Searching for Gravitational Waves from Coalescing Binary Systems

Stephen Fairhurst

Cardiff University and

LIGO Scientific Collaboration

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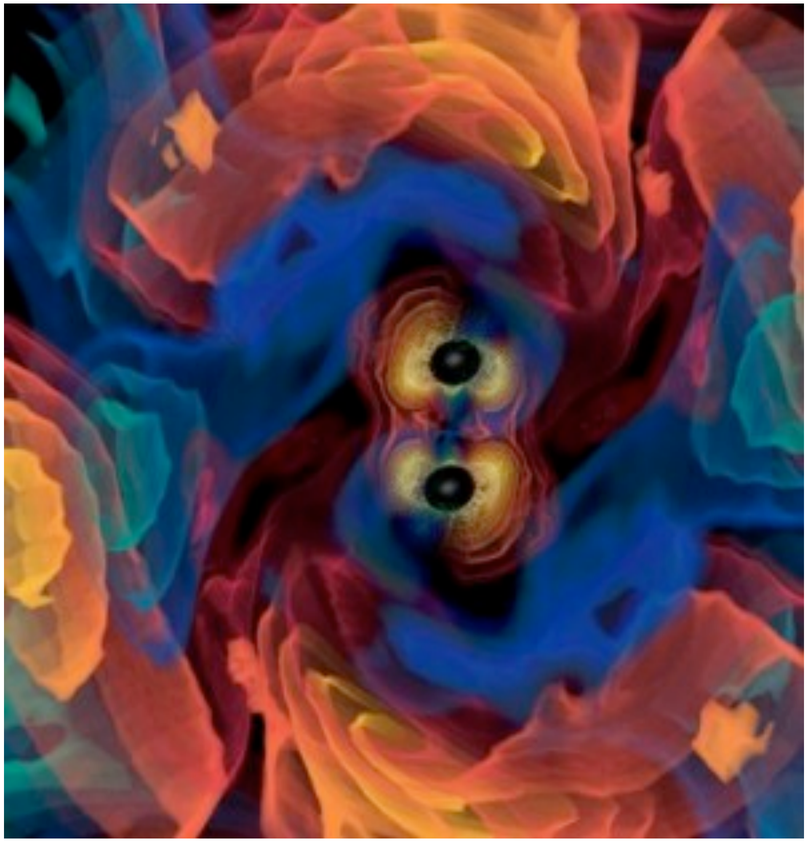
Outline

- Motivation
- Searching for Coalescing Binaries
- Latest Results and Future Prospects



Motivation

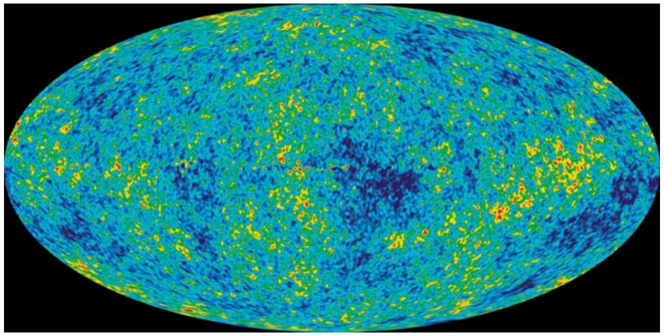
Why a gravitational wave talk at Abhayfest?

- A search of Abhay's publication list reveals:
  - A. Ashtekar, J. Bicak, Bernd G. Schmidt, Behavior of Einstein-Rosen **Waves** at Null Infinity, Physical Review D 55, 687-694 (1997)
  - A. Ashtekar, Quantization of the **Radiative Modes** of the Gravitational Field, In: Quantum Gravity 2
  - A. Ashtekar and M. Streubel, Symplectic Geometry of **Radiative Modes** and Conseved Quantities at Null Infinity
- Sad to say, none of these are required reading for new GW PhD students
- However, Abhay has made a big contribution to the LSC...

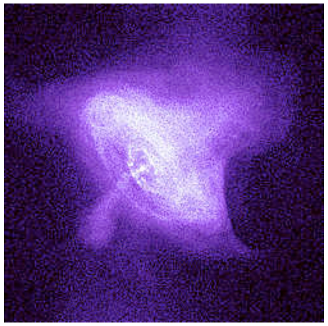
Motivation

The LSC search groups:

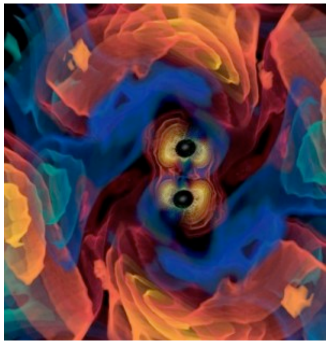
- Stochastic Sources



- Continuous Waves



- Coalescing Binaries



- Unmodeled Burst Sources

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CARDIFF UNIVERSITY

Motivation

The LSC search groups - Abhay's contribution:

- Stochastic Sources

Joe Romano,
"Geometrodynamics vs. Connection Dynamics"

- Coalescing Binaries

Chris Van Den Broeck,
"Black Holes and Neutron Stars: Fundamental and Phenomenological Issues"

SF, "Isolated Horizons and Distorted BH"

- Continuous Waves

Badri Krishnan,
"Isolated Horizons in Numerical Relativity"

- Unmodeled Burst Sources

??

Motivation

Why a gravitational wave talk at Abhayfest?

- The Quantum Alternative?

U(1) polymer and fock representations

Abhay Ashtekar [1] , Stephen Fairhurst [1,2] and Amit Ghosh [1]

1. Center for Gravitational Physics and Geometry
Department of Physics, The Pennsylvania State University
University Park, PA 16802, USA and

2. Theoretical Physics Institute
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I've moved 10,000 miles since the last edit

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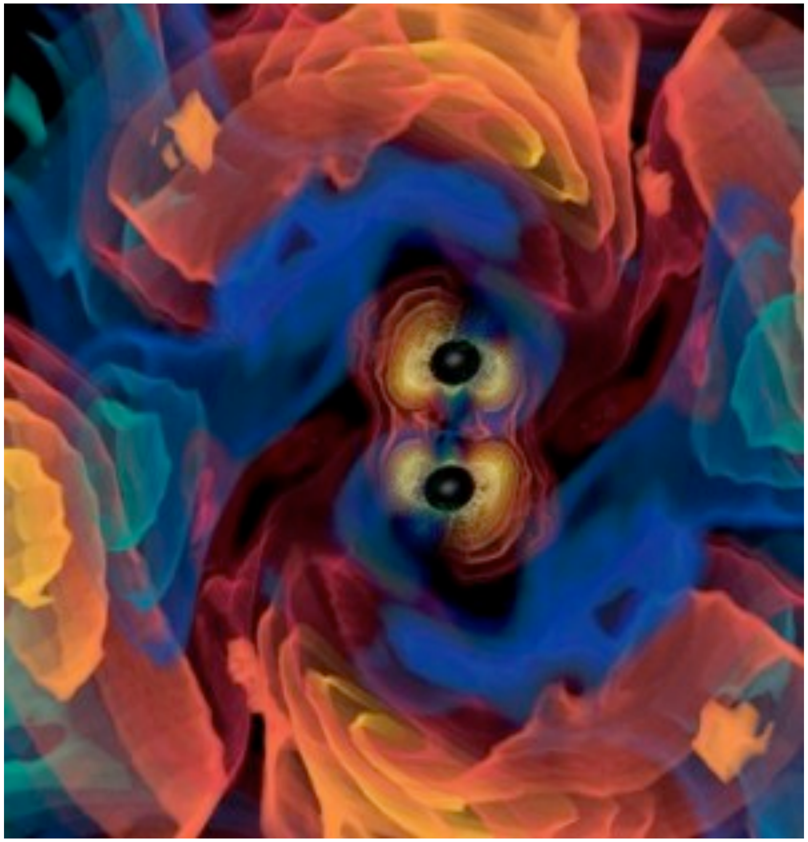

Why search?

Many payoffs from observing GW from binaries:

- Determine the gravitational waveform emitted during merger
  - Compare with strong gravity predictions (numerical relativity)
  - Constrain Neutron Star equation of state.
- Perform “Multi-messenger Astronomy”
  - Determine if short γ-ray bursts have binary coalescence progenitor.
  - Perform joint observations with radio, optical, x-ray, γ-ray, neutrino, …
- Tests of cosmology:
  - Independent measurement of distance (GW), redshift (EM)
- Test general relativity:
  - Bound the mass of the graviton.
  - Test alternative theories of gravity.

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Make the first detection

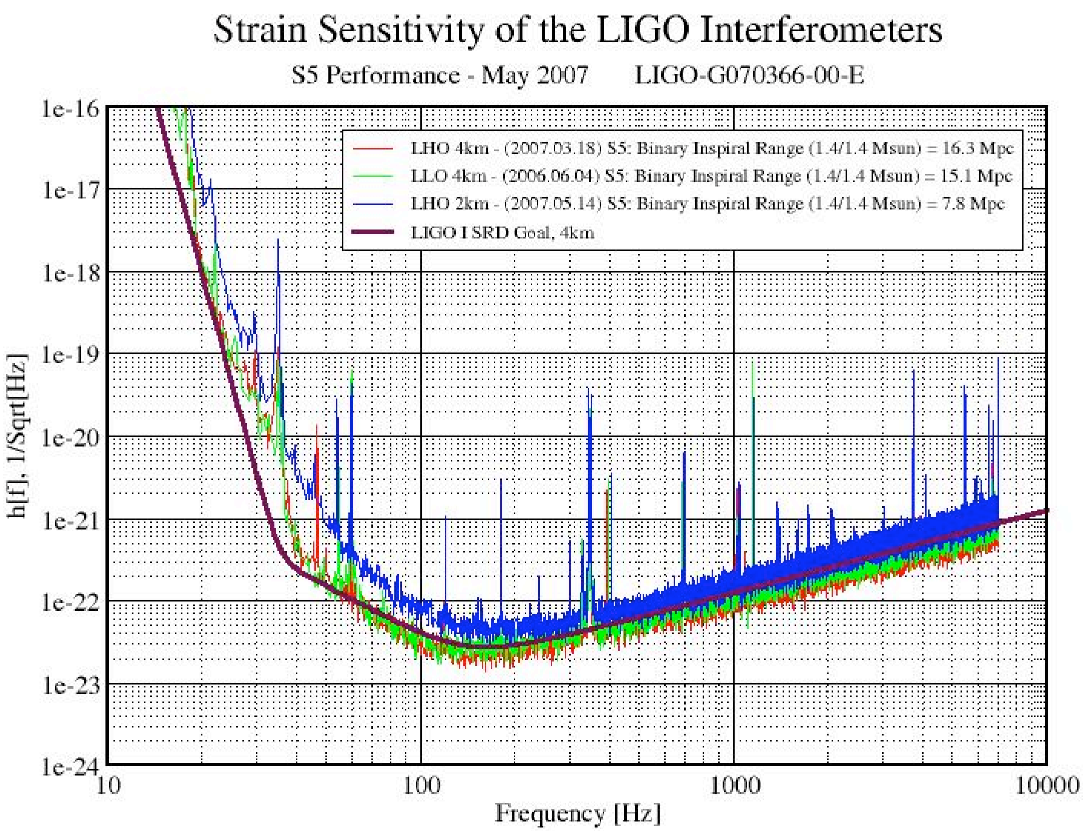
The LIGO Detectors

Livingston, LA
4km detector “L1”

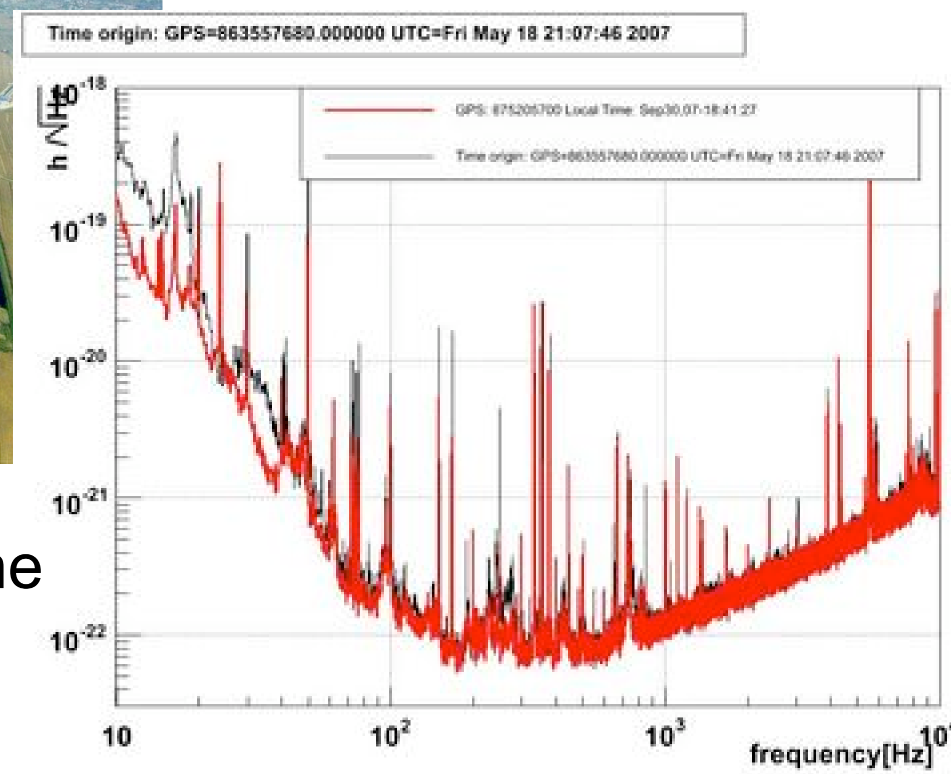
Hanford, WA
4km detector “H1”
2km detector “H2”

LIGO Science Runs

- Five science runs, S1 - S5.
- S5:
  - at design sensitivity
  - from November 2005 to September 2007
  - 1 year of two site coincident data.



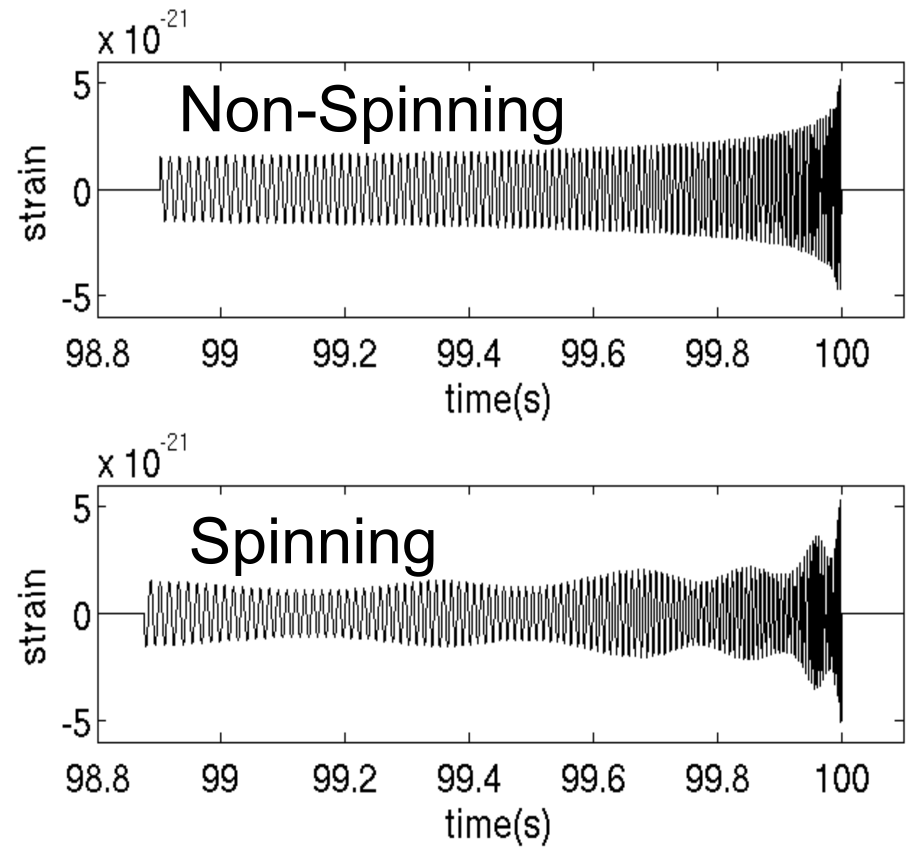
Virgo



The Virgo detector joined the last 6 months of the S5 run

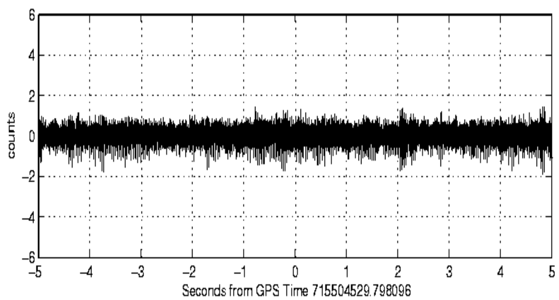
How do we search?

- Gravitational waves are emitted as the binary inspirals.
- The waveform depends upon masses, spins, binary orientation.
- Inspiral waveform can be well modeled by post-Newtonian formalism.
- When the waveform is known, use matched filtering.



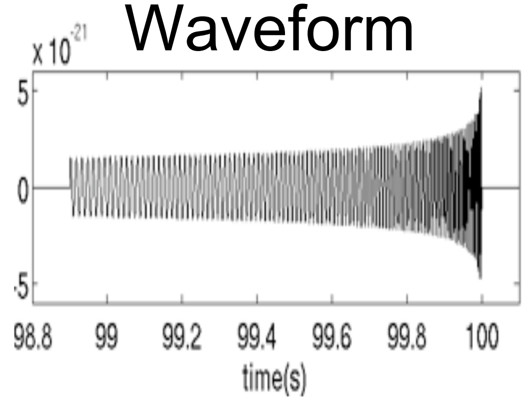
Matched Filtering (in pictures)

Data



x

Waveform



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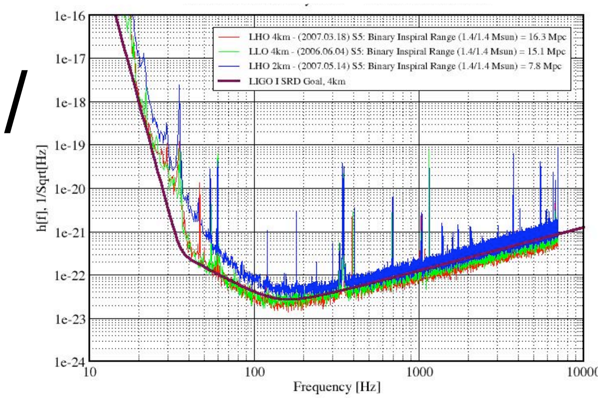
Sensitivity



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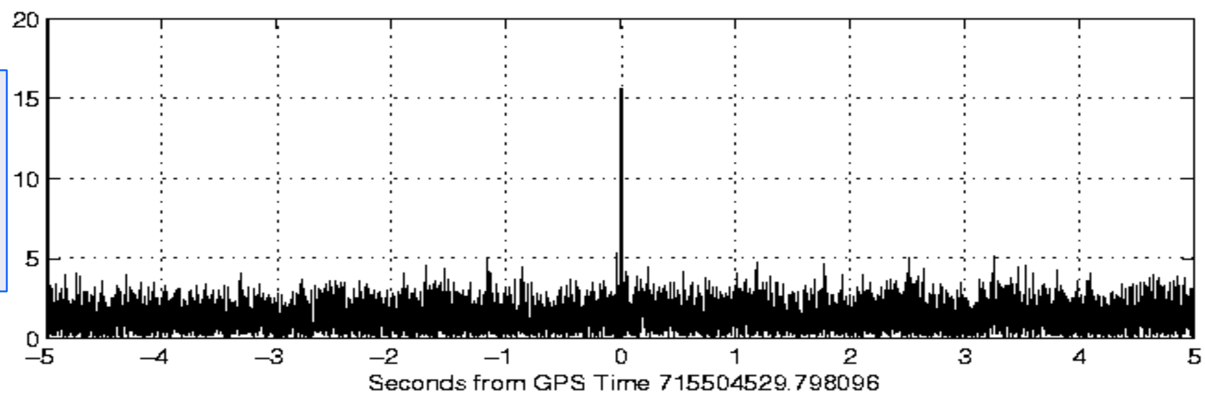
SNR



Coalescence Time

Geometry of the parameter space

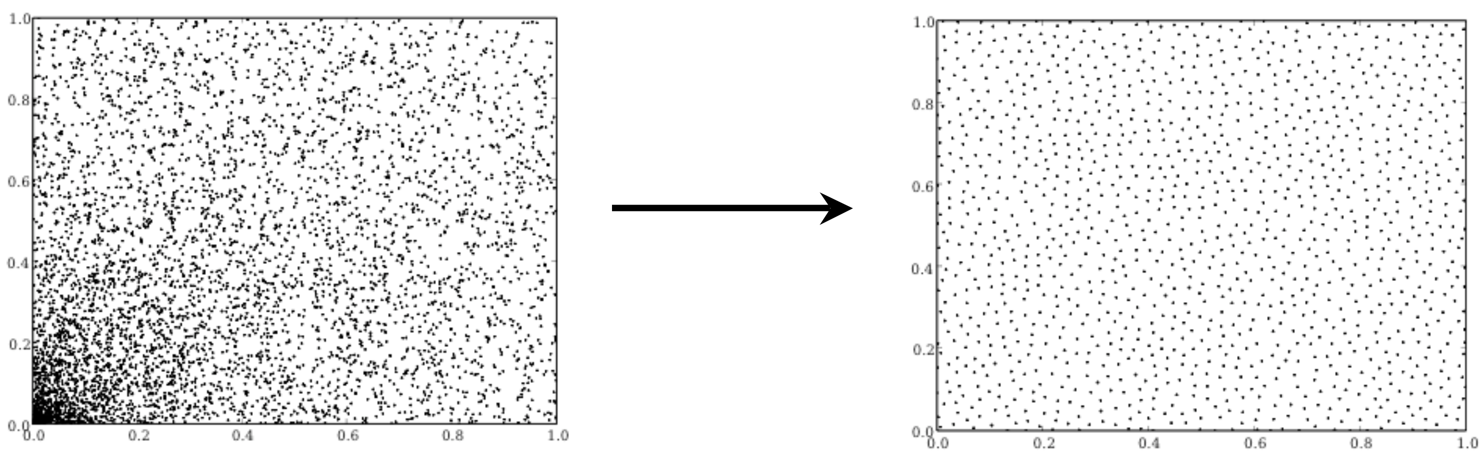
- Need to search a large parameter space
  - Binary components with mass from 1 to 20$M_\odot$ (or higher)
  - Spins of the components
  - Sky location, orientation of the signal

- Facilitated by introducing a "metric" on the parameter space

$$\frac{< h(\mathbf{x})|h(\mathbf{x}+\mathbf{dx}) >}{|h(\mathbf{x})||h(\mathbf{x}+\mathbf{dx})|} = 1 - g_{ab}(\mathbf{x}) dx^a dx^b$$

Template placement

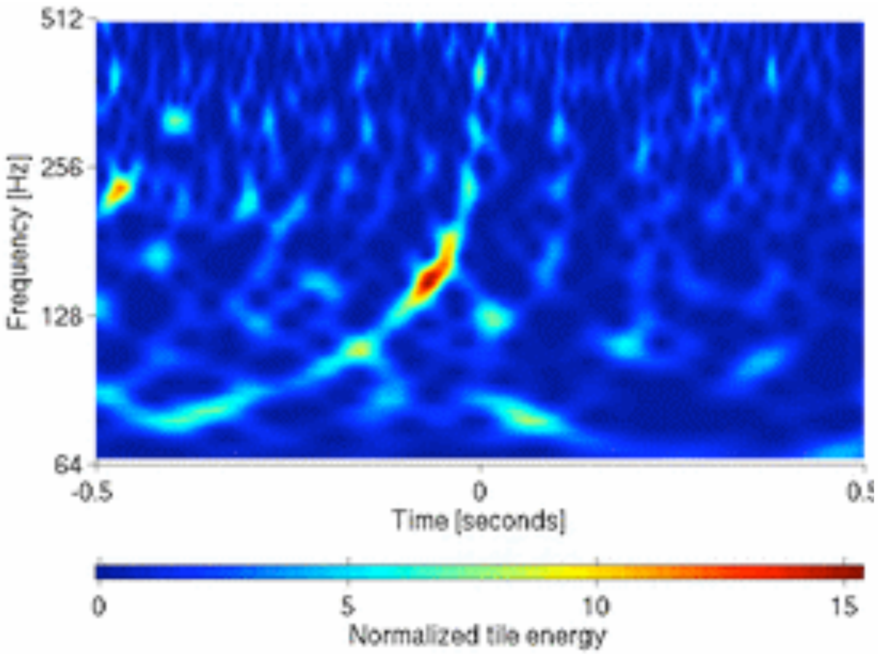
- Need to cover the mass space, ensuring that for any point, no more than 3% of signal is lost
- Use metric for efficient placement of templates (Owen, Sathyaprakash)
- Difficult to place grid in higher dimensions
  - Use “random bank” (Harry, Allen, Sathyaprakash; …)
  - Place initial points randomly, use metric to determine which to keep



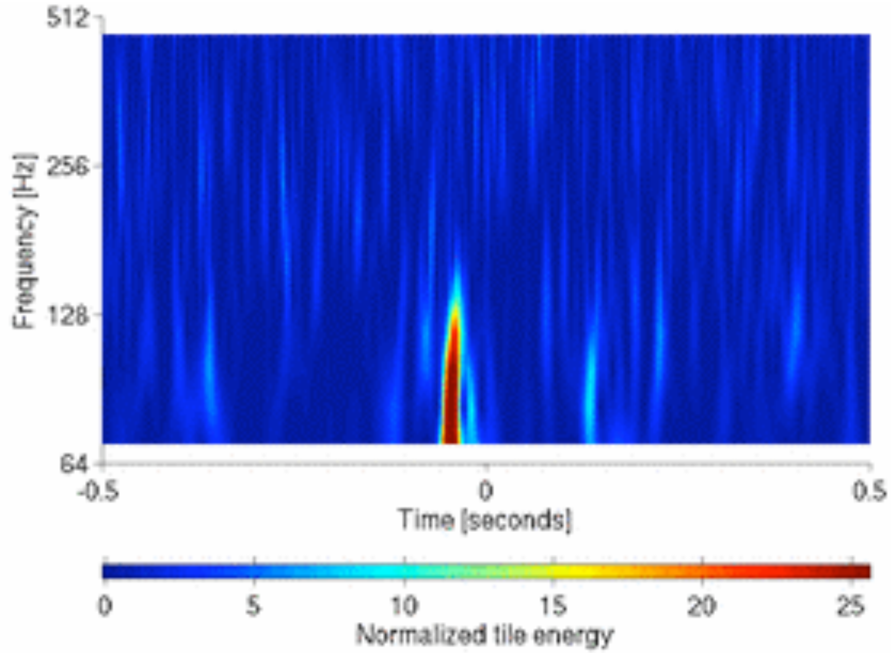
Life isn't Gaussian

- Time-frequency "Q-scans" showing excess power

Inspiral Hardware Injection



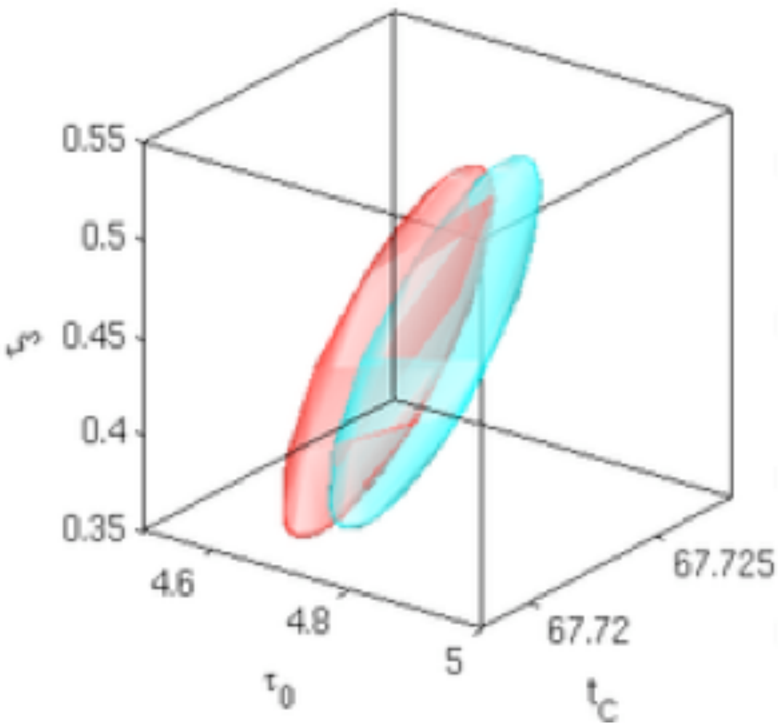
Non-stationary time



Coincidence between detectors

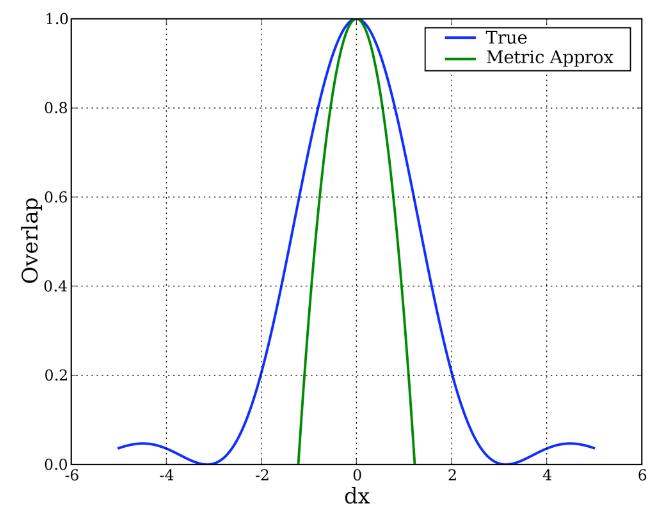
- Reject false alarms by requiring event is seen at 2 locations with similar time and masses.

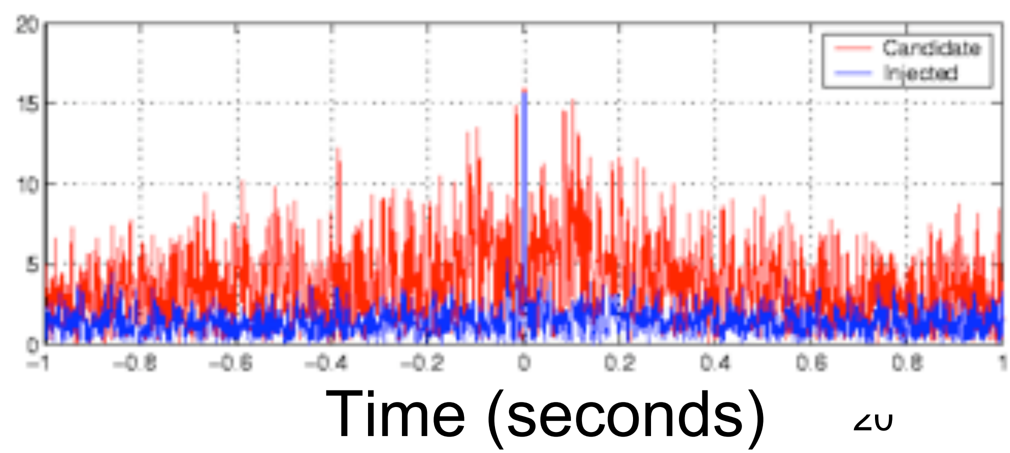
- Account for correlations between parameters by using metric.
  (Robinson, Sengupta, Sathyaprakash)



Signal Consistency Tests

- We know how the SNR varies over parameter space for a true signal.
- Various tests developed to check if it does (Allen; Rodrigues; Hanna)
- Example: loudest surviving event in S1





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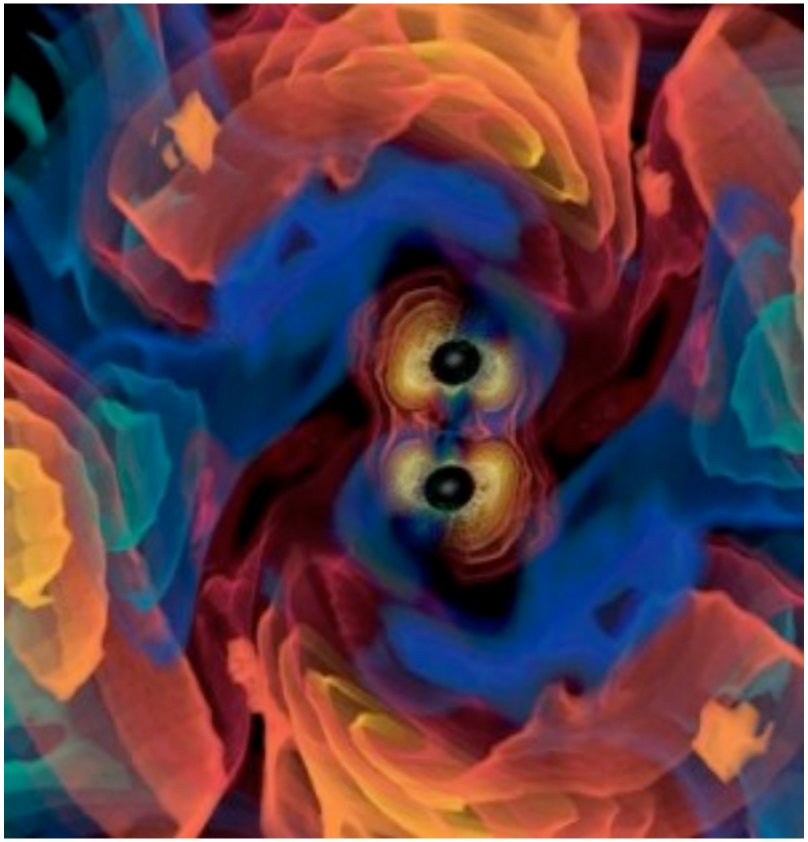


Results

- Data from the first 18 months of the S5 run have been analyzed (Abbott et. al. arXiv:0901.0302, 0905.3710)
  - Last 6 months being searched jointly with Virgo

- No GW candidates in the first 18 months of data
  - Set upper limits on the rate of binary coalescences (Brady, SF; Biswas, Brady, Creighton, SF)
  - Binary coalescence rate in a galaxy approximately follows star formation rate, or blue light luminosity
    - Quote results per L_{10} per year;
    - 1 $L_{10} = 10^{10} L_{\odot,B}$; Milky Way ~ 1.7 L_{10}

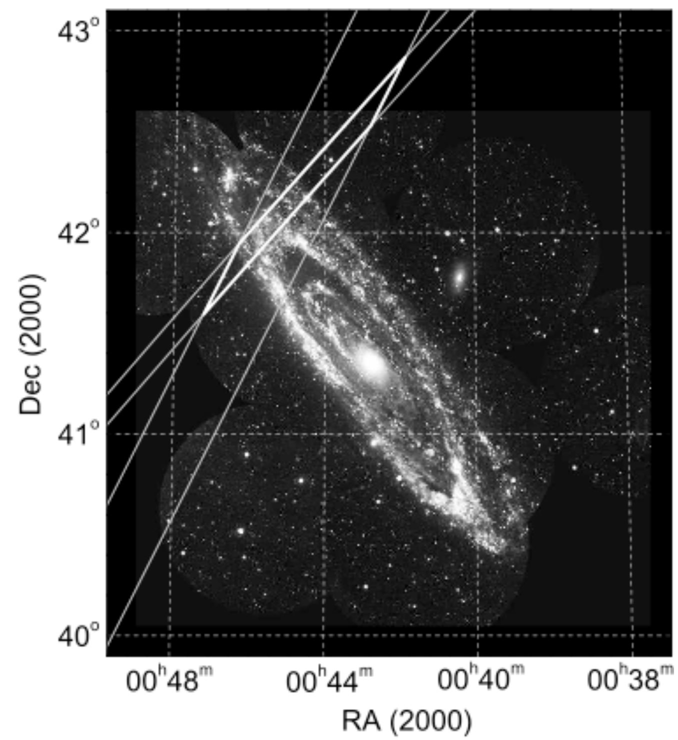
Upper Limits

- BNS rate < $1.4 \times 10^{-2}\ L_{10}^{-1}\ yr^{-1}$
- BBH rate < $7.3 \times 10^{-4}\ L_{10}^{-1}\ yr^{-1}$
- BHNS rate < $3.6 \times 10^{-3}\ L_{10}^{-1}\ yr^{-1}$
  - All rates quoted at 90% confidence
  - NS taken as 1.35 $M_{\odot}$; BH as 5.0 $M_{\odot}$

- These results are 1 to 2 orders of magnitude above optimistic astrophysical predictions, ~3 orders of magnitude above best estimates.

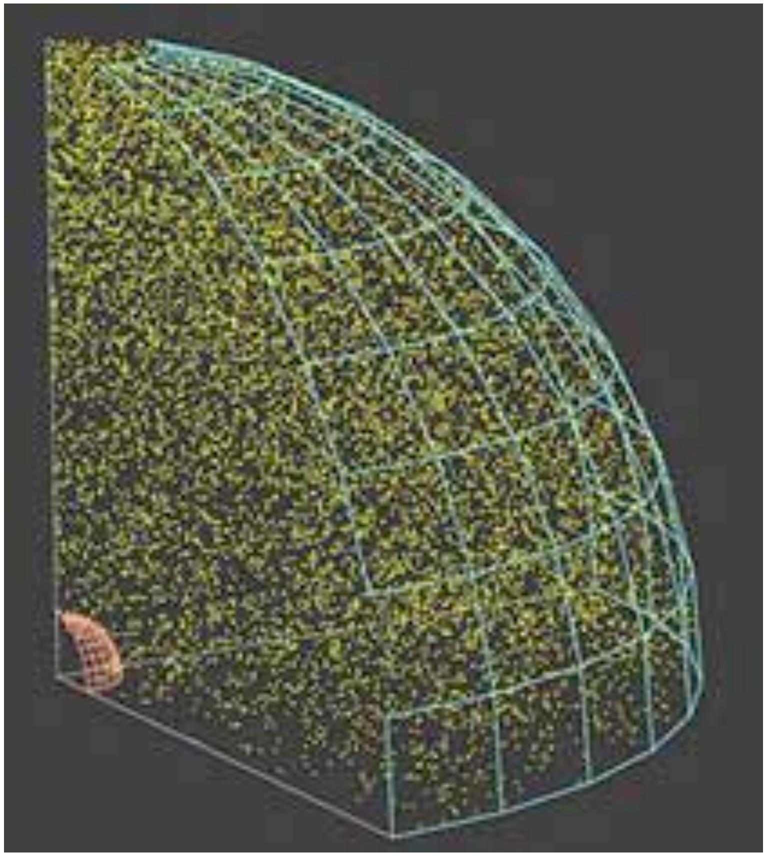
GRB searches

- Binary mergers are one candidate progenitor for short GRBs
- Search for GW around time of GRB 070201 (Abbott et. al. arXiv:0711.1163)
  - Exclude at 99% confidence that this is a merger in Andromeda
  - Gives weight to SGR scenario for this GRB
- Search around times of all 22 short GRBs during S5 data ongoing



Future Prospects

- Enhanced LIGO science run begins in 1 month
  - Hoping for factor of 2 improvement in sensitivity
  - Would increase search volume by almost an order of magnitude
- Advanced LIGO scheduled for 2014
  - Order of magnitude more sensitive than initial detector
  - Sensitive to 1000 times as large source volume



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