P(\text{line} \mid \text{data}, \mathcal{I})}$$

- unphysical prior results in a free parameter, can be used to tune the statistic: reproduce $\mathcal{F}$-stat sensitivity in quiet data, improve over it in presence of lines
- but tuning requires Monte Carlo studies with simulated signals
- historical note: early results presented at SCMA5 @ PennState 2011 [B7]
- recently extended [B8] to also provide robustness against transient line-like disturbances and transient CW-like signals [B9]

B.III Applications: Einstein@Home

- the world's largest computation resource for GW data analysis: distributed volunteer computing, already found >50 EM pulsars, still looking for GWs
- line-robust statistic [B5] as main ranking statistic for E@H analysis of initial LIGO S6 science run (all-sky and directed at CasA) and advanced LIGO O1
- also transient-enhanced statistic [B8] for O1 search

B.IV Open Challenges

- ongoing work at AEI Hannover (Prix & Hu): remove need for empirical tuning, based on a physical amplitude prior [B10]
- new project at Glasgow, 2016–2018 (Keitel, Woan, Pitkin, Pearlstone): Bayesian search for transient CWs building on [B8, 9] and/or Bayesian blocks [B11]

B.V References

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