The Q Pipeline search for gravitational-wave bursts with LIGO

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Overview of the problem

- For many potential sources of gravitational-wave bursts (core collapse supernovae, binary black hole mergers, etc.), the waveform is not sufficiently well known to permit matched filtering
- Signals are expected to be near the noise floor of the LIGO detectors, which are subject to occasional transient non-stationarities
- Searches must be able to keep up with the LIGO data stream using limited computational resources
- This talk presents:
- Simple parameterization to describe unmodeled bursts
- Efficient algorithm to search data from multiple detectors for statistically significant signal energy that is consistent with the expected properties of gravitational radiation

Parameterization of unmodeled bursts

- Characteristic amplitude (||h||):

$$\|h\|^2 = \int_{-\infty}^{+\infty} |h(t)|^2 \, dt = \int_{-\infty}^{+\infty} |\tilde{h}(f)|^2 \, df$$

- Normalized waveform (ψ):

$$h(t) = \|h\| \psi(t) \qquad \tilde{h}(f) = \|h\| \tilde{\psi}(f)$$

- Time (τ), frequency (ϕ), bandwidth (σ_t) and duration (σ_f):

$$\tau = \int_{-\infty}^{+\infty} t |\psi(t)|^2 \, dt \qquad \sigma_t^2 = \int_{-\infty}^{+\infty} (t - \tau)^2 |\psi(t)|^2 \, dt$$

$$\phi = 2 \int_{0}^{+\infty} f |\tilde{\psi}(f)|^2 \, df \qquad \sigma_f^2 = 2 \int_{0}^{+\infty} (f - \phi)^2 |\tilde{\psi}(f)|^2 \, df$$

- Time-frequency uncertainty: $\sigma_t \sigma_f \geq \frac{1}{4\pi}$

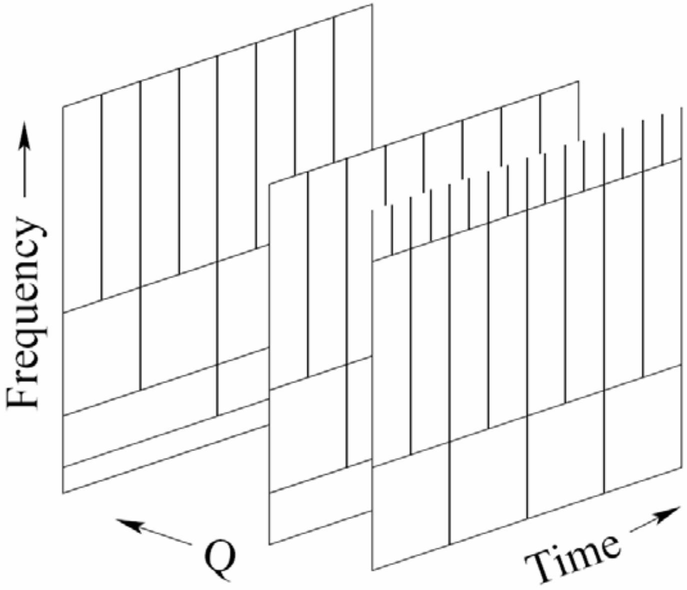
- Quality factor (Q) (aspect ratio): $Q = \frac{\phi}{\sigma_f}$

Signal space and template placement

- Multiresolution basis of minimum uncertainty waveforms
- Overcomplete basis is desirable for detection
- Use matched filtering template placement formalism

$$\mu(\delta\tau, \delta\phi, \delta Q) \simeq \frac{4\pi^2\phi^2}{Q^2}\,\delta\tau^2 + \frac{2+Q^2}{4\phi^2}\,\delta\phi^2 + \frac{1}{2Q^2}\,\delta Q^2 - \frac{1}{\phi Q}\delta\phi\,\delta Q$$

- Tile the targeted signal space with the minimum number of tiles necessary to ensure no more than a given worst case energy loss due to mismatch
- Naturally yields multiresolution basis similar to discrete dyadic wavelet transform
- Logarithmic in frequency and Q, linear in time



The Q transform

- Project onto basis of minimum uncertainty waveforms

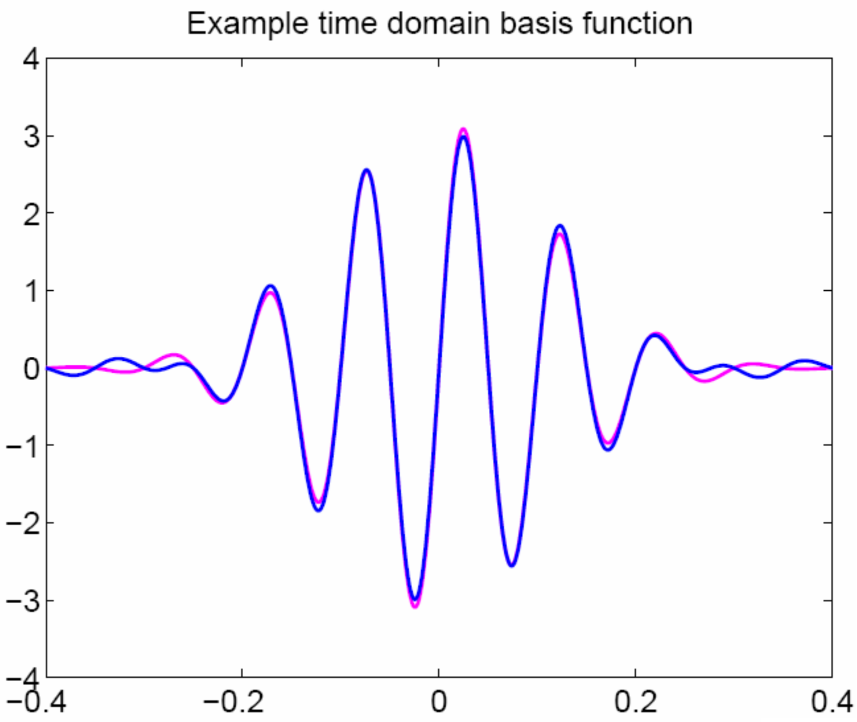
$$X(\tau, \phi, Q) = \int_{-\infty}^{+\infty} x(t)\, w(t-\tau, \phi, Q)\, e^{-i2\pi\phi t}\, dt$$

- Alternative frequency domain formalism (heterodyne detector) allows efficient computation using the fast Fourier transform

$$X(\tau, \phi, Q) = \int_{-\infty}^{+\infty} \tilde{x}(f + \phi$$

- Frequency domain bi-square uncertainty with finite frequer

$$\tilde{w}(f, \phi, Q) = \begin{cases} \left(\frac{315}{128\sqrt{11}} \frac{Q}{\phi} \right)^{1/2} \Big[\\ 0 \end{cases}$$



White noise statistics

- Whitening the data prior to Q transform analysis greatly simplifies the resulting statistics
- Equivalent to a matched filter search for waveforms that have minimum uncertainty *after* whitening
- The squared magnitude of Q transform coefficients are chi-squared distributed with 2 degrees of freedom
- Define the normalized tile energy

$$Z = |X|^2 / \langle |X|^2 \rangle$$

- For white noise, Z is exponentially distributed

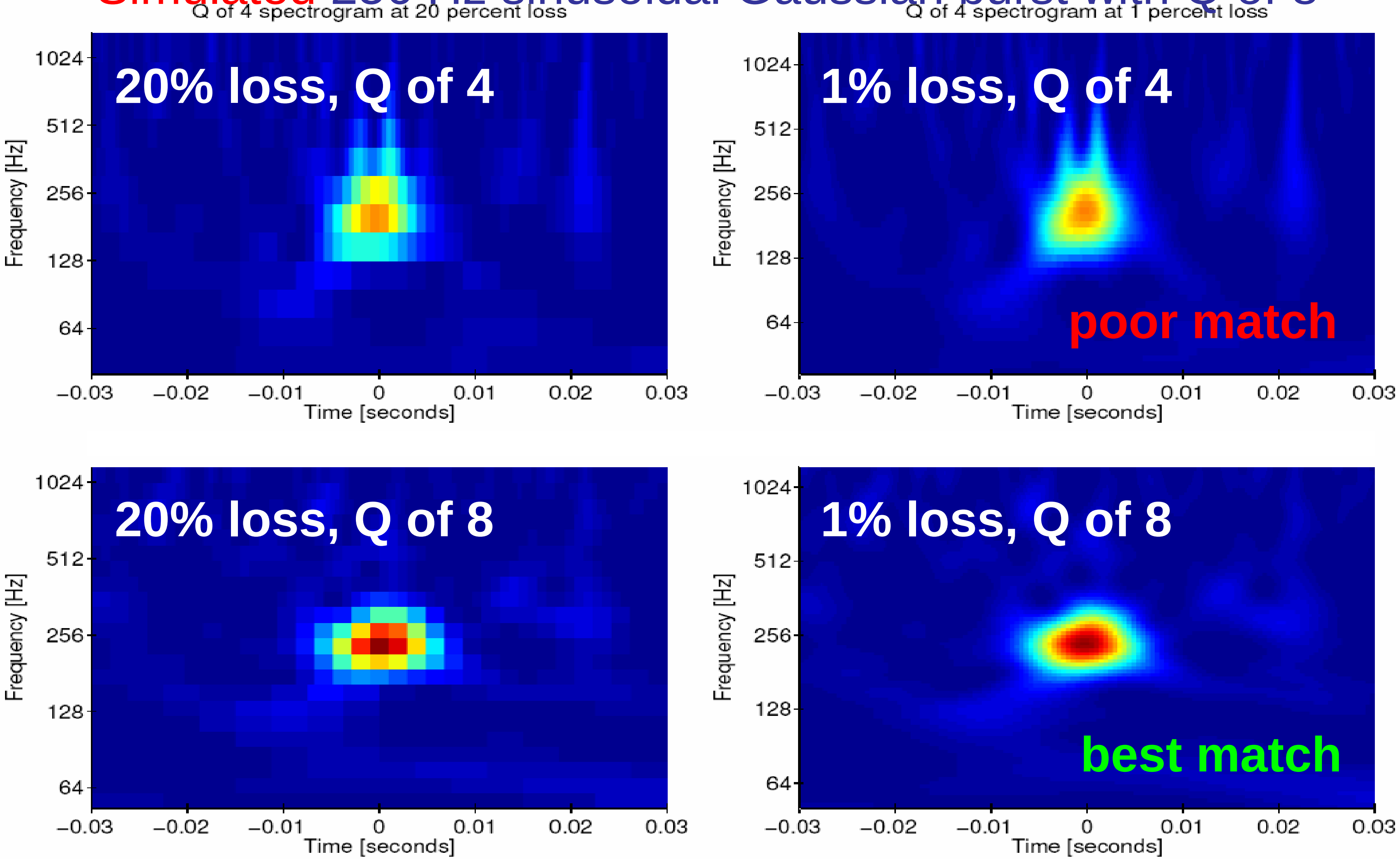
$$f(Z)\,dZ = \exp(-Z)\,dZ \qquad P(Z' > Z) = \exp(-Z)$$

- Matched filter SNR for minimum uncertainty bursts

$$\rho = \sqrt{2Z}$$

Example Q transform

- Simulated 256 Hz sinusoidal Gaussian burst with Q of 8



Preliminary look at LIGO data

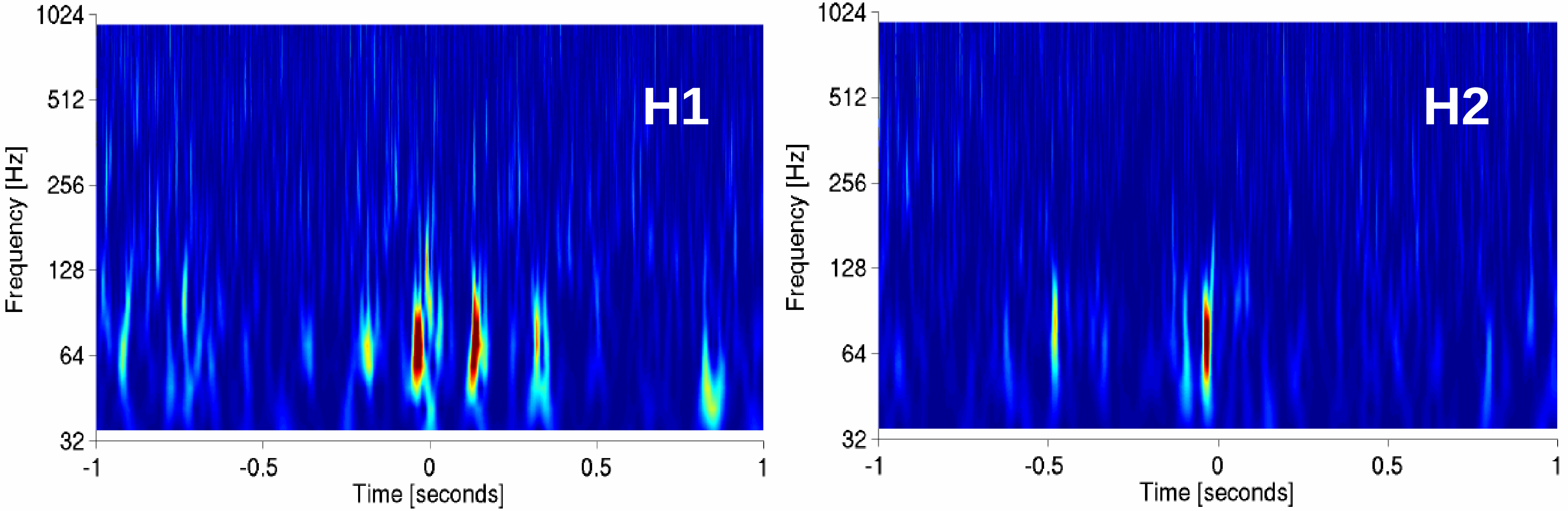
- Understand the performance of the method on real data
- Hanford 2km and 4 km detectors
    - Analyzed 44.4 days of good quality S5 data
- Hanford 2km, 4km, and Livingston 4km detectors
    - Analyzed 27.9 days of good quality S5 data
- Searched in frequency from 90 Hz to 1024 Hz
- Searched in Q from 4 to 64
- Single detector threshold: $Z > 19$
- N detector threshold: $\Sigma Z > 25.5N$
- Tested for time-frequency coincidence between sites
    - 15 ms coincidence window between sites
    - 5 ms coincidence window between Hanford detectors
    - Non-zero overlap in frequency

Preliminary look at LIGO data

- Accidental rate estimated by non-physical time shifts
  - 100 time shift experiments from -50 to +50 seconds
- Hanford 2km, 4km, and Livingston 4km
  - Observed 6 time-shifted coincident events
- Hanford 2km and 4km
  - Observed 1231 time-shifted coincident events
  - Expect additional events at zero time shift due to shared environment of Hanford detectors
  - Collocated Hanford detectors permit powerful consistency tests
- Follow up coincident events by looking at auxiliary detector and environmental monitor data

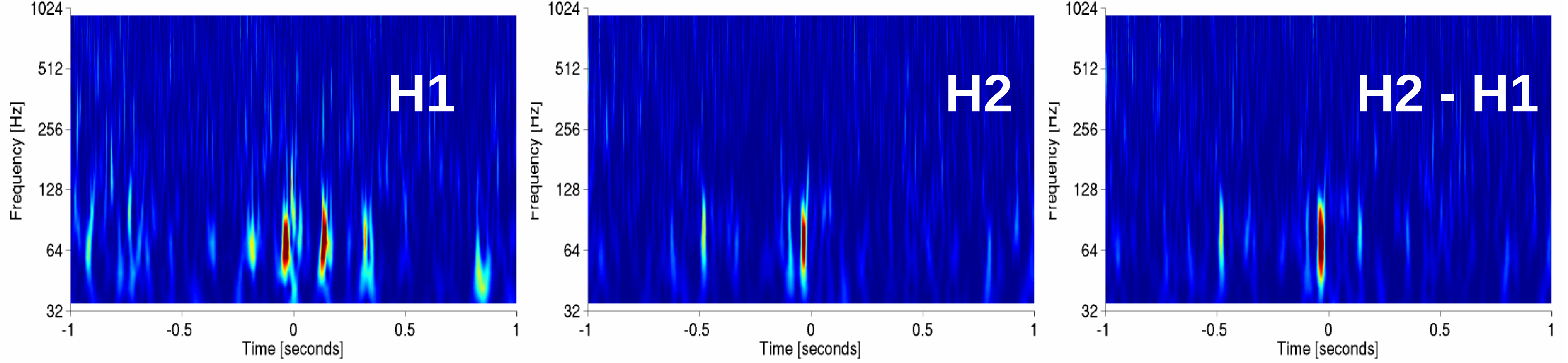
Example follow-up of events

- Q transform can also be applied to follow up events
- Used to identify statistically significant signal content in
  - Gravitational-wave data (inconsistencies)
  - Auxiliary detector data (detector anomalies)
  - Environmental monitoring data (environment vetoes)
- Example spectrograms of time-shifted coincident event:

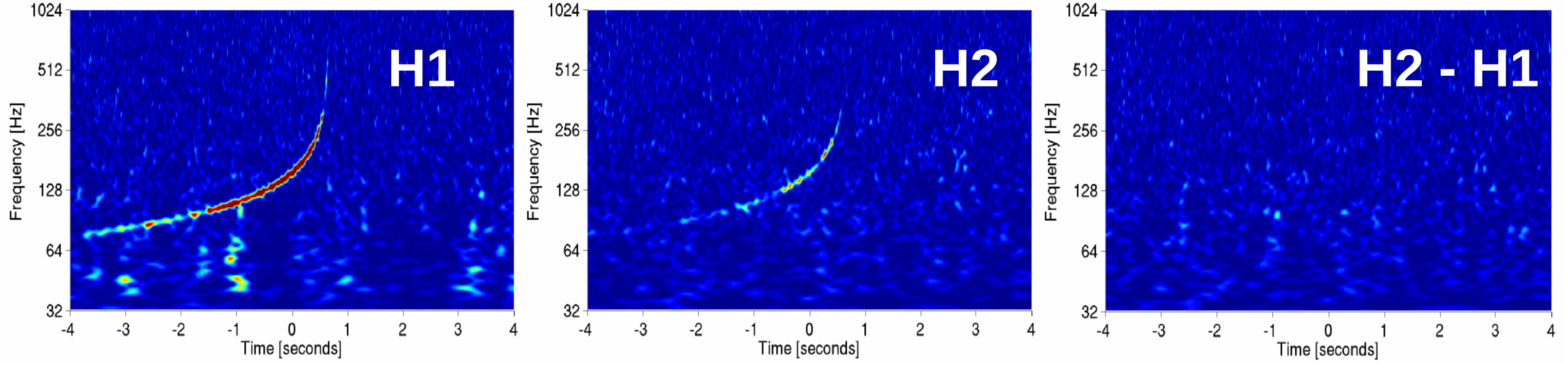


Example consistency tests

- Is Hanford detector difference consistent with noise?
- Example time-shifted coincident event:



- Example simulated 1.4, 1.4 solar mass inspiral at 5 Mpc



Summary

- LIGO has reached its design sensitivity of an RMS strain of 10^{-21} integrated over a 100 Hz band, is now collecting one year of coincident science data, and continues to undergo improvements in sensitivity
- Search algorithms for unmodeled gravitational-wave bursts are now running in real time on current data
- The single detector Q pipeline trigger generation runs ~4 times faster than real time on a single 2.5 GHz CPU
- Many of these same tools are also being applied to identify and exclude anomalous detector behavior
- Follow-up tests of interesting events, simulated signals, and detector anomalies are currently under development
- Tests for consistency of candidate events in multiple detectors are currently under development