Coherent network search for the detection of pulsar glitches

Kazuhiro Hayama(1)
Shantanu Desai(3), Soumya Mohanty(1),
Malik Rakhmanov(2), Tiffany Summerscales(4),
Sanichiro Yoshida(2)
(1) University of Texas at Brownsville
(2) Southeastern Louisiana University
(3) Pennsylvania State University
(4) Andrews University

G070851-00-Z

Abstract

Pulsar glitches are a sudden spin-up of neutron star followed by a long term relaxation period. The increase of the energy of the rotation is typically 10^{43} erg. The time scale of the sudden spin-up is limited to within 2 minutes observationally. The mechanism is understood in terms of spin-down induced quakes in the neutron star's crust or the transfer of angular momentum from a superfluid in the inner crust. Though physical mechanism of the glitches are not certain and need more understanding of neutron star superfluidity, the drastic energy changes should excite gravitational waves. The observations of pulsar glitches could infer not only the mass and radius of the stars, but also the superfluid nature, leading to insight into the mechanism of the pulsar glitches. Several pulsar glitches were observed during S5. We propose to look for gravitational wave signals associated with pulsar glitches using coherent network analysis. Coherent network analysis optimally utilizes the global network of interferometric gravitational wave detectors currently in operation, and improves directional searches, resulting in an enhanced detection efficiency.
We demonstrate the search method and study its performance for pulsar glitches using simulated detector noise.

Pulsar Glitch

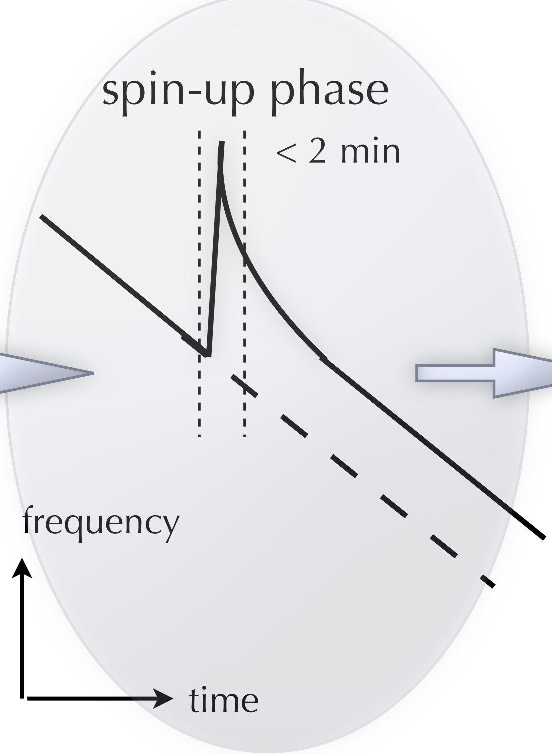
- Observation
  - Discontinuities of the rotation rate of pulsars
  - The increase of the energy of the rotation is typically 10^{43} erg, which corresponds to the total radiation energy of the sun over 100 years.
  - The the time scale of the sudden spin-up is limited, observationally, to be less than 2 min.
  - Can predict the timing of next glitch. (N. Ito, PTP 1983, Y. Mochizuki)
    - The interval between pulsar glitches can be predicted to within a few days
- Mechanism
  - spin-down induced quakes in the neutron star's crust
  - the transfer of angular momentum from a superfluid in the inner crust

Example: Vela pulsar glitch

The profile parameters have been changed due to the glitch occurred on Aug. 12 2006.

Before

- F0
  11.191297629221427
- F1
  -1.564376516769E-11
- F2
  2.103488694919E-21



After

- F0
  11.1946499395
- F1
  -1.5666E-11
- F2
  1.028E-21

Thank to ATNF young pulsar timing project, and T. Akutsu

F0: Barycentric rotation frequency (Hz)
F1: Time derivative of barycentric rotation frequency (s^{-2})
F2: Second time derivative of barycentric rotation frequency (s^{-3})

Interferometric gravitational wave detector network

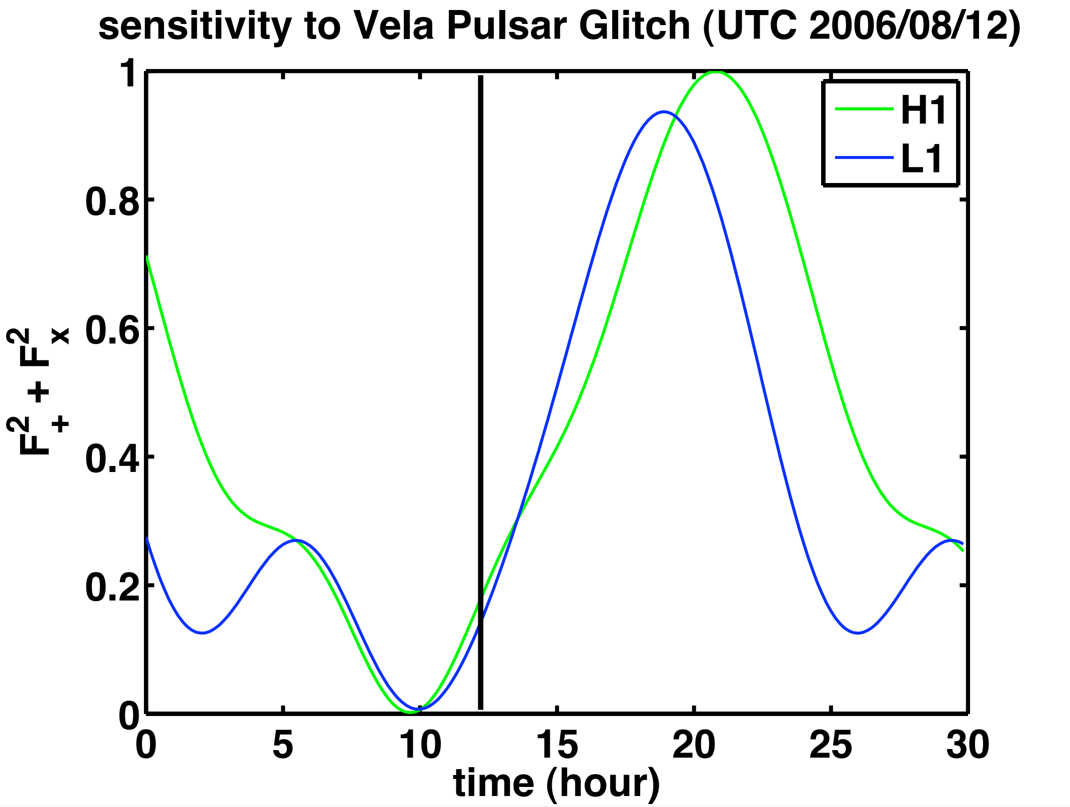
Interferometric gravitational wave detector network

Using data from a network

- False alarm rate can be reduced
- A global network of detectors can compensate for null regions in the sky of individual detectors, providing all time-all sky coverage
- more than three detectors provide sky position
  - With regularization and certain types of signals, one could better than a ring on the sky with two non-colocated detectors.
- Signal-to-noise ratio is increased by combining the data streams coherently

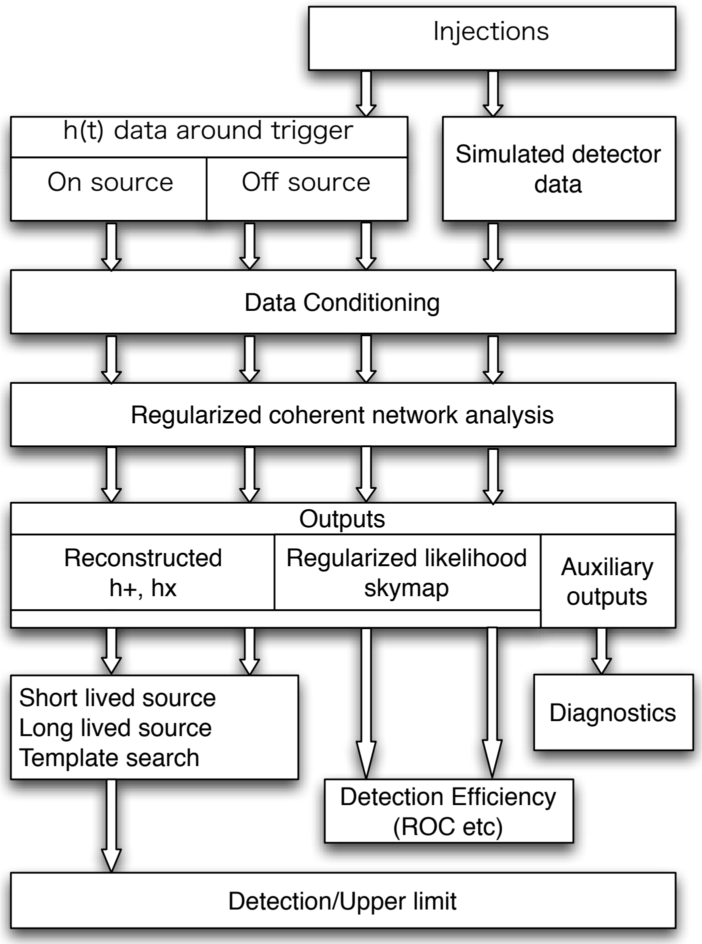
Detector Response

When the glitch occurred, LHO 2km/4km and LLO were in science mode. The sensitivity for Vela pulsar glitch is 0.157 for LHO, 0.121 for LLO.



Analysis pipeline

RIDGE triggered search pipeline



Injections

h(t) data around trigger

On source

Off source

Simulated detector data

Data Conditioning

Regularized coherent network analysis

Outputs

Reconstructed h+, hx

Regularized likelihood skymap

Auxiliary outputs

Short lived source
Long lived source
Template search

Diagnostics

Detection Efficiency (ROC etc)

Detection/Upper limit

- RIDGE: a coherent network analysis pipeline Hayama et al. CQG 24 (2007)

  Feature

  - New data conditioning
    - Time domain noise floor whitening

      S. Mukherjee CQG 21 (2003)
    - Remove lines by Median Based Line Tracker

      S. Mohanty CQG 19 (2002)
  - Tikhonove-regularized coherent network analysis

    M. Rakhmanov CQG 23 (2006)

Bayesian approach is also going on. See J. Clerk's poster

Coherent network analysis

$$\begin{bmatrix} x_1(t) \\ \vdots \\ x_d(t) \end{bmatrix} = \begin{bmatrix} F_{1+}(\theta,\phi) & F_{1\times}(\theta,\phi) \\ \vdots & \vdots \\ F_{d+}(\theta,\phi) & F_{d\times}(\theta,\phi) \end{bmatrix} \begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ \vdots \\ n_d(t) \end{bmatrix}$$

data = detector response x gravitational wave + noise

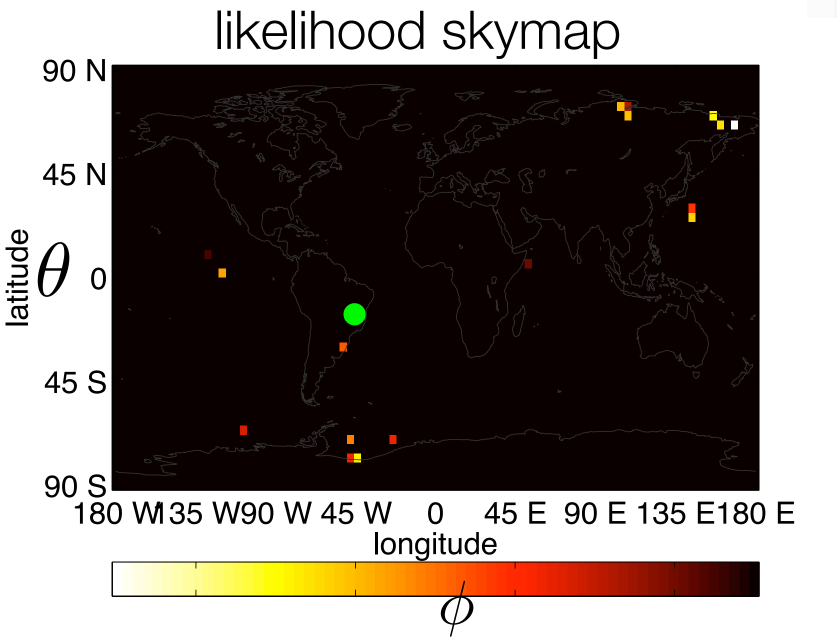
GW $\xi_i(t) = F_{i+}(\theta,\phi)h_+(t) + F_{i\times}(\theta,\phi)h_\times(t)$

- Maximize the likelihood of the data over the space of signal waveforms and sky positions
- Statistic is the minimum of the calculated likelihood sky-map of residual values $\| \text{ data}(x) - \text{estimated signal}(\xi) \ \|$

$$L = \sum_{i=1}^{d} \left(\sum_{t=0}^{T} \| \ x_i(t) - \xi_i(t+\tau_i,\theta,\phi) \ \|^2 \right) \rightarrow \text{minimum}$$

Tikhonov regularization

- Due to the degree of freedom of the response matrix, the inverse problem becomes ill-posed.
  (When $F_\times(\theta,\phi) \propto F_+(\theta,\phi)$, matrix becomes rank deficient.)
- The error in the best-fit is amplified
- Technique to address this rank deficiency we adopt is Tikhonov regularization



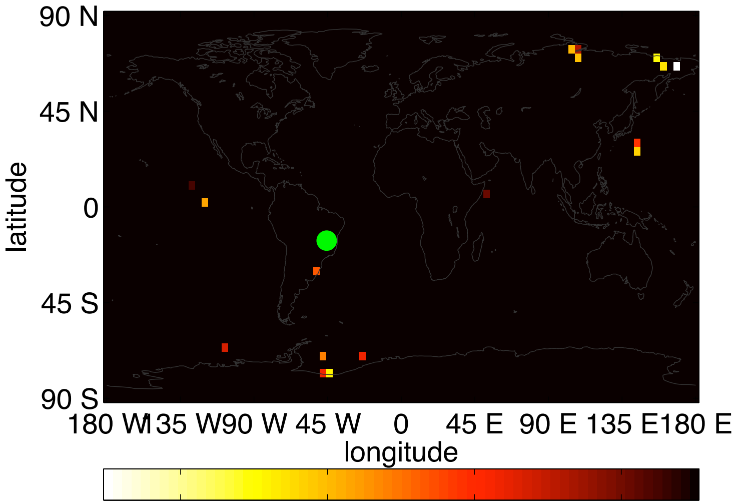
Injected signal:
sineGaussian235HzQ9

Impose regulator on standard maximum likelihood

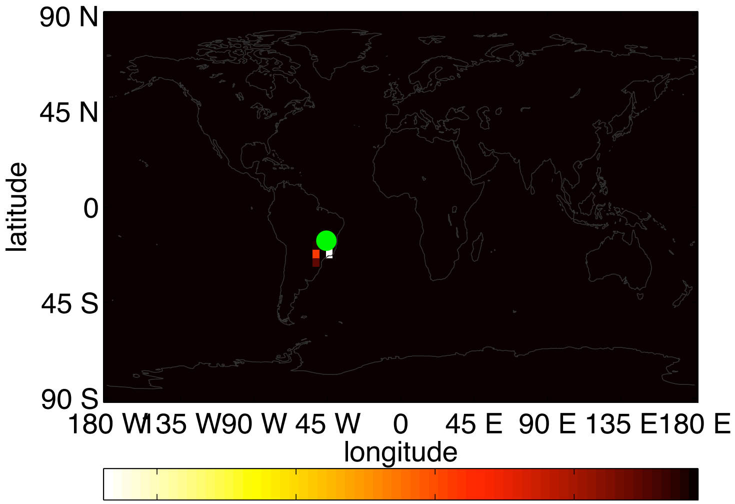
Effect of regulator

- Before adding regulator, likelihood values beyond a given threshold are scattered
- After adding regulator, the values converge around the true solution

Before adding regulator



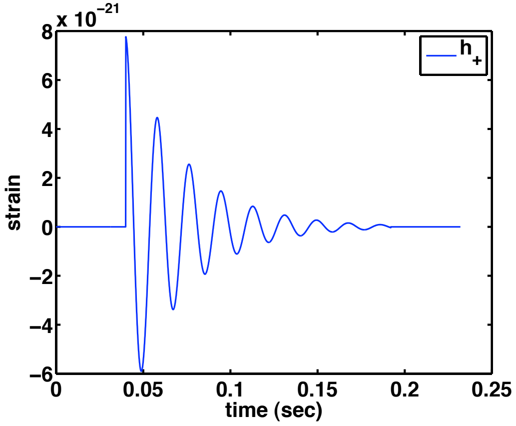
After adding regulator

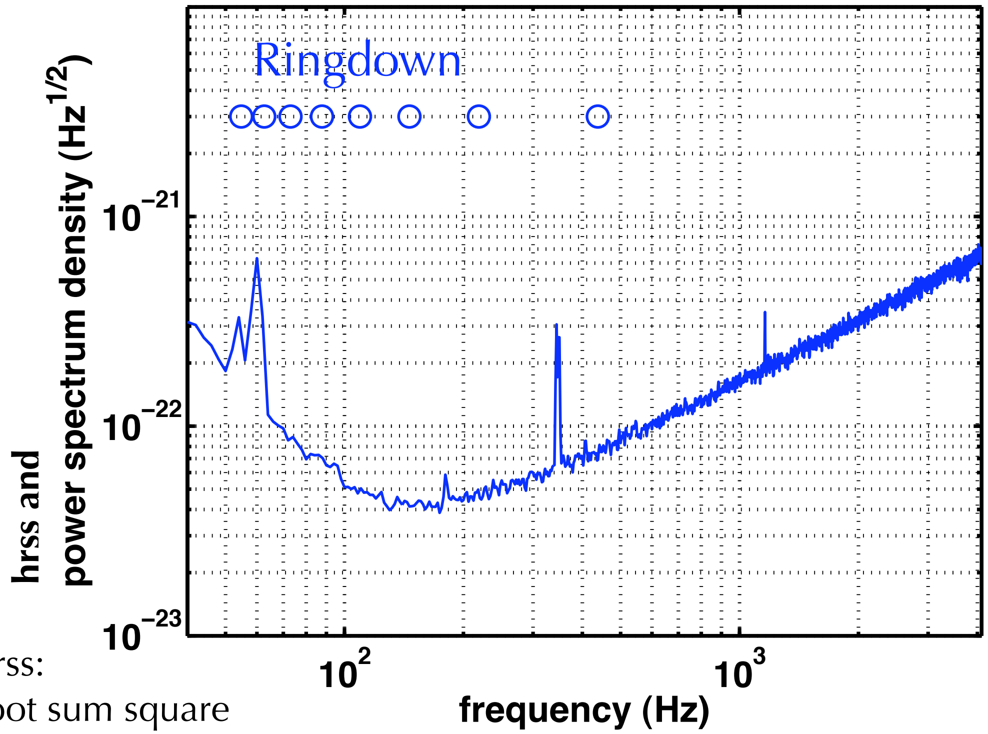


Simulation of the detection of ringdown

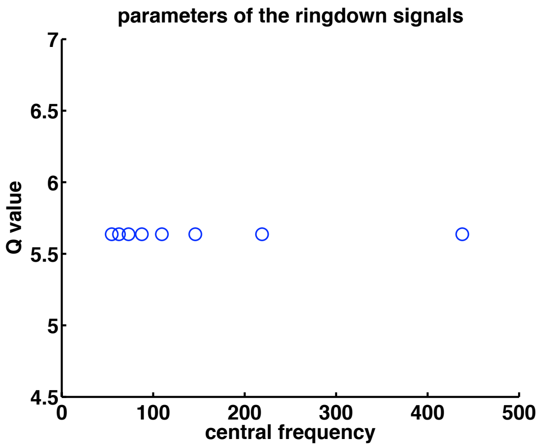
- Data: simulated Gauss noise with the design sensitivity of LHO 2km/4km and LLO
- Signal: Exponential decay signal with 2 polarization waves at Vela pulsar.

$$h_+(Q, f_c, t) =$$
$$A \exp(-\pi f_c t/Q) \sin(2\pi f_c t)$$

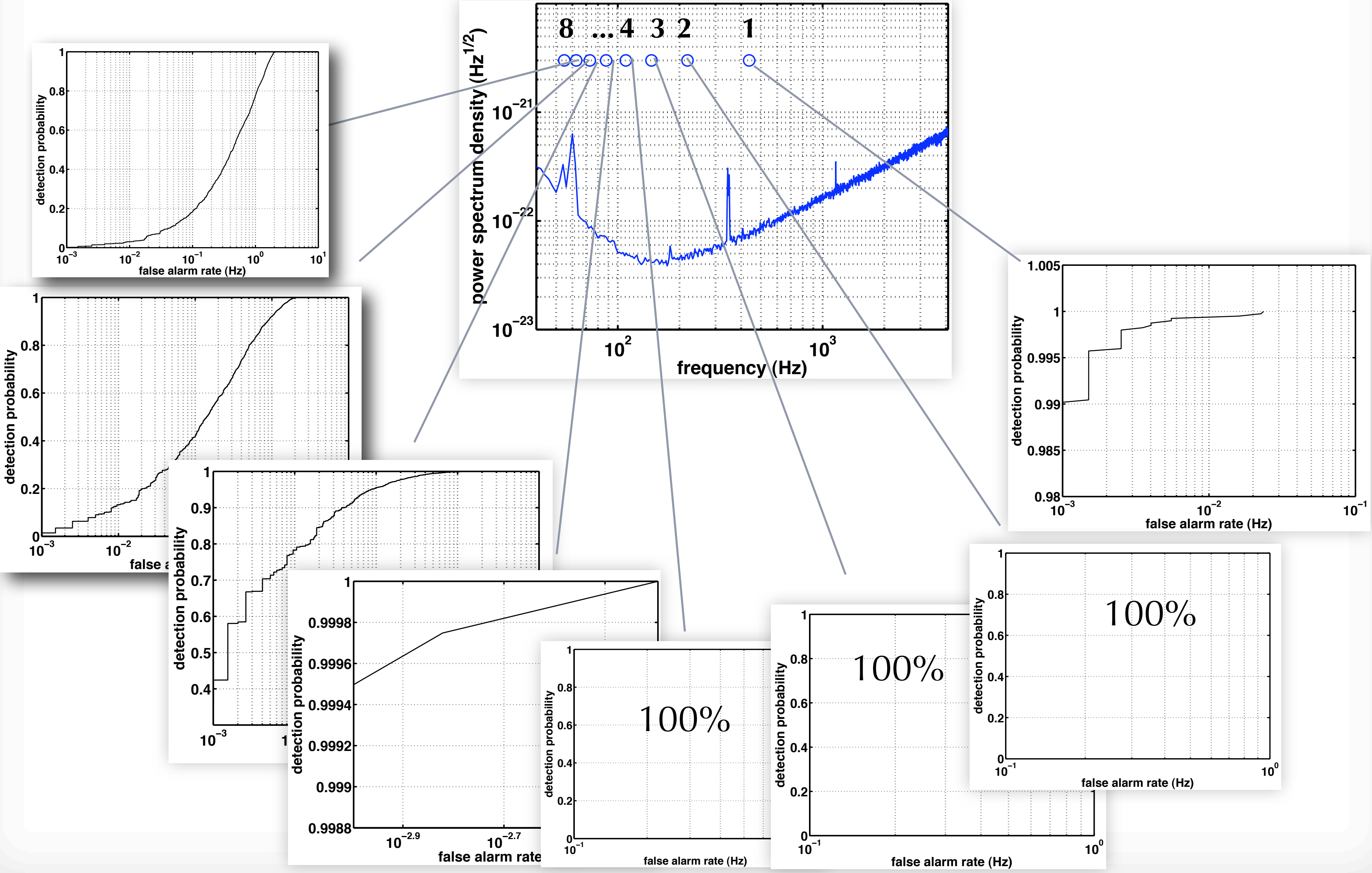




hrss:
root sum square



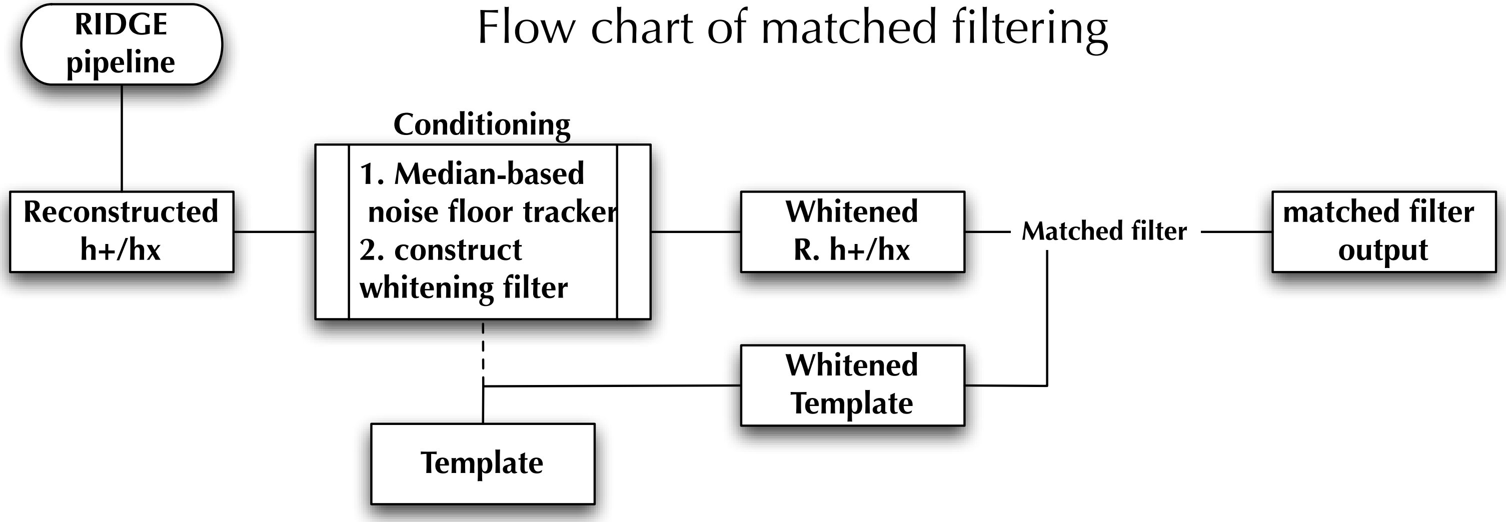
Detection efficiency



Reconstructed waveforms

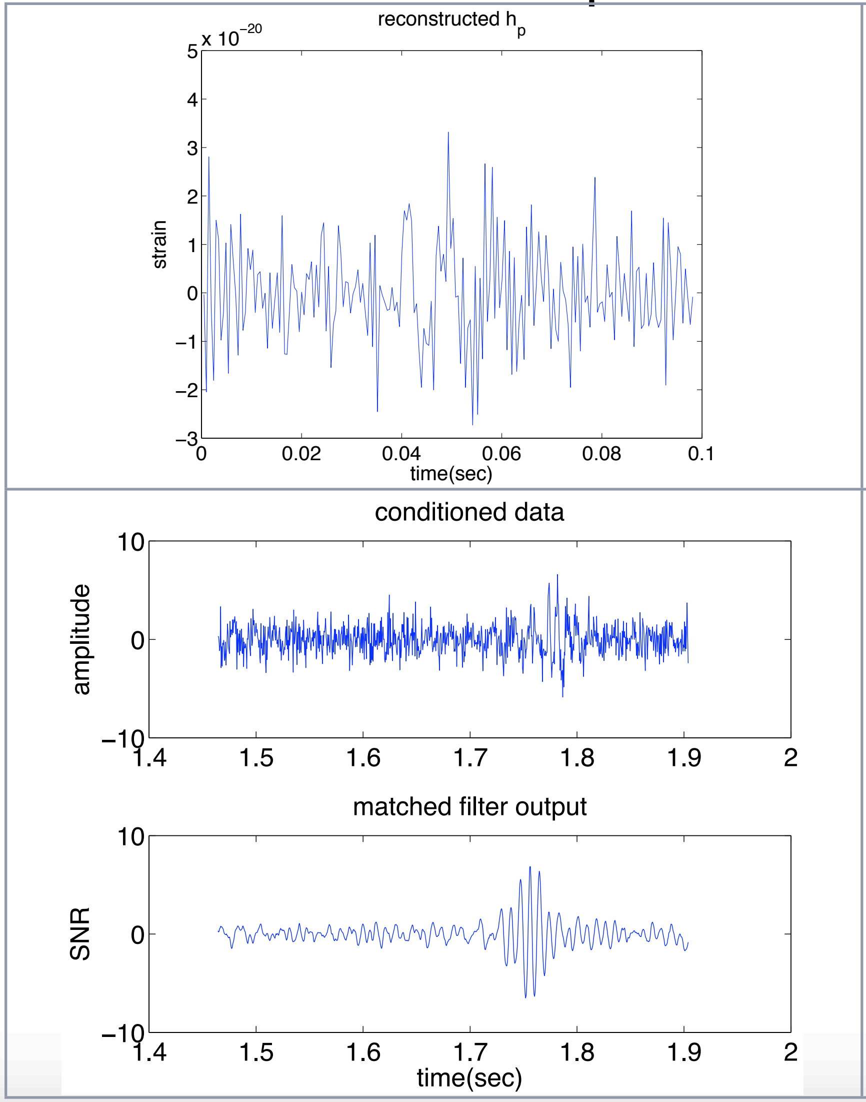
- By regularized Moore-Penrose inverse, both polarization waveforms are reconstructed.
- The reconstructed waveforms are contaminated with noise because detector noise are also included in the procedure of reconstruction.
- We evaluate the performance of reconstruction using matched filtering approach.

Flow chart of matched filtering

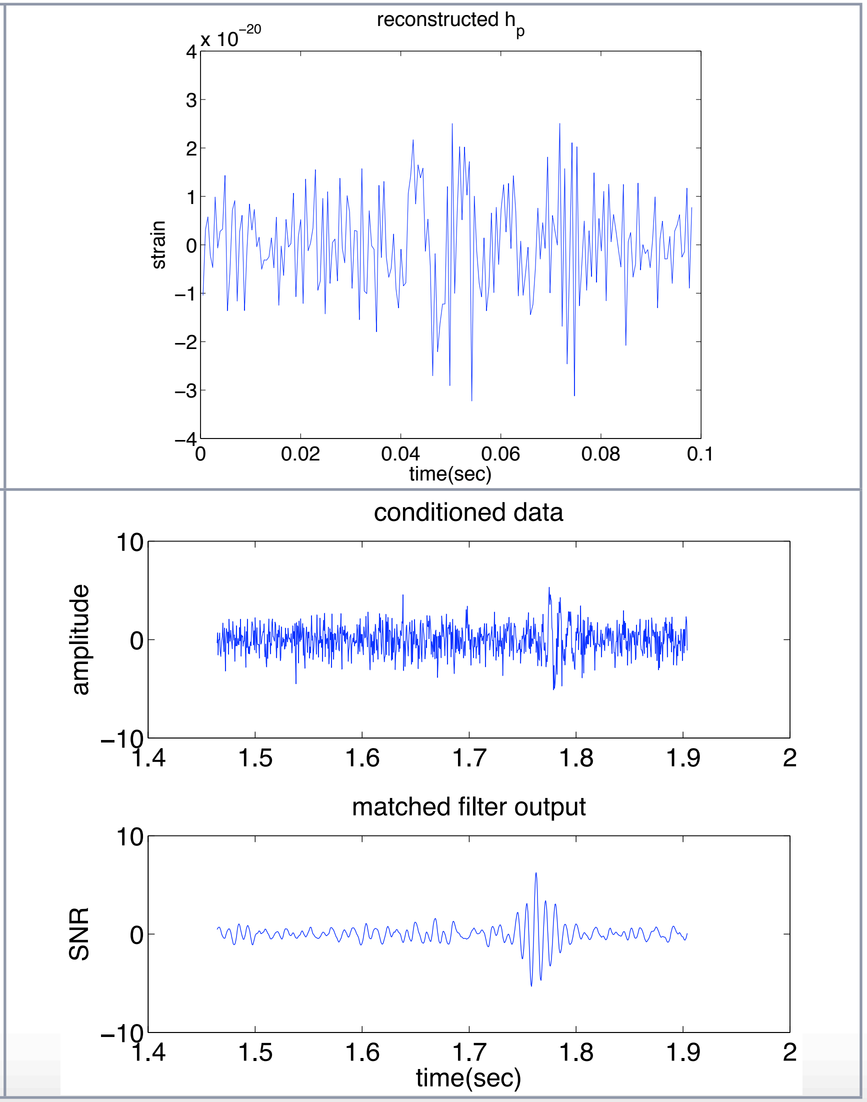


Reconstructed waveforms

reconstructed h plus



reconstructed h cross



Parameter estimation

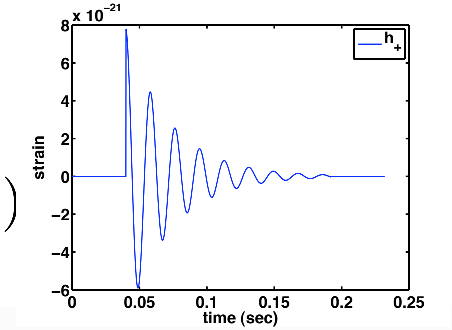
- Ringdown waveforms are characterized by two parameters: central frequency, Q-value
- We study the parameter estimation using matched filter on reconstructed h+/hx.
  - Calculate distribution of matched filter output by changing Q, fc.
  - The aim of this study is to
    - Know how well parameters are estimated to obtain astrophysical information
    - Construct efficient template parameter space for doing matched filter approach for the detection of ringdowns GW from pulsars.

Ringdown form

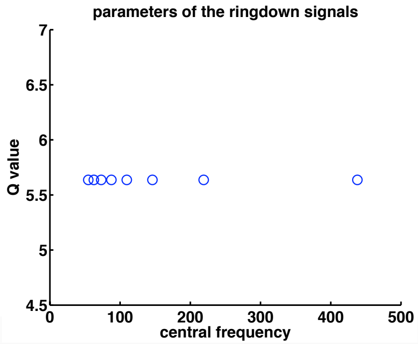
$$h_+(Q, f_c, t) =$$

$$A\exp(-\pi f_c t/Q)\sin(2\pi f_c t)$$

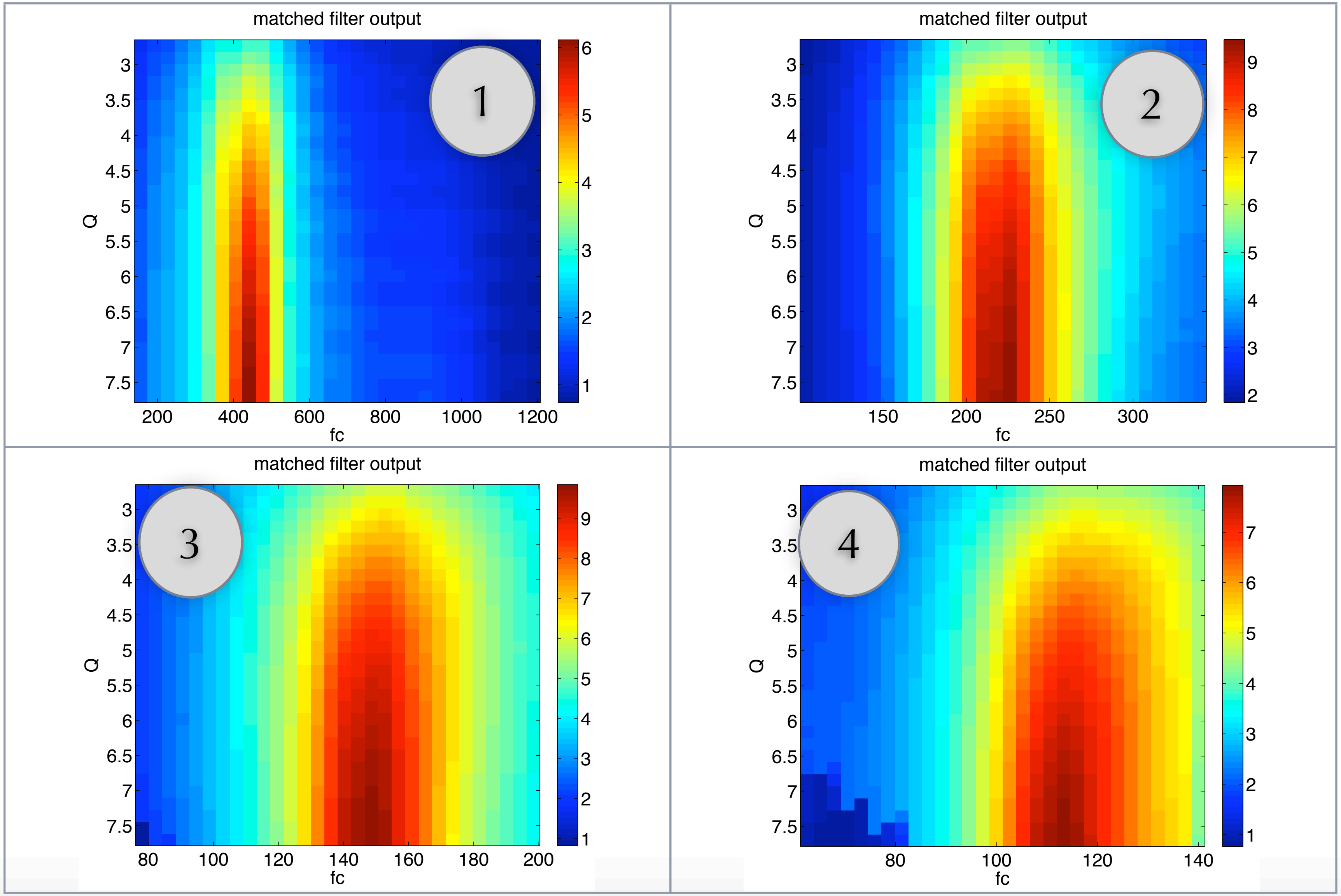
waveform



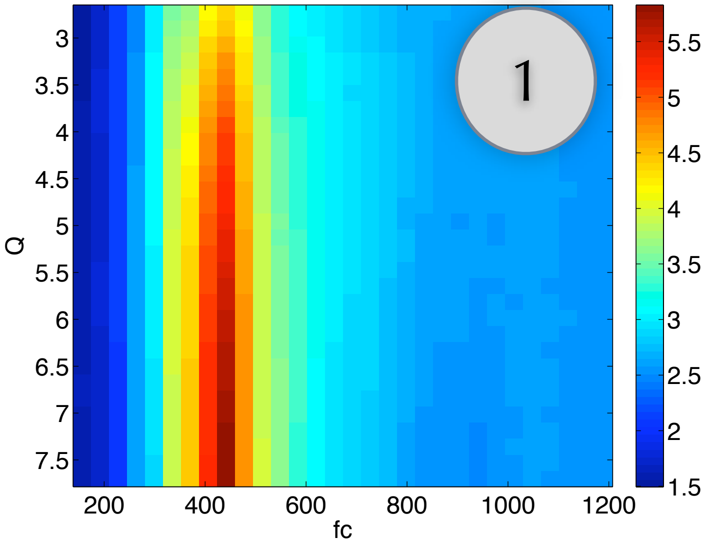
fc vs Q

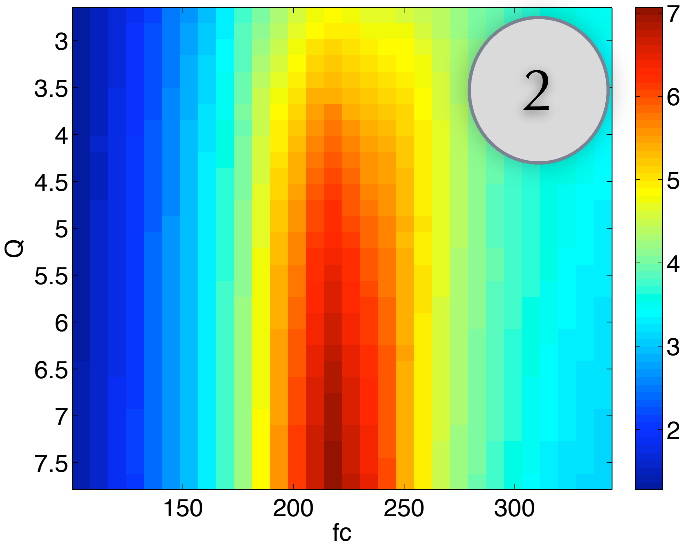


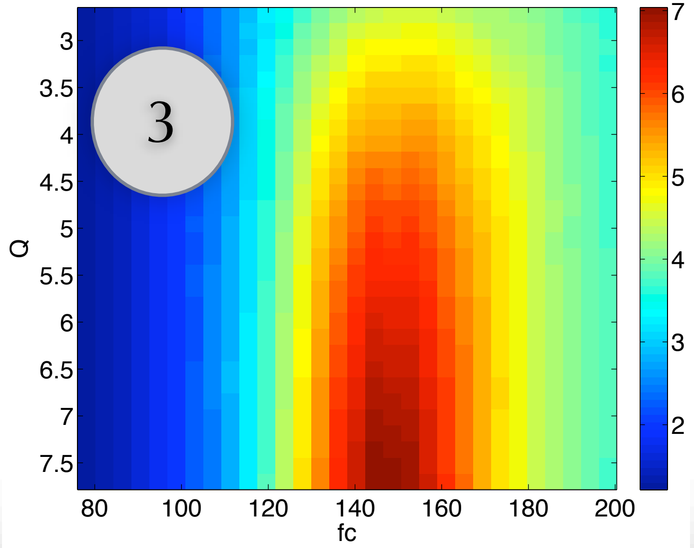
Parameter estimation (h+)

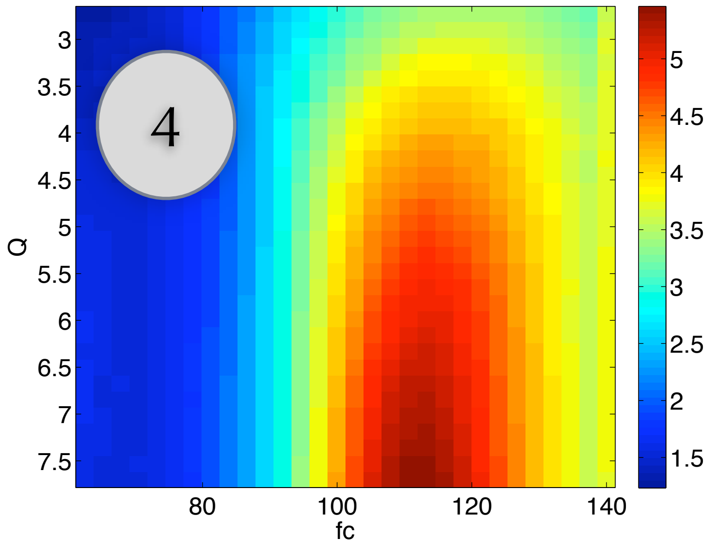


Parameter estimation (hx)


matched filter output


matched filter output


matched filter output


matched filter output

Analysis step for the detection of GW from pulsar glitches

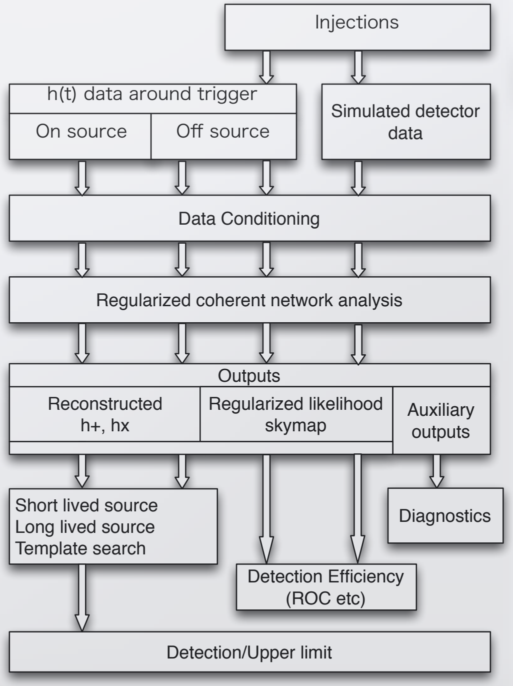
Step 1

- Make list of glitches during S4, S5
- For S6,
  - Predict next pulsar glitch
  - Adjust the observation schedule to the predicted event (within a few days)
  - Optimal observation!

Step 2

- Analyze data with coherent network analysis

RIDGE triggered search pipeline



Injections

h(t) data around trigger

On source

Off source

Simulated detector data

Data Conditioning

Regularized coherent network analysis

Outputs

Reconstructed h+, hx

Regularized likelihood skymap

Auxiliary outputs

Short lived source
Long lived source
Template search

Diagnostics

Detection Efficiency (ROC etc)

Detection/Upper limit

Step 3

- Upper limit/ Detection
- Astrophysical interpretation
  - neutron star superfluidity
  - Rotation of a pulsar and oscillation modes