Listening to the Universe with Advanced LIGO

Signal Detection and Inference in Gravitational-Wave Astronomy

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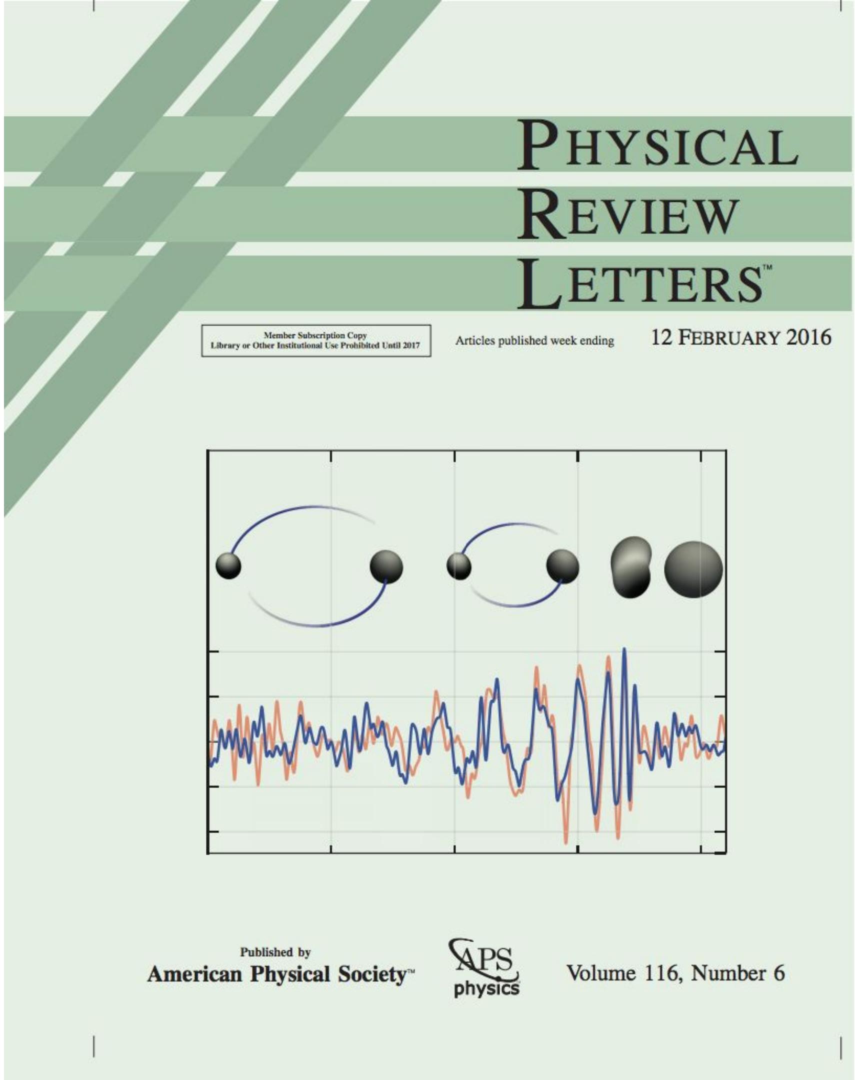
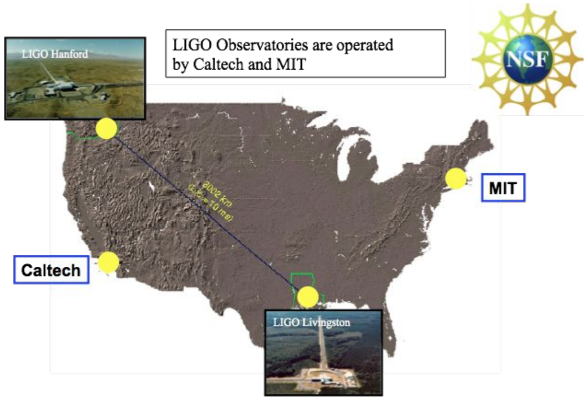
GW astronomy

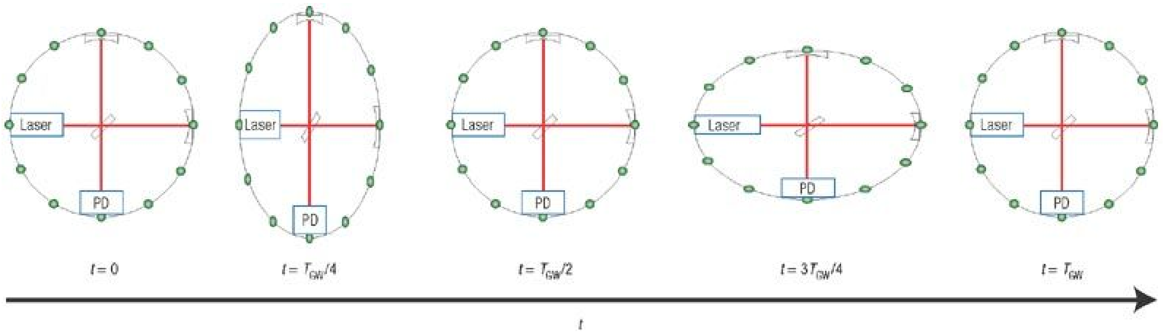
- September 14 2015
- Two black holes 29 and 36 times the mass of the sun merged to form a new black hole
- 1.3 Billion light years away
- New black hole is 62 times the mass of the sun
    - 3 times the mass of the sun converted directly into energy in the form of gravitational waves

Phys. Rev. Lett. 116, 061102



michelson interferometer





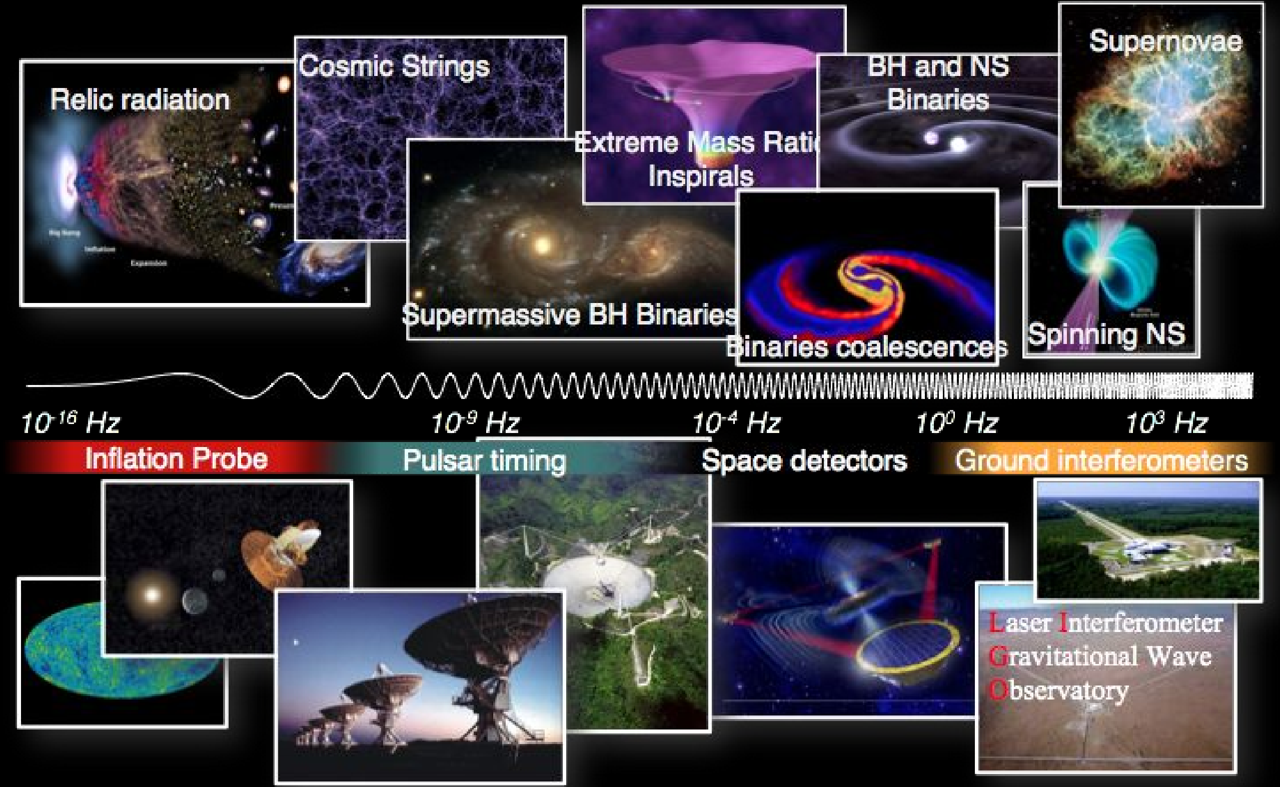
Credit: D. Reize
Nature Photonics **2**, 582 - 585 (2008)

$$\Delta L = h \times L$$

Longer arms, bigger signal!

- Strains around 10^{-20} km/km (change of around 1000th proton width over 4km)

astrophysical sources



Slide Credit: Matt Evans (MIT)

GW science

physics

- test fundamental properties of space-time
- how does matter behave under extreme gravity?
- do black holes have structure?

astrophysics

- what triggers gamma ray bursts?

Cosmology/cosmogrophy

- Mapping the gravitational wave sky

From signals to astronomy

- Detecting GW signals against detector noise
  - Transient sources
  - Continuous sources

- Inference: extracting physics & astrophysics from GWs from binary black holes

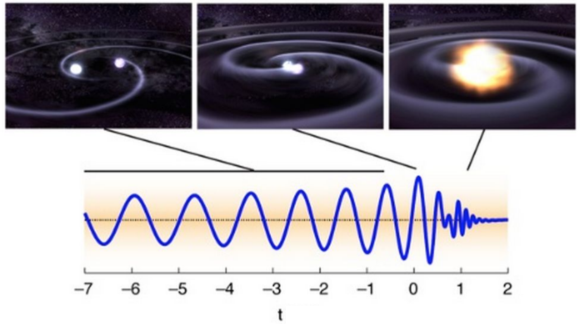
Transient GWs: compact binary coalescence

- Well modelled:
    - Approximate (semi-) analytic methods
    - Supercomputer simulations - “numerical relativity”

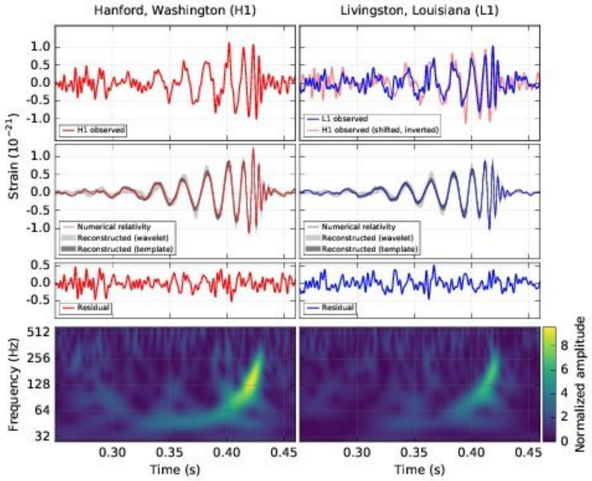
Computational cost

- Use matched filtering to rank events/triggers by their SNR

- Space of all signals described by 15-parameter space of filters: in practice we’re limited to searching within a subset of template space



Credit: J. Veitch



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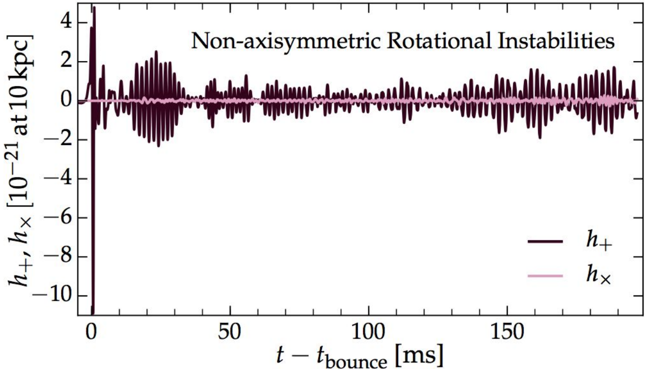
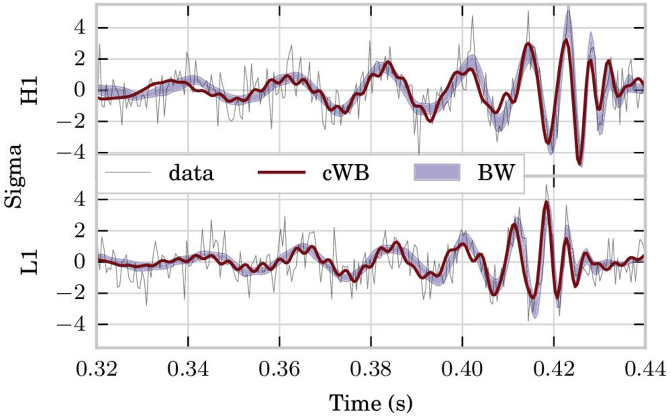
“Generic” transient searches

- Includes:
  - Compact binaries
  - “Bursts” of GWs
  - Supernovae

- Unmodeled searches
  - superposition of wavelets/sine-Gaussians to “build” generic filters



Scheidegger *et al.* 2010



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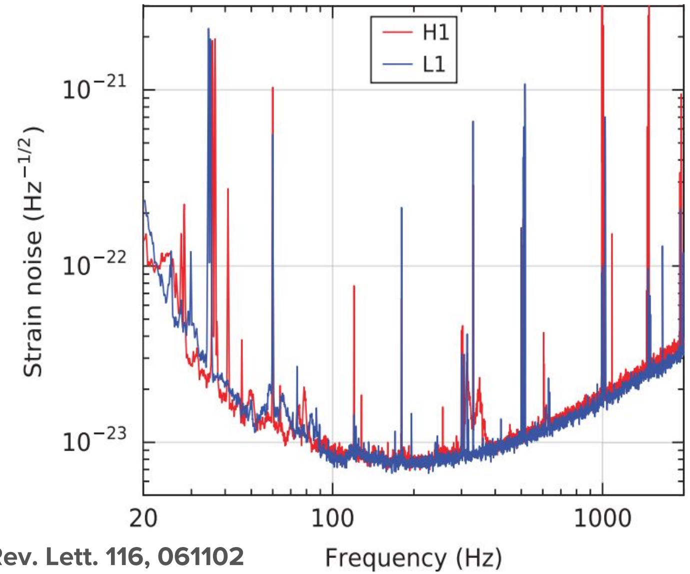
Noise and glitches

- Signals should be coherent/coincident in detectors (modulo light-travel-time) and glitches shouldn't be.



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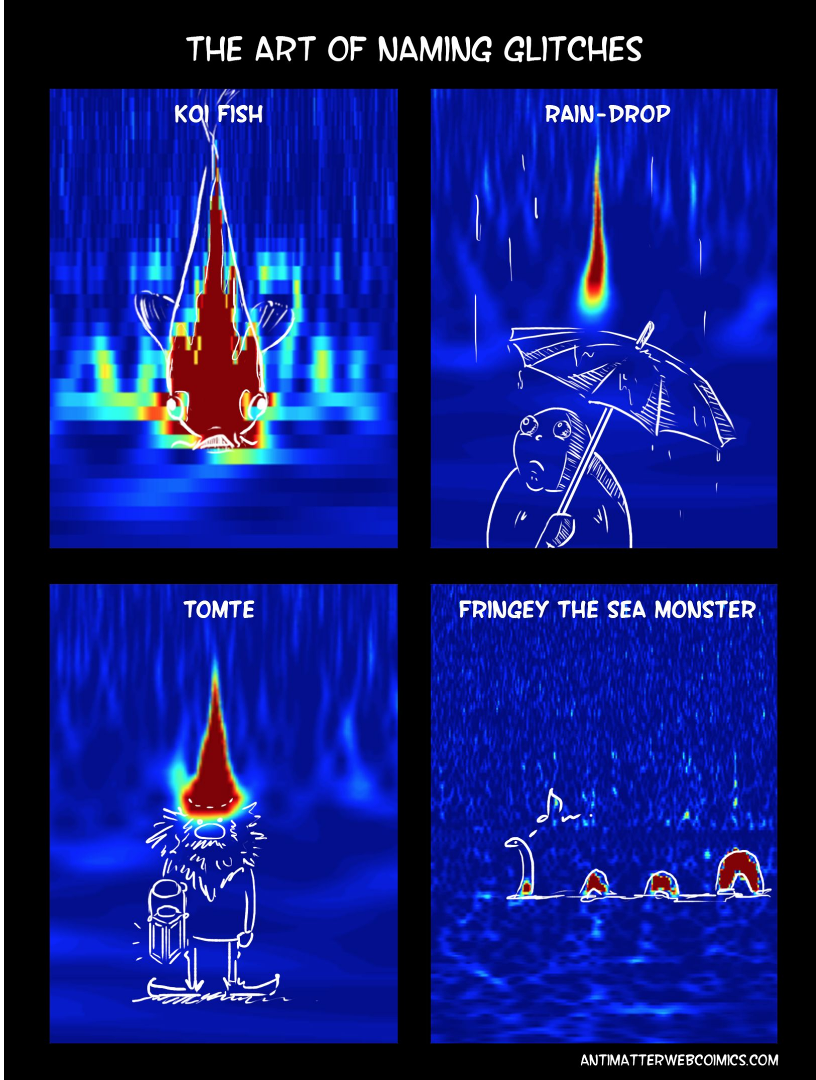
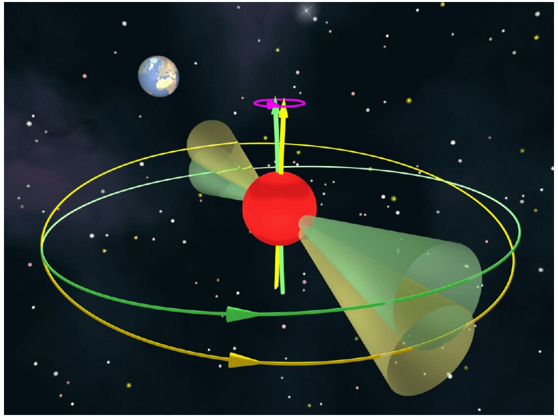


Continuous waves: Pulsars

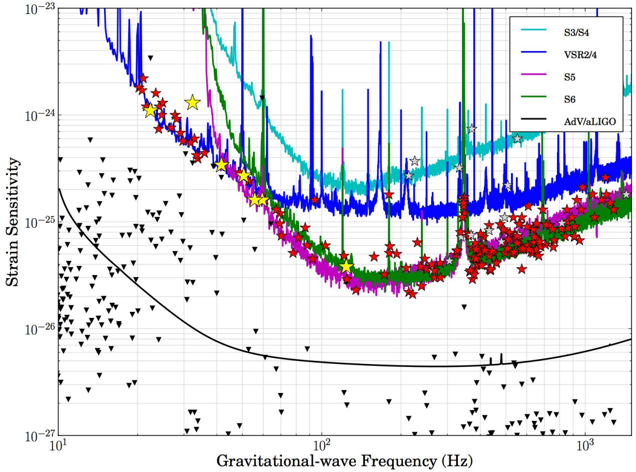
Computational cost

- Pulsars emit continuous stream of GWs at roughly constant frequency
  - Targeted searches of known pulsars (Crab, Vela): use EM data to assume GW frequency is locked to (twice) EM frequency
  - Directed search: (Cas A, Sco X-1) search over some parameters, e.g. inclination & frequency derivatives
  - All Sky (blind) search: Search over all possible sky locations and orientations

- Computationally limited. High-cost analyses use volunteer computing: Einstein@home (c.f., SETI@home)

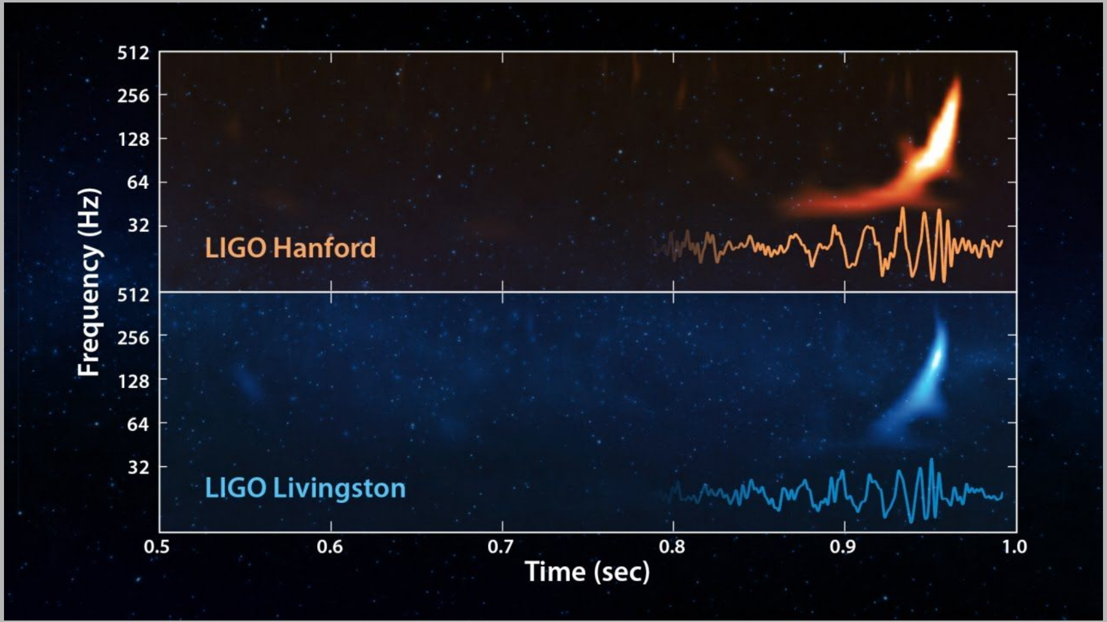


Credit: SKA

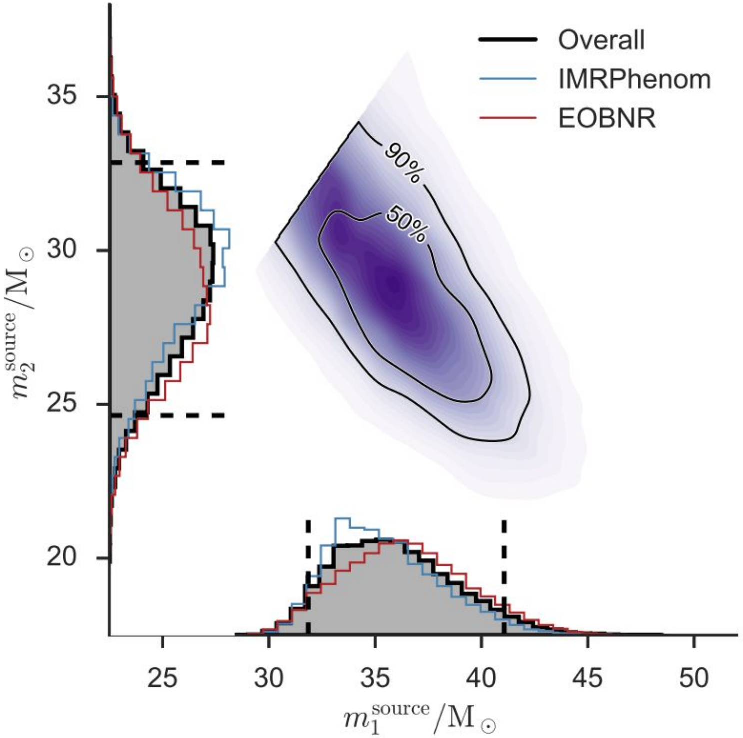


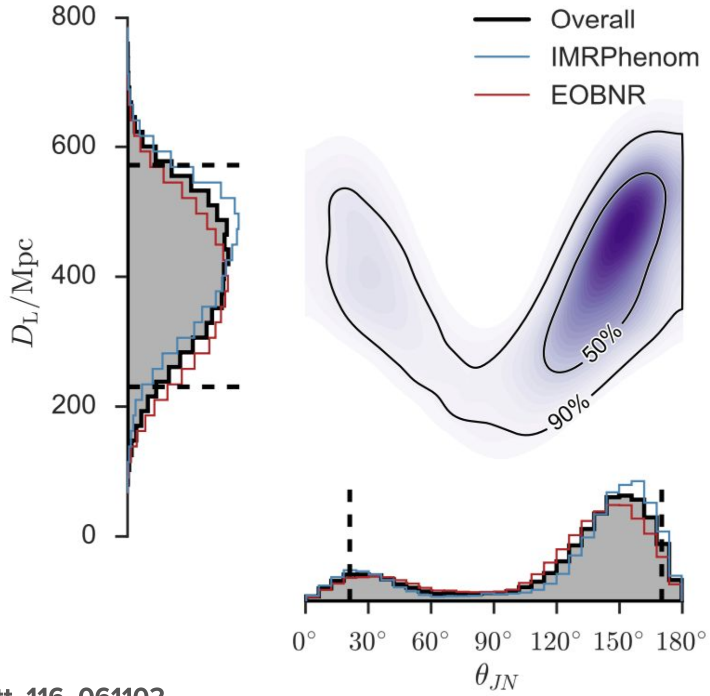
The Astrophysical Journal, 785:119, 2014

Astrophysical inference on binary black holes



parameter estimation





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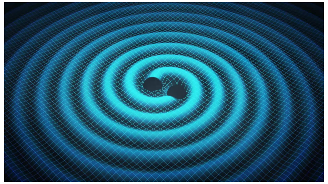
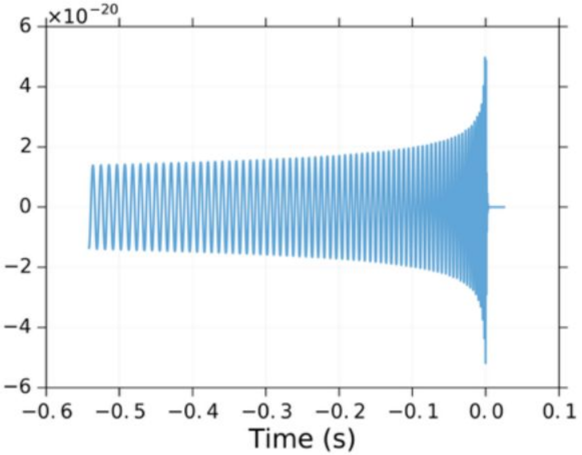
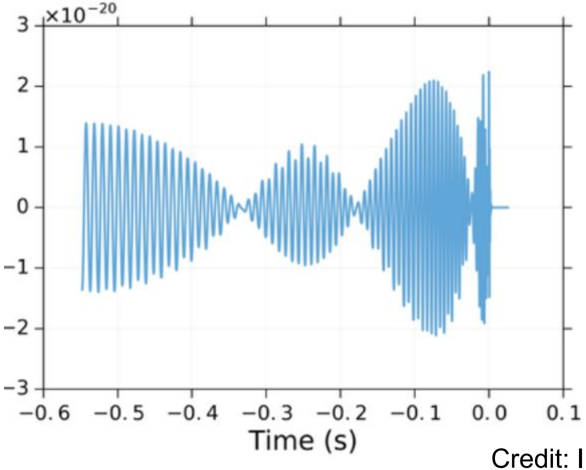


$$d(t) = h(\vec{\lambda}; t) + n(t)$$

$$\vec{\lambda} = (m_1, m_2, \vec{S}_1, \vec{S}_2, \mathrm{ra}, \mathrm{dec}, \mathrm{t.o.a}, \mathrm{dist}, \ldots)$$





Credit: I. Harry

Parameter estimation

- Toolbox:
  - *Markov Chain Monte Carlo (MCMC)* to stochastically sample the posterior over parameter space
    - enhanced with parallel tempering & kernel density estimation to explore multi-modal distributions
    - highly tuned jump proposals
    - optimized model order reduction strategies to accelerate computer/supercomputer simulations and inference
  - *Nested sampling (model selection)*
- Can be highly computationally intensive for long-duration signals/best models.
  - ROM, ensemble sampling

Looking forward

- Era of GW astronomy has just begun.

- Study population of compact binaries
- Tests of gravity/spacetime
  - Extra GW polarizations from CWs?
- Multi-messenger astronomy
  - EM partners joining with GW efforts to locate counterparts to LIGO events
- New detectors in India (LIGO India) and Japan (KAGRA)

- Many HPC, analysis and modeling challenges!