Gravitational waves from compact binary coalescence

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Overview

- Gravitational waves from compact binary stars
  - Evidence for gravitational waves
    - Hulse-Taylor binary pulsar
  - Compact binary objects
    - Inspiral -> Merger -> Ringdown
  - GW emission from a compact binary
- Searches for compact binary signals in GW data
  - The matched filter
  - Noise interference
  - Latest results
- Outlook for the future

Reminder: gravitational waves

- ‘Ripples in spacetime’:

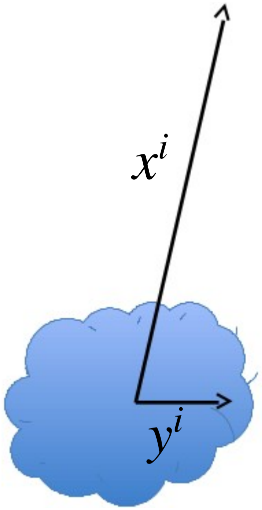
$$g_{ab} = \eta_{ab} + h_{ab}$$

with a wave equation:

$$\partial^c \partial_c h_{ab} = \left(-\frac{\partial^2}{\partial t^2} + \nabla^2 \right) h_{ab} = -16\pi T_{ab}$$

- Can solve wave equation generally:

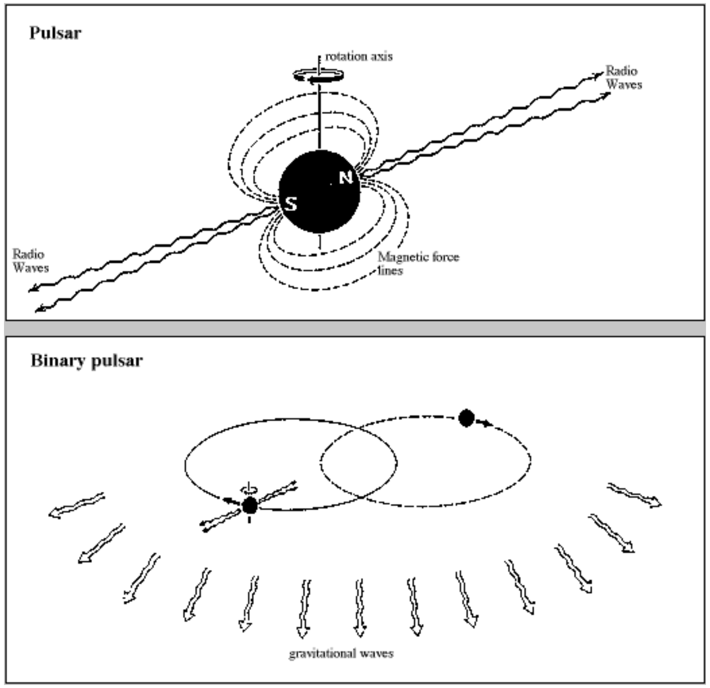
$$h_{ij}(t,x) = \frac{2}{r}\frac{\partial^2}{\partial t^2} \underbrace{\int y^i y^j \, T^{00}(t-r, y^i)\, d^3y}_{\text{mass quadrupole moment in TT gauge}}$$



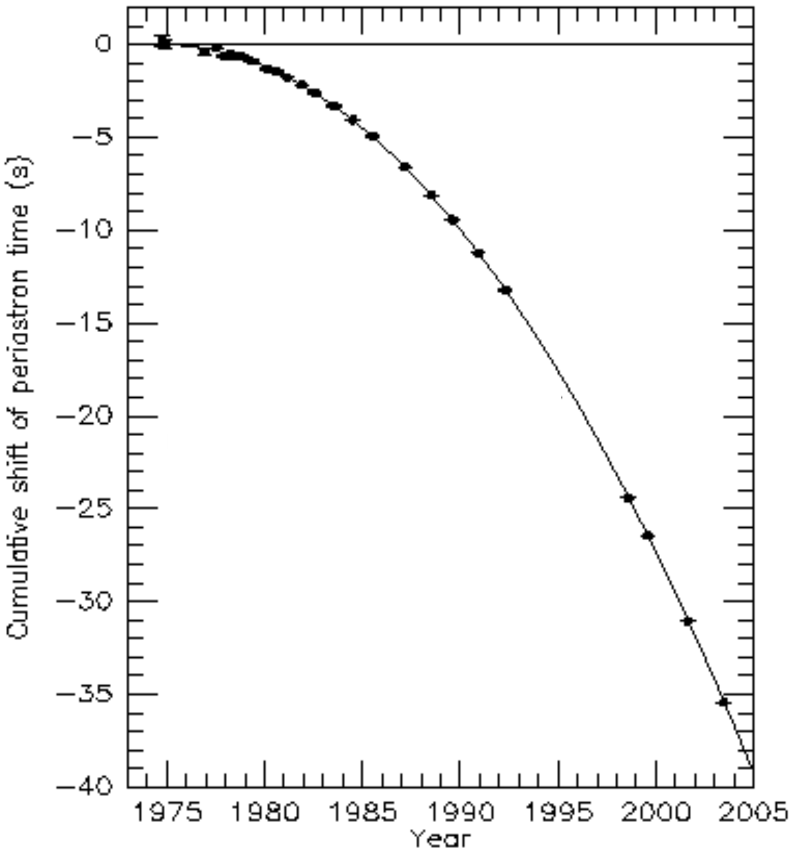
Evidence for gravitational waves

- Amazing indirect evidence for gravitational waves from PSR 1913+16

  'Hulse-Taylor pulsar'
- Pulsar in binary system with another neutron star
  - Detected in 1974
  - Nobel prize in 1993
- General relativity theory predicts radiation of energy, Newtonian gravity doesn't
  - Nice test



http://www.nobelprize.org/nobel_prizes/physics/laureates/1993/



Hulse-Taylor pulsar

Decay of orbital period exactly matches prediction from general theory of relativity due to gravitational radiation

Compact binary objects

- Neutron stars:
  - Remnant from core-collapse supernovae
  - Mass ~ 1-2 $M_\odot$
  - Hard to probe with EM
- Black holes:
  - Massively dense star with escape velocity > c
  - Mass 5-…$M_\odot$
  - Evidence for them at galactic centres
  - Cannot probe with EM

Compact binary objects

- Two compact stars in gravitationally bound rotation
    - Simple example of non-axisymmetric massive system
- Rotation causes energy radiation as gravitational waves
- Emission causes loss of rotational energy

$$E_{\text{orbit}} = E_{\text{kin}} + E_{\text{pot}} = -\frac{-Gm_1m_2}{2R}$$

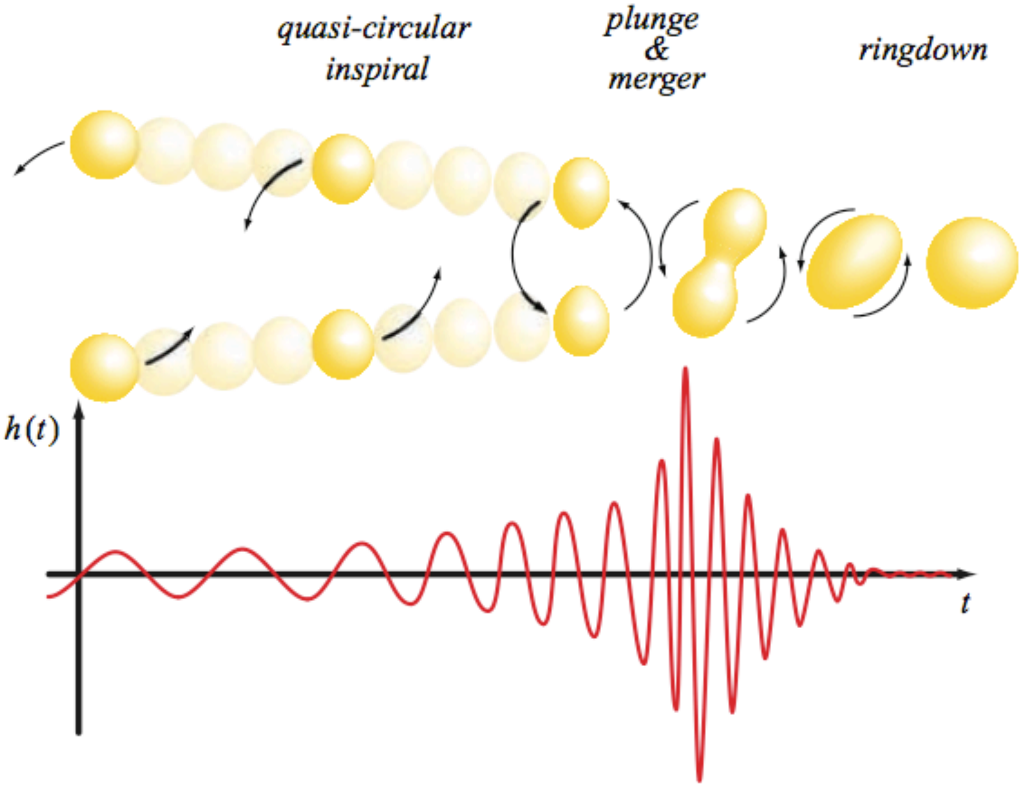
- Orbit decays
- Objects eventually coalesce to form single black hole

Compact binary objects

- Inspiral phase:
  - Approximately circular, stable orbits
  - Use linearised GR:

$$h_+ = -\frac{8m\omega^2 R^2}{r}\cos(2\omega t)$$

- Merger phase:
  - Violent coalescence of objects
  - Large-amplitude, short-duration burst of energy
  - Use numerical methods to simulate
- Ring-down phase:
  - New black hole oscillates down to stable state
  - Use perturbation theory



Baumgarter & Shapiro, *Numerical Relativity*, CUP

Inspiral-merger-ringdown

Gravitational waveform for coalescence of two compact stars

Data analysis

- Inspiral waveforms are easy to predict
  - Majority of energy emitted during inspiral
  - Simple expansion of Newtonian gravity
  - Dependence on object mass, spin and orientation
- Can search data for evidence of signals

Data analysis I: the matched filter

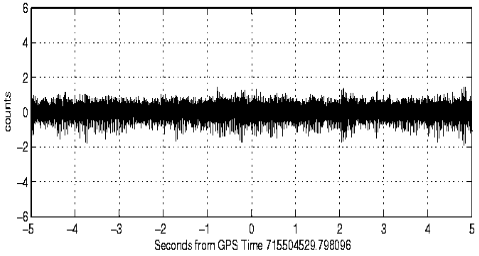
- Typically, signals will be buried in detector noise
- Need analytical method to search data for known waveform
  - The Weiner filter is the optimal method

$$z(t) = 4\Re \int_0^\infty \frac{\tilde{t}^*(f)\tilde{h}(f)}{S_n(f)} e^{2\pi i f t} df$$

  - Compares a known waveform template against the data weighted by sensitivity

Data analysis I: the matched filter

Detector data



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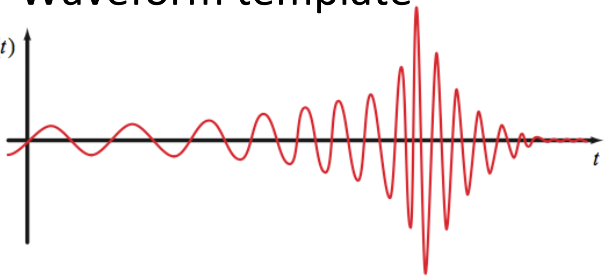
Waveform template



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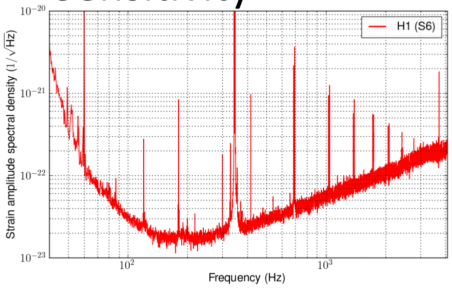
Sensitivity



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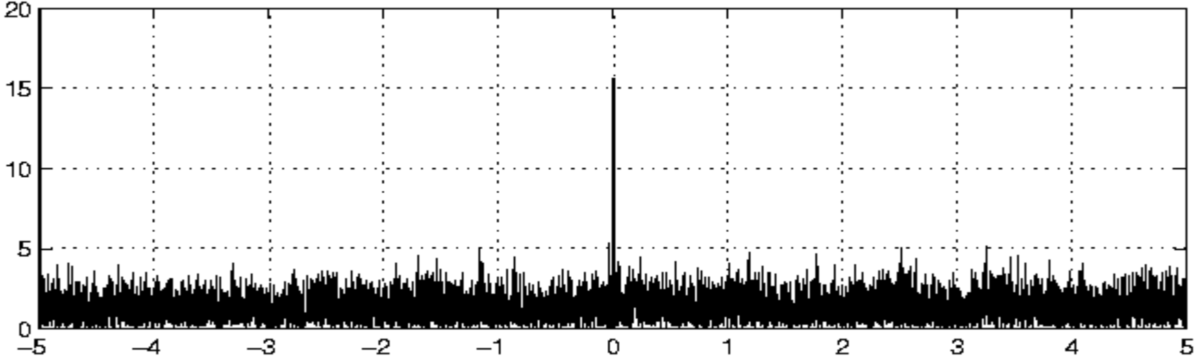
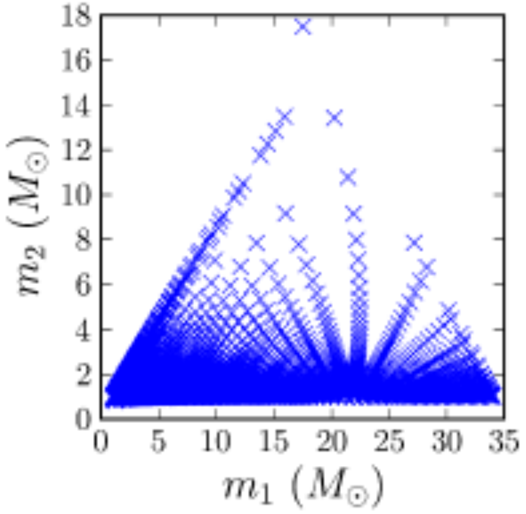
Signal-to-noise ratio



Data analysis II: the search

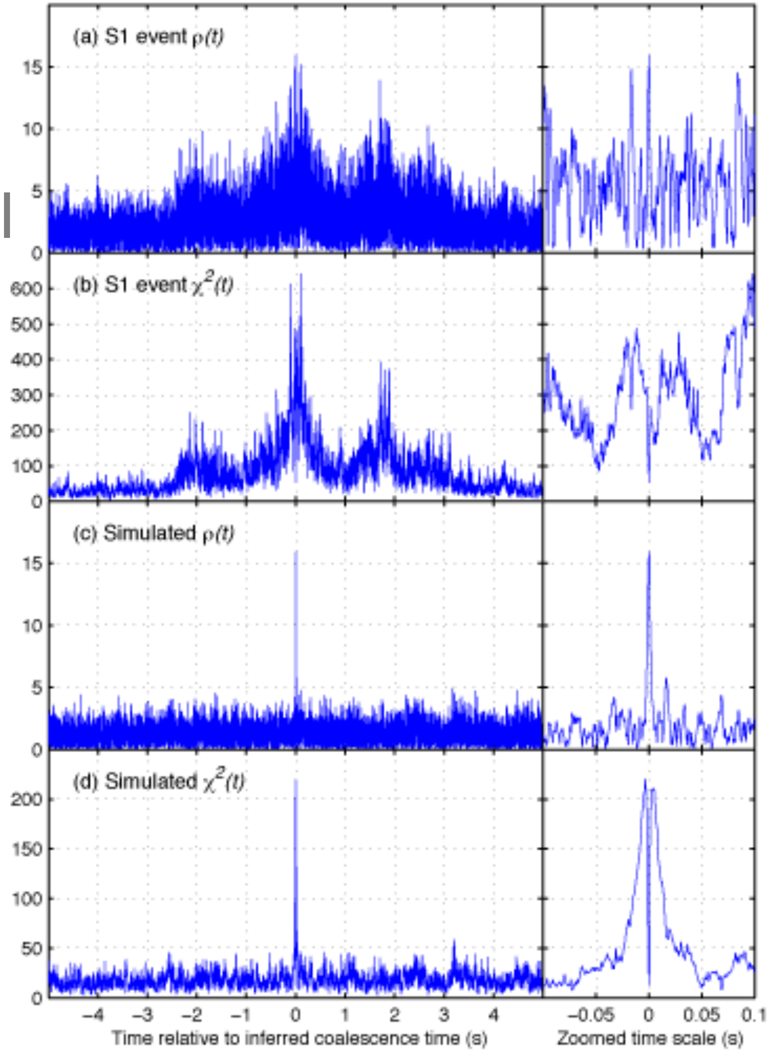
- Perform search over a large bank of waveforms
    - Current methods use inspiral only
    - Full inspiral-merger-ringdown analyses in testing



- Output is list of events ranked by signal-to-noise ratio (SNR)
- Compare data from different detectors for coincidences
    - Potential signal **must** be seen in multiple detectors

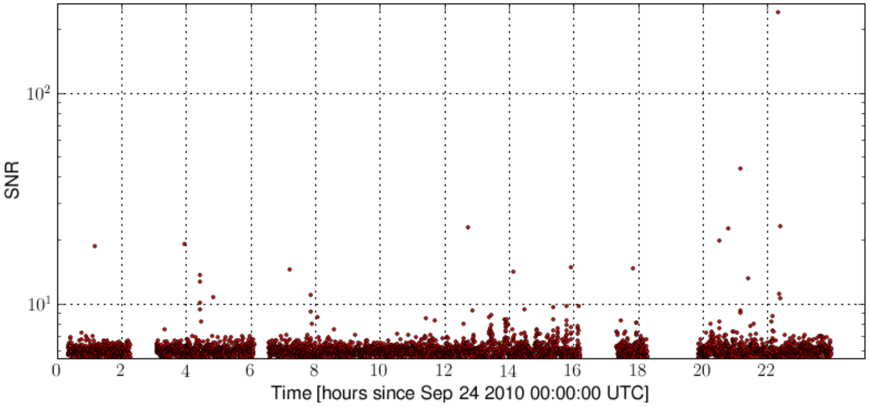
Data analysis II: the search

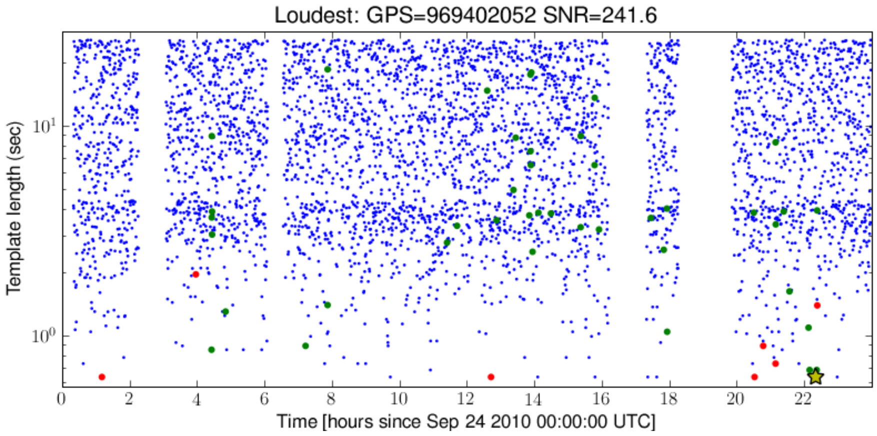
- Test candidate events for consistency
    - Does event look like signal for full duration?
    - Does event look like a noise event
- Train against simulations:
    - Insert known waveforms into data to simulate a signal
    - Use data from these simulations to train tests



Data analysis II: the search

- Eventually end up with list of events
    - Some will be random noise bursts that happen to look like a bit like a CBC waveform
- List of events ranked by 'false-alarm probability'
    - How much does this look like the background of non-signal events?

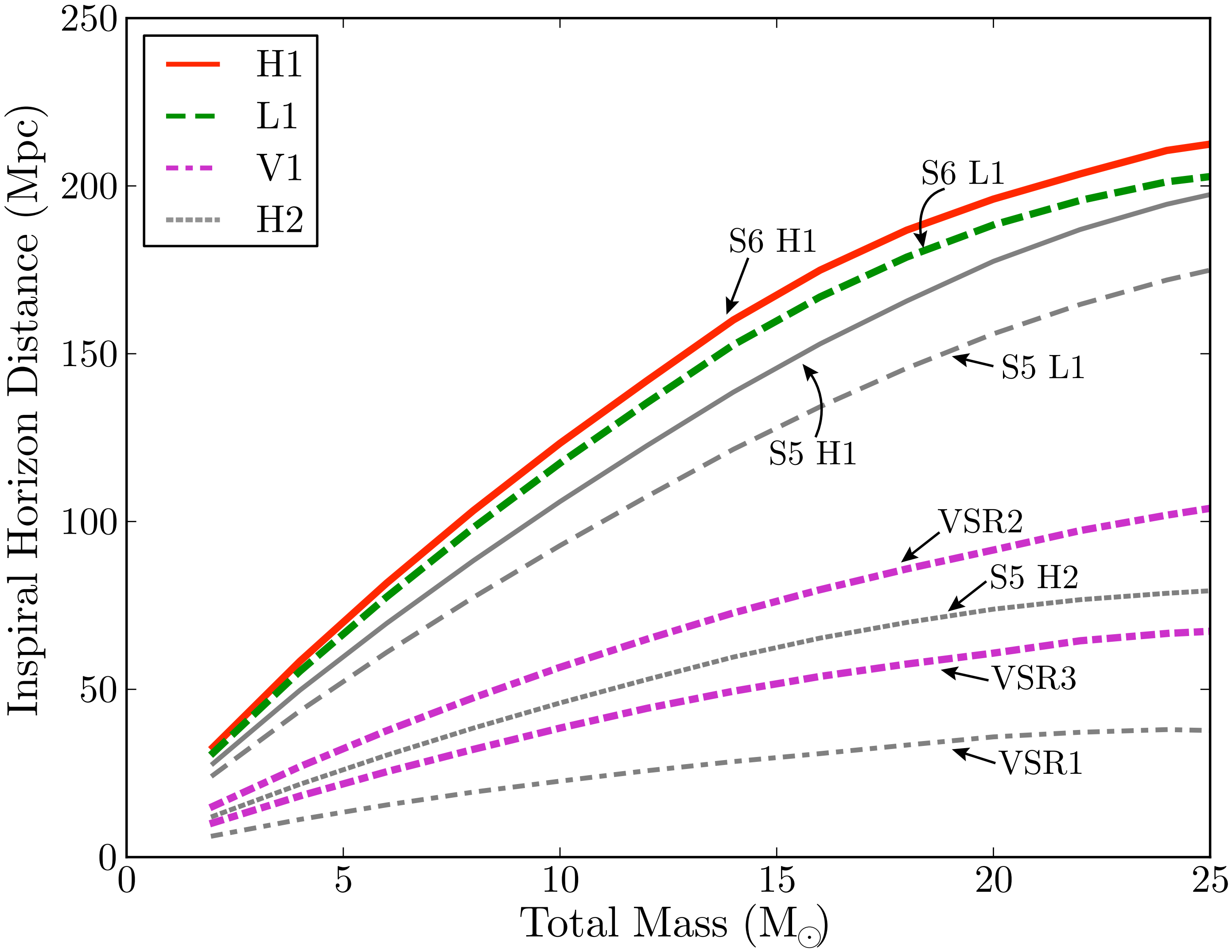



Loudest: GPS=969402052 SNR=241.6

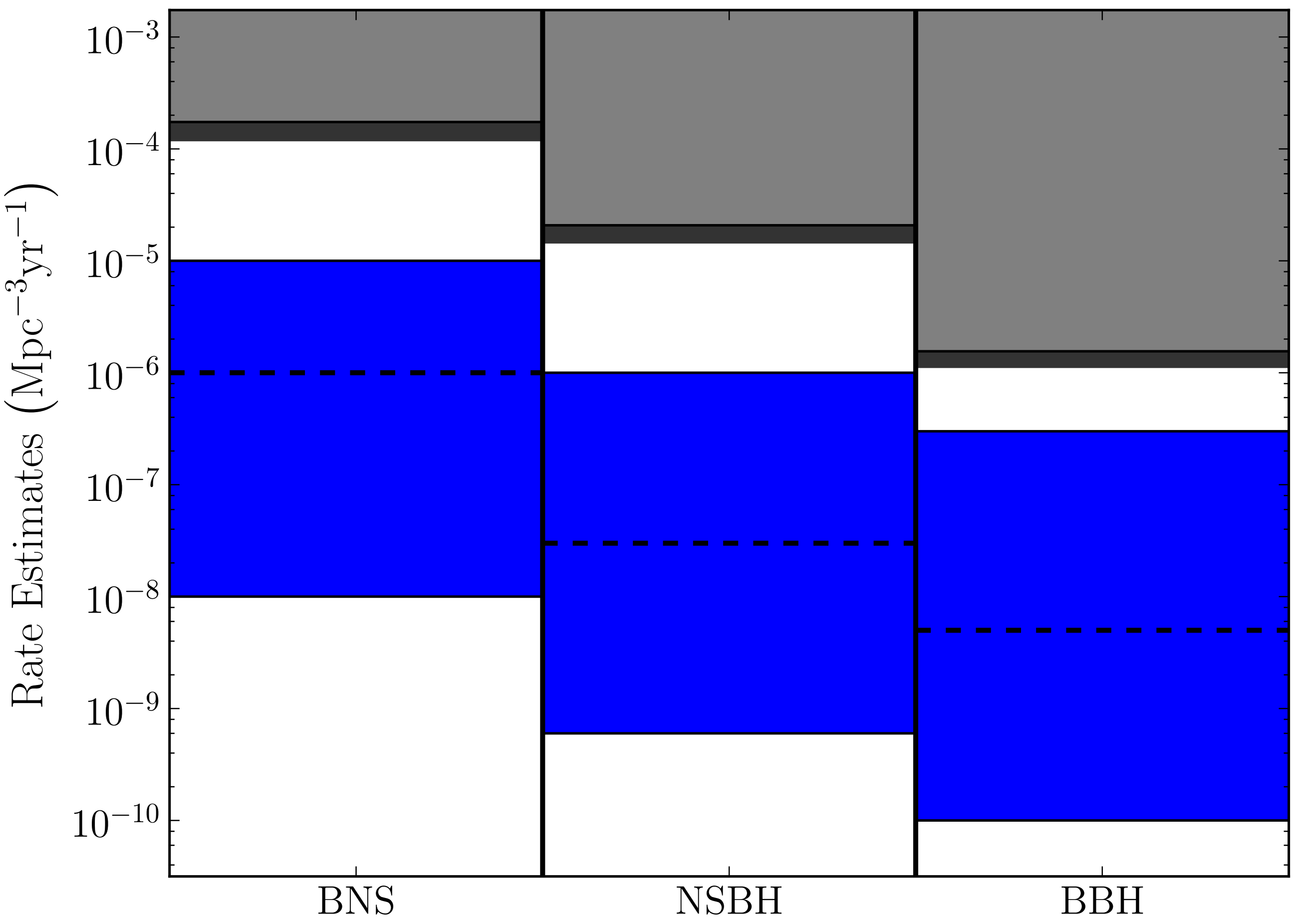
Data analysis III: results

- Main search results published for last science run
  - Search for 'low mass' binary signals, up to 25$M_\odot$ combined
  - All-sky – no knowledge of source direction
  - All-time – no knowledge of source timing
  - Data from LIGO detectors ('H1' and 'L1') and Virgo detector ('V1')
  - ~1 year of detector data for each detector

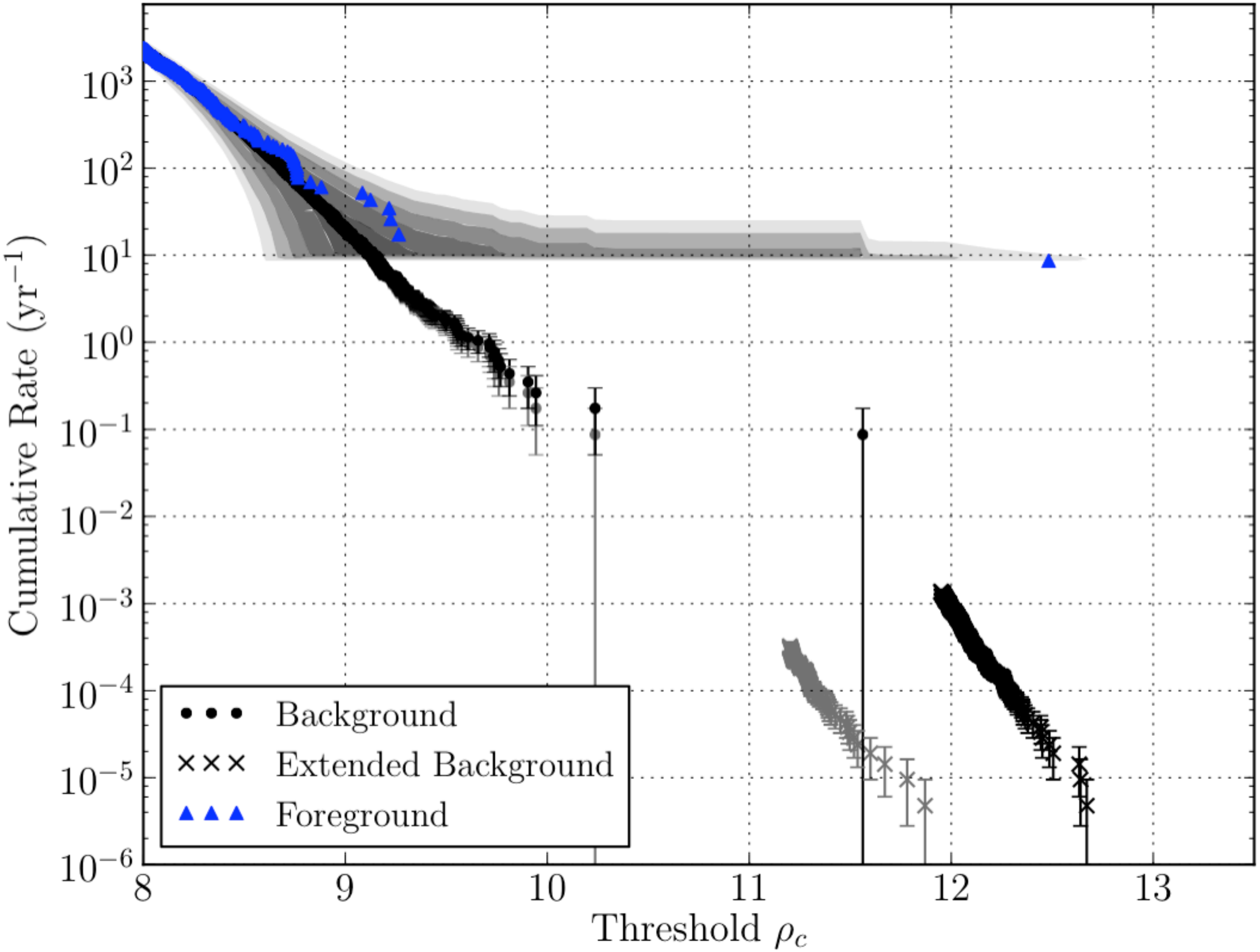
Data analysis III: results



Data analysis III: results



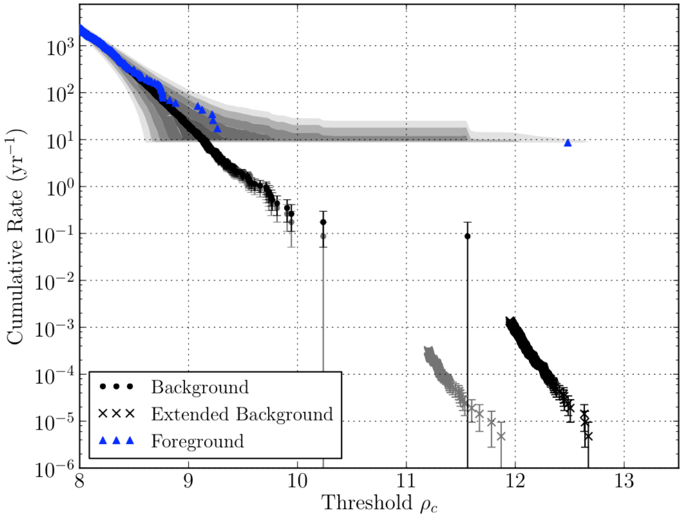
Data analysis III: results



Data analysis III: results

- No detections made!
- Results quoted as upper-limits on event rate
  - Getting close to plausible astrophysical rates i.e. astrophysically interesting statements
- Last science run results included

  ‘Blind Injection Challenge’
- Signal injected into data unknown to analysis groups as test
  - We passed.



Triggered search for GRBs

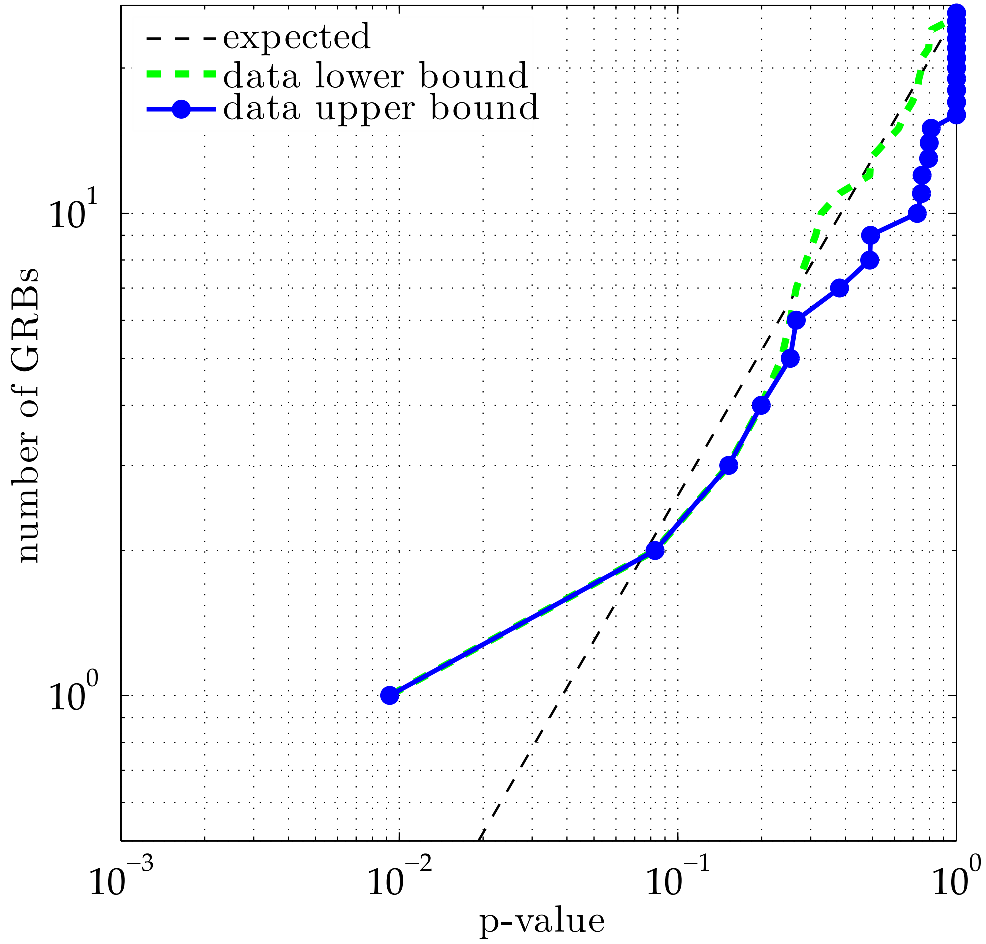
- Short gamma-ray bursts thought to emit from BNS or NSBH coalescence
- Gravitational wave merger signal expected to coincide with GRB signal (within seconds)
- Can perform search for known GRBs in past data
    - Swift and Fermi satellites detect GRBs every day
    - Detection statement is published
    - GW data analysts then search data with knowledge of timing and sky location of source

Triggered search for GRBs

- Known parameters allow more sensitive search
  - Short time window cuts down on false-alarm probability (less time ~ less noise)
  - Waveforms more specific due to known sky location, so less false alarms
- Also allows faster search
  - Smaller parameter space means less computing
  - Can accept lower thresholds for more sensitivity
- Same analysis principles

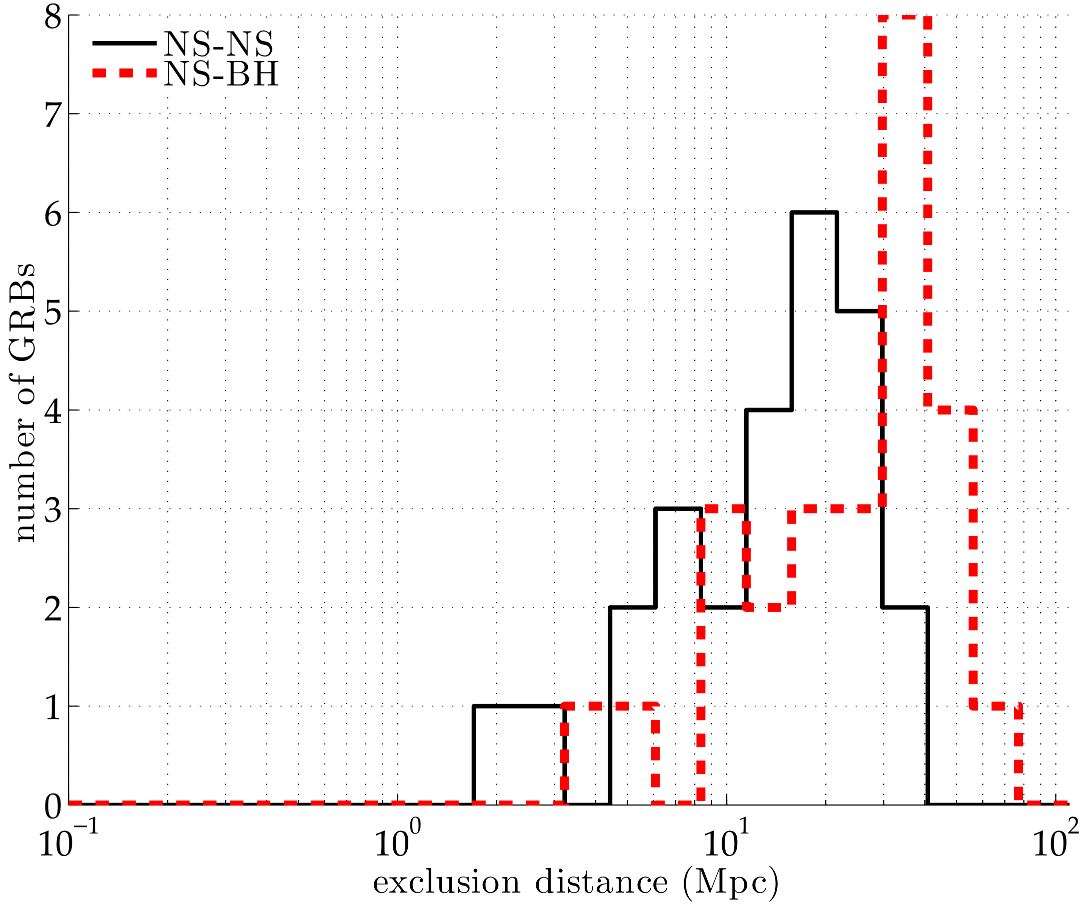
Triggered search for GRBs: results

- Last science run analysed 26 short GRBs from Swift or Fermi triggers



Triggered search for GRBs: results

- No detections
- Lower-limits placed on distance to source



Future prospects

- Advanced LIGO will be 10x more sensitive in distance, 1000x in volume
    - So, detection rate will be 1000x higher
- Unambiguous detection of gravitational waves from CBCs will happen.
    - Expect tens of detections per year as of 2018

Future prospects