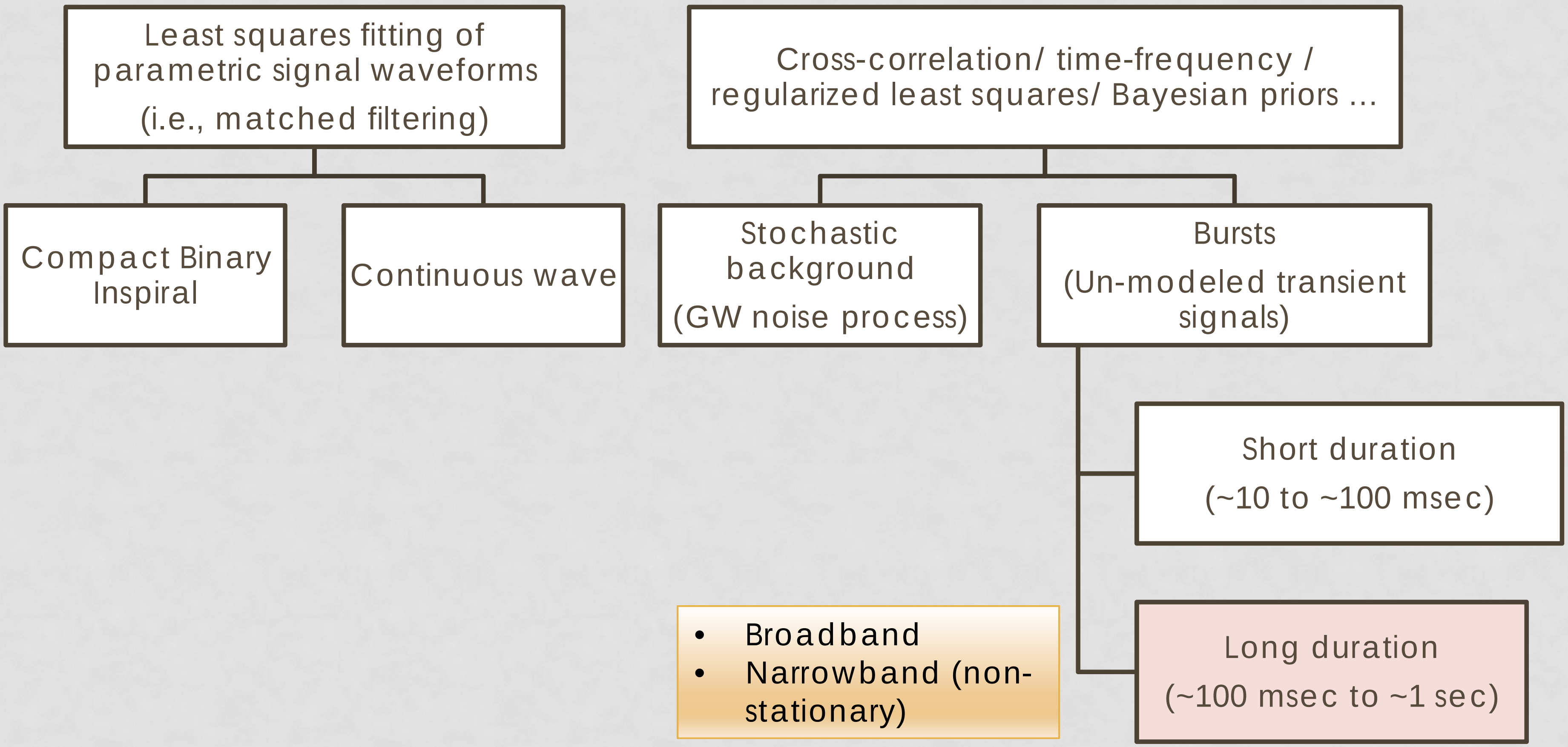
Un-modeled Narrowband Transient Gravitational Wave Signals

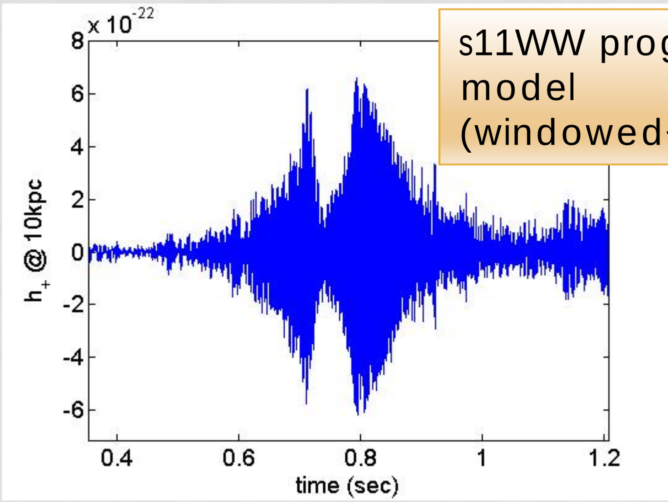
Meeting the detection and Estimation challenge

Soumya D. Mohanty
Dept. Physics and Astronomy
Center for Gravitational Wave Astronomy
UT Brownsville

GW DATA ANALYSIS METHODS

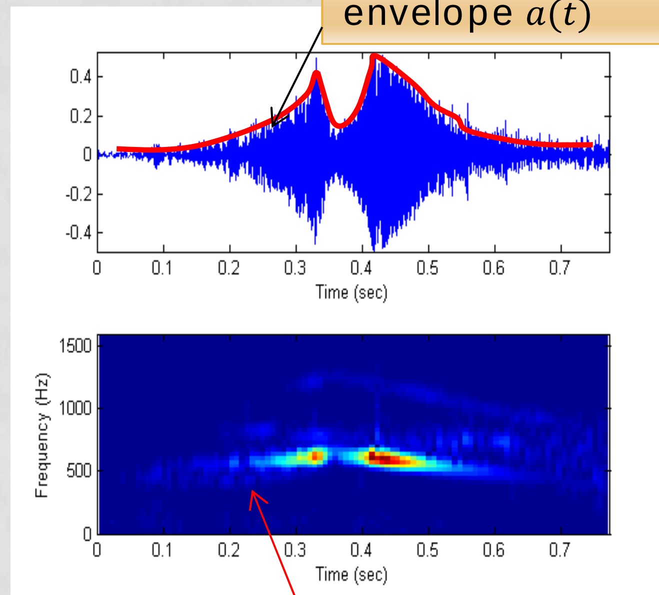


UN-MODELED NARROWBAND TRANSIENT GW SIGNALS



s11WW progenitor model (windowed+filtered)

Acoustic mechanism for shock revival in post-bounce phase of a core collapse supernova (CCSN).
-- Ott et al, Phys. Rev. Lett. (2006)



Unknown amplitude envelope $a(t)$

Unknown frequency evolution $\dot{\varphi}(t)$

$$s(t) = a(t)\cos\big(\varphi(t)\big)$$

$a(t)$ is an unknown amplitude envelope; $\varphi(t)$is an unknown phase

Narrowband: $a(t)$ and instantaneous frequency, $\dot{\varphi}(t)$, change over much longer timescales than the instantaneous period $(2\pi/\dot{\varphi})$

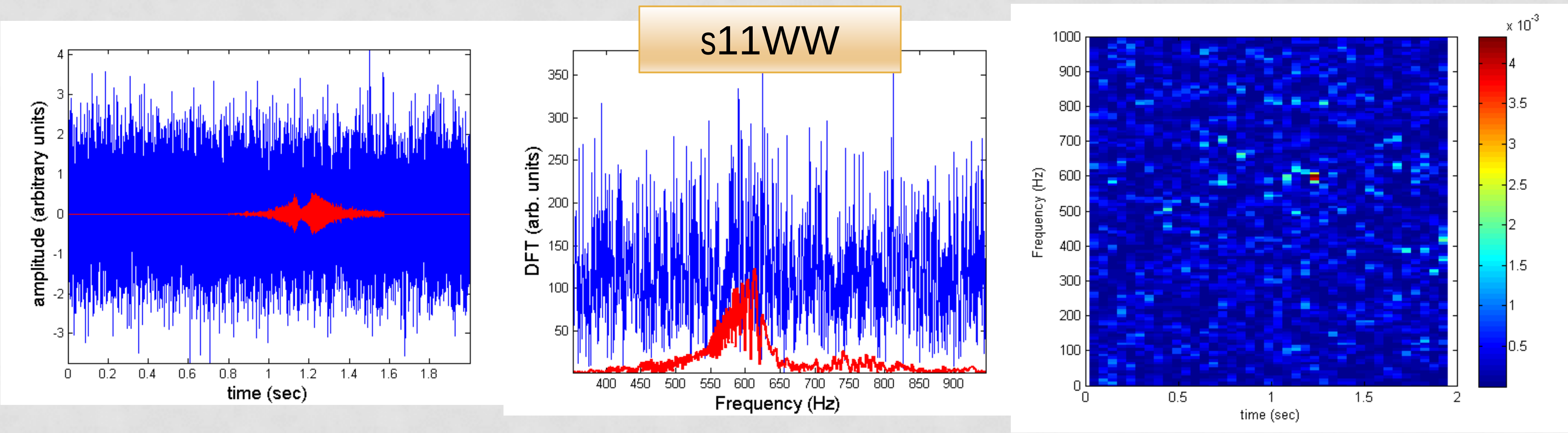
Non-stationary: Instantaneous frequency can evolve over a large range

- Instabilities in collapsar BH accretion torus (van Putten, Phys. Rev. D (2004))
- Crustal modes of Magnetars (Murphy et al, Phys. Rev. D (2013))

THE CHALLENGE

Advanced LIGO Matched filtering Signal to Noise Ratio (SNR) @ 10 kpc is in the range 5 to 20 for most long duration CCSN signals **with optimal source and detector orientation .** (Murphy *et al.* *ApJ* (2009))

We consider SNR=10 signals in white Gaussian noise.



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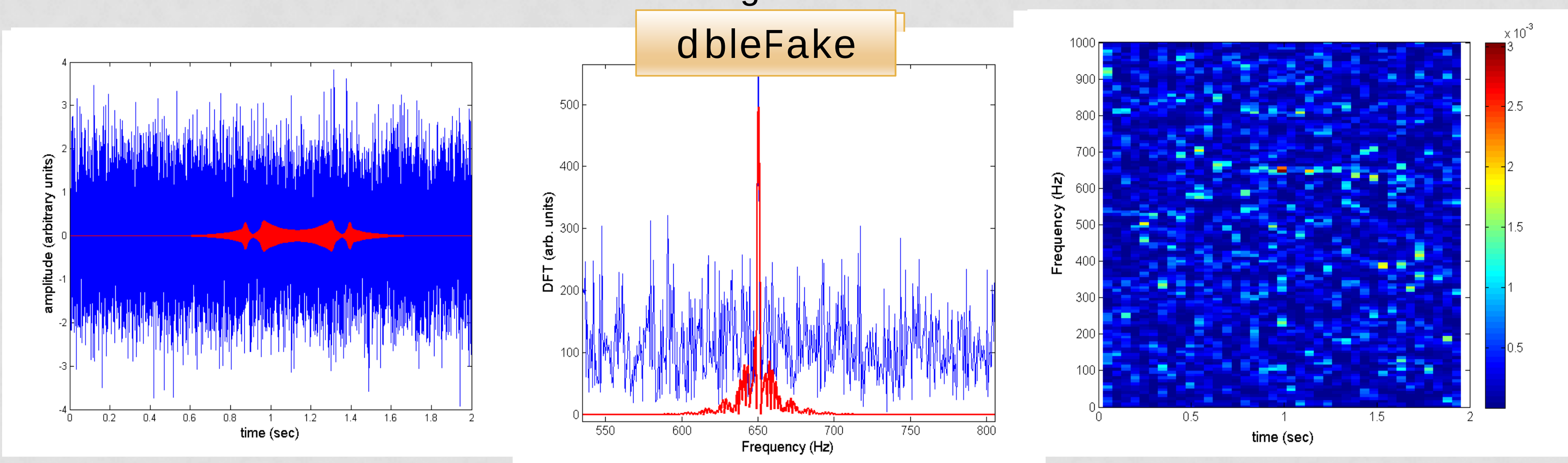


<u>Detection Challenge</u>: Detect signal at a fairly low false alarm probability
<u>Estimation Challenge</u>: Estimated signal should match true signal in at least some characteristic features
Time-frequency methods are ineffective, especially for estimation

ALGORITHM

$\bar{y}$ data vector $\in R^N$ and $\bar{s}$ signal vector $\in S \subset R^N$

$\bar{s}$: samples of the analog signal

$$s(t;\bar{\tau},\bar{\psi}) = a(t;\bar{\tau})\cos\phi(t;\bar{\psi})$$

$a(t;\bar{\tau})$: cubic spline with knots at $\bar{\tau} = (\tau_1, \tau_2, \ldots, \tau_M)$

$$\Rightarrow a(t;\bar{\tau}) = \sum_{i=1}^{M} \alpha_i \times \underbrace{B_i(t;\bar{\tau})}$$

Basis Functions of the linear space of cubic splines with knots at $\bar{\tau}$

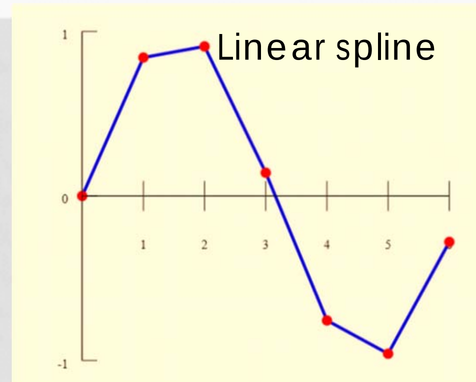
Enforces smoothness of $a(t)$

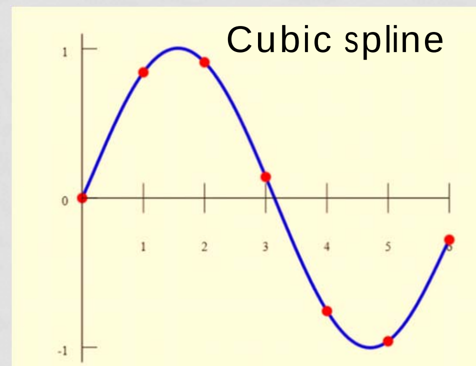
$$\phi(t;\bar{\psi}) = \int_0^t f(t';\bar{\psi})dt'$$

$f(t;\bar{\psi})$: linear spline with knots at $\bar{\psi} = (\psi_1, \ldots, \psi_K)$

Minimize over $\bar{\tau}, \bar{\psi}, \{\alpha_i\}, i = 1, \ldots, M$

$$\underbrace{\mathrm{L}(\bar{\tau},\bar{\psi};\bar{y})}_{\text{Fitness function}} = \underbrace{\|\bar{y} - \bar{s}(t;\bar{\tau},\bar{\psi})\|^2}_{\text{Standard MLE functional}} + \lambda \underbrace{\sum_{i=1}^{M} \alpha_i^2}_{\text{Penalty term}}$$



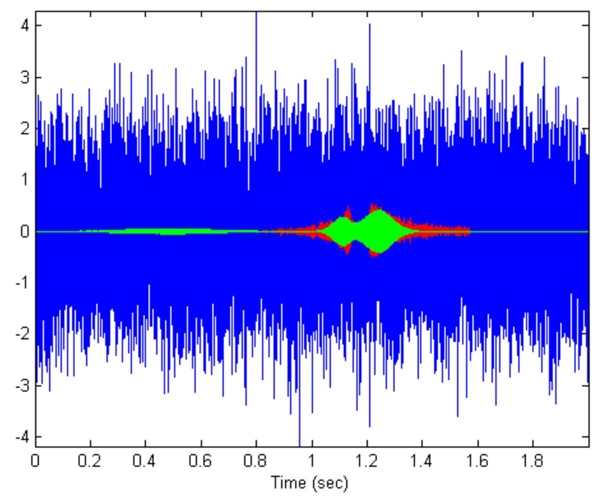


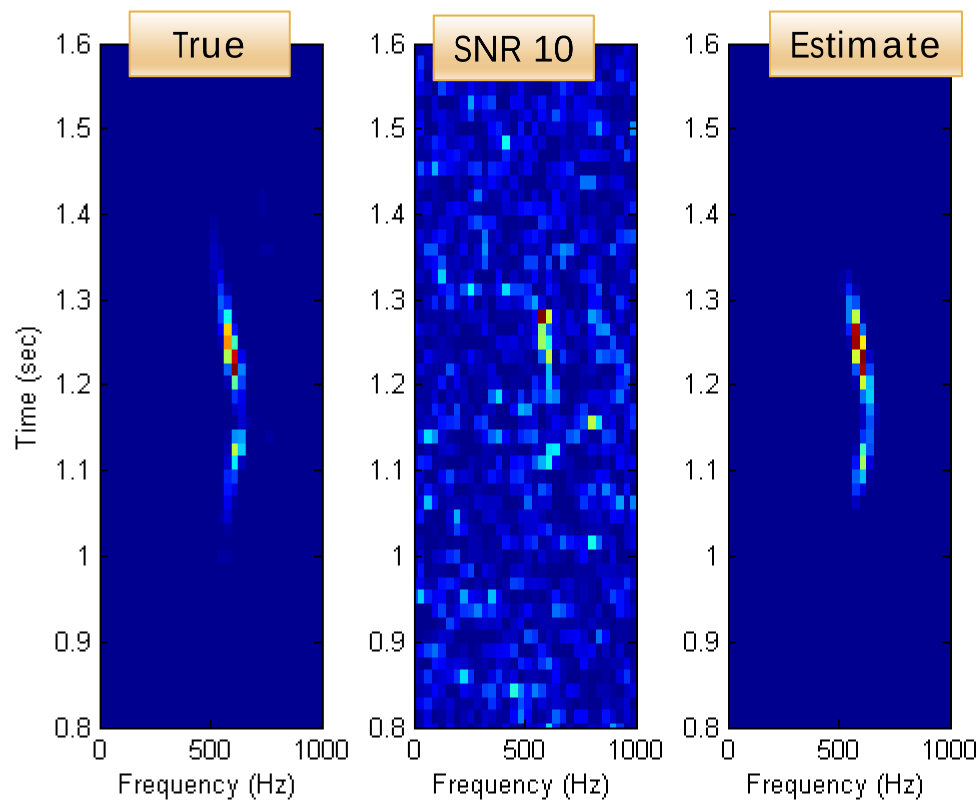
- α_i solved analytically for given $\bar{\tau}$ and $\bar{\psi}$
- Minimization over $\bar{\tau}$ and $\bar{\psi}$: Particle Swarm Optimization (Kennedy, Eberhart, 1995)

Rupert, Wand, Caroll, *Semiparametric Regression*

EXAMPLES

- Data length 2 sec; 10 temporal and 5 frequency knots+5 frequency values
- PSO based optimization over a 20 dimensional search space
- Max. instantaneous signal frequency for the search : 800 Hz.





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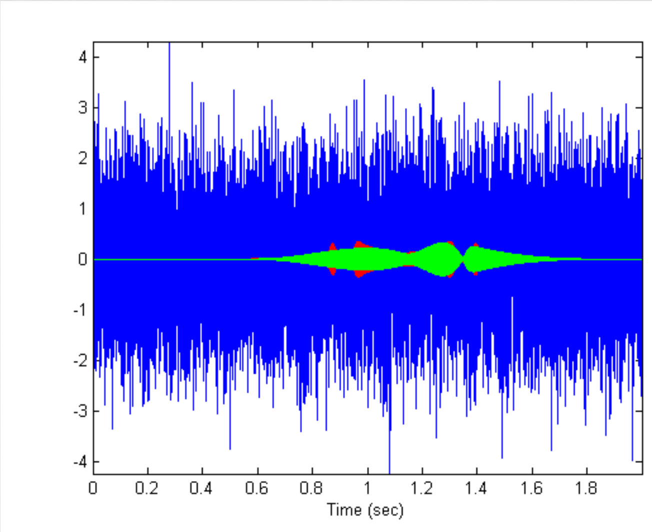
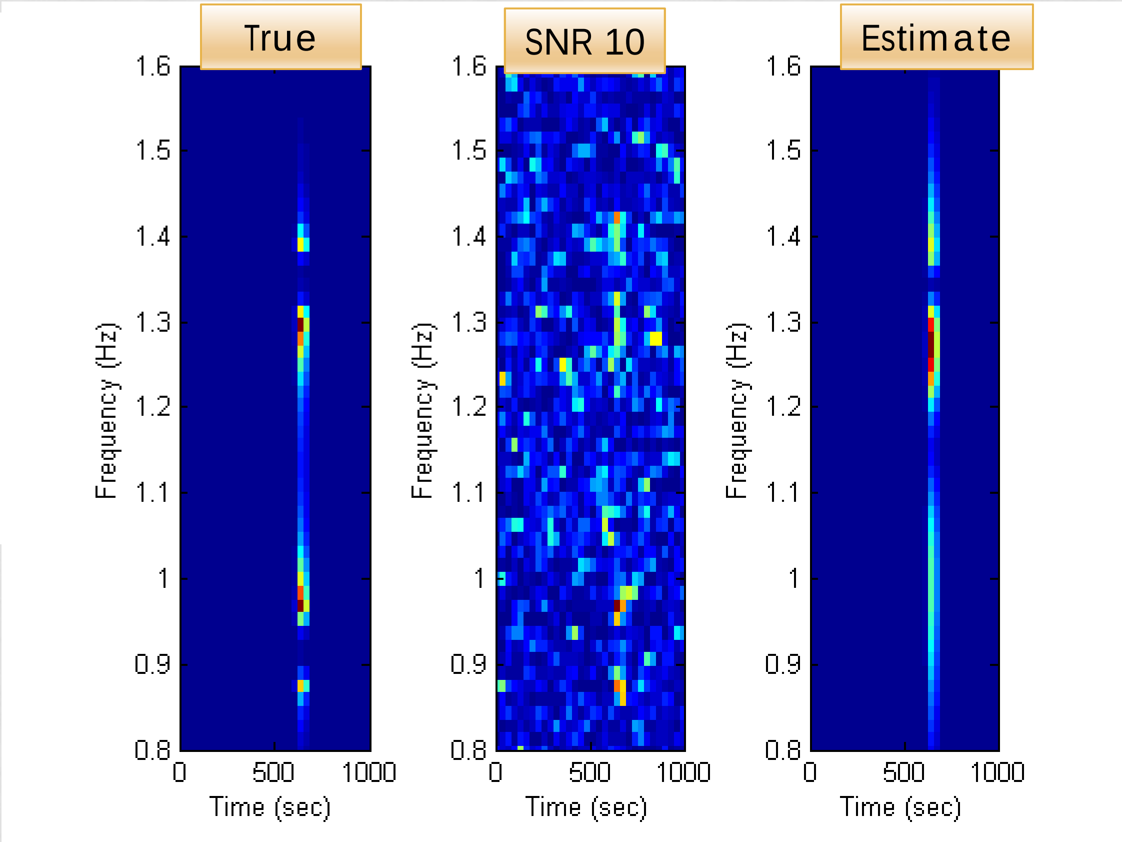
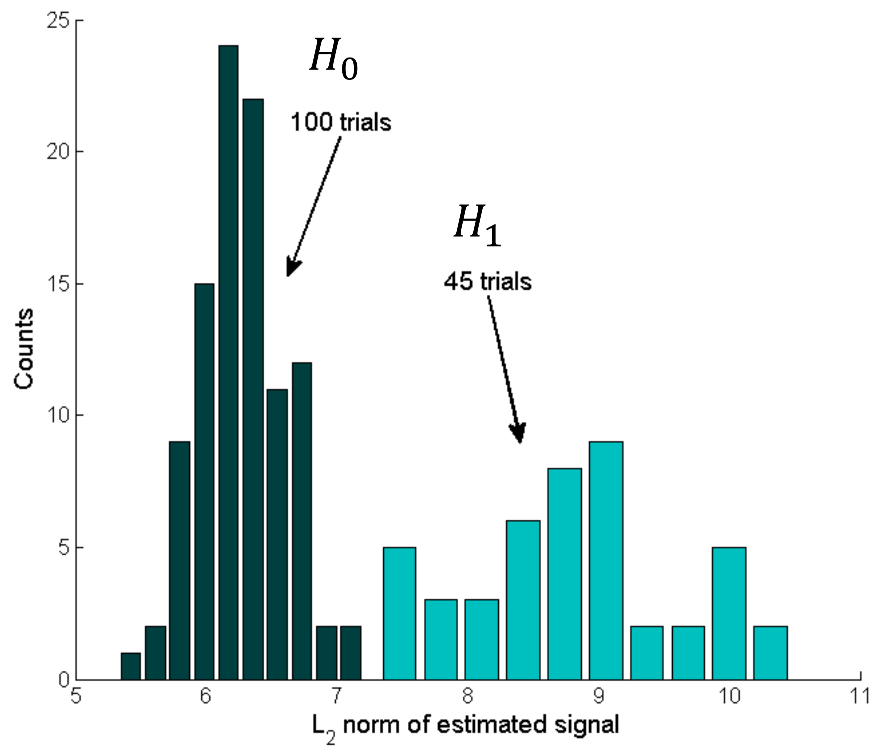




RESULTS: DETECTION PERFORMANCE

White Gaussian noise;
s11WW @ matched filtering SNR = 10
Detection statistic (λ): L_2-norm of estimated signal



Effective SNR

$$\frac{mean(\lambda|H_1) - mean(\lambda|H_0)}{stdev(\lambda|H_0)}$$

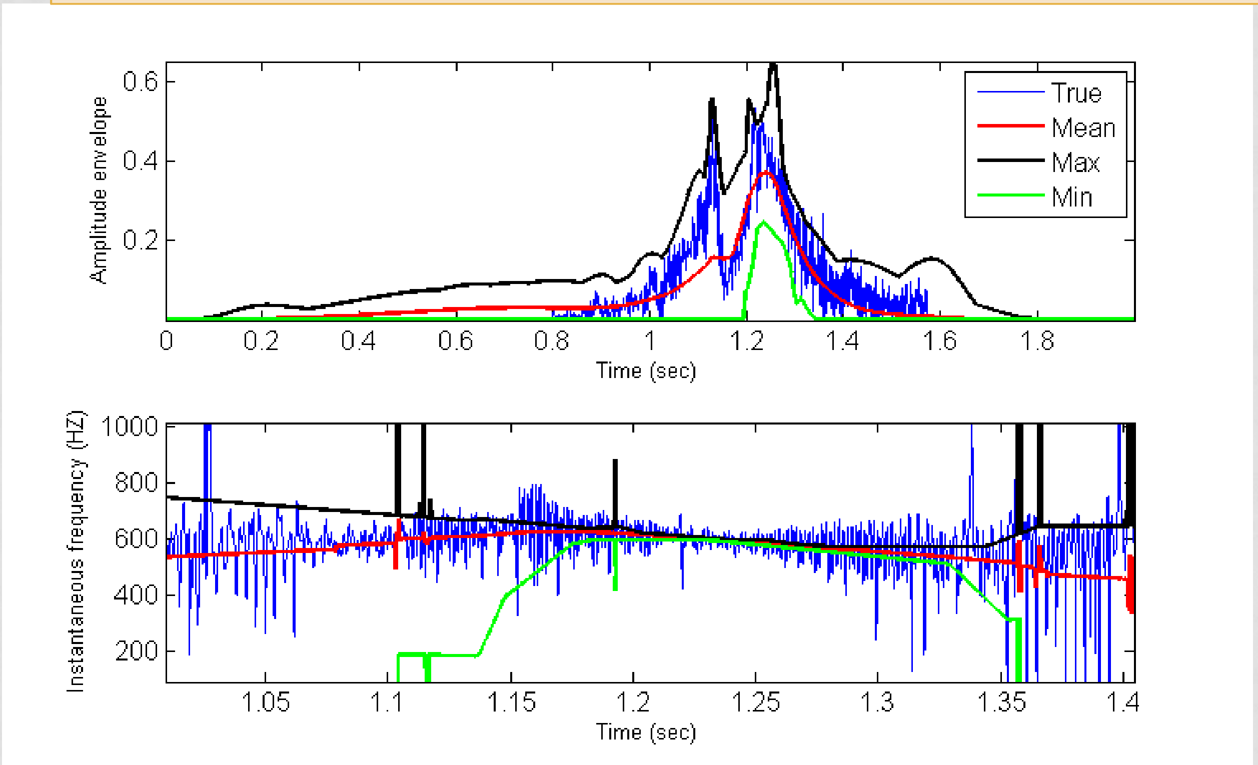
- s11WW signal: 7.6
- dbleFake signal: 10.6 (≈ matched filtering SNR!)

- Plain Time-frequency method with hand-tuned TF parameters.
- λ : magnitude of the loudest pixel in:
  - H_0: [0, 800] Hz and [0, 2.0]sec
  - H_1: [500,700]Hz and [0.8,1.5]sec
  - s11WW signal: 5.5
  - dbleFake signal: 5.4

ESTIMATION PERFORMANCE

- Sample-by-sample match of true and estimated signals is not a useful measure of estimation performance
- We need to know how well some basic features are estimated .

Amplitude envelope and instantaneous frequency of the **analytic representation of the signal** (Hilbert transform)



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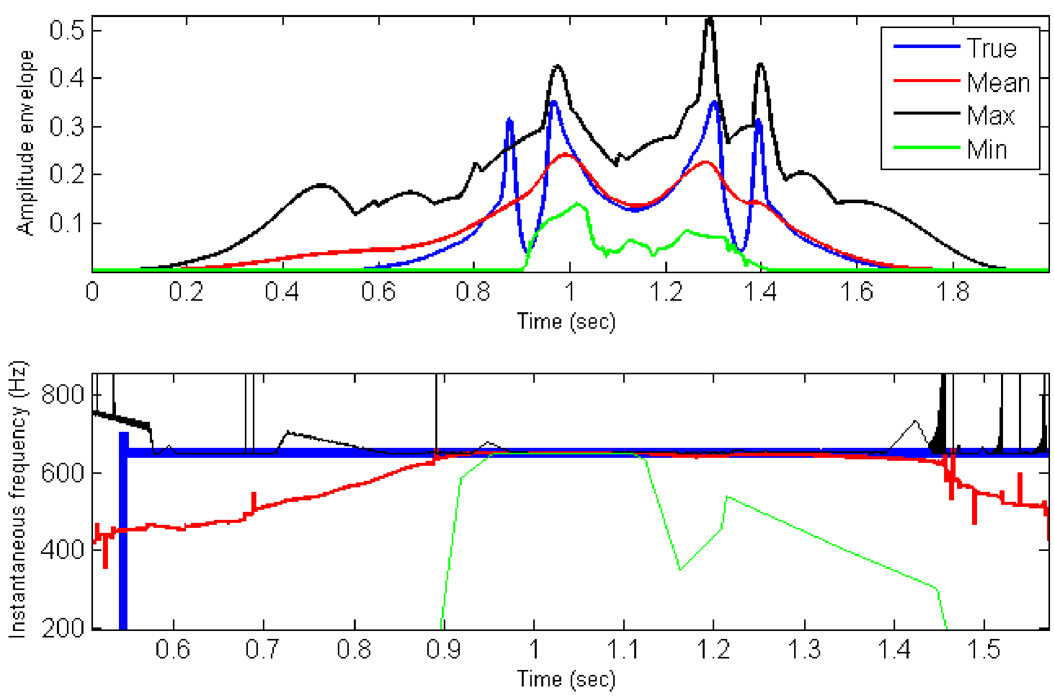

SUMMARY

- A GW search algorithm for situations where time-frequency methods don't work well
  - At best, TF analysis misidentifies a long duration signal as a short burst
- Can resolve widely different amplitude and carrier frequency evolutions
  - Good match of the estimated amplitude envelope and instantaneous frequency on the average
  - Better discrimination of source models in terms of their GW signals
- Detection performance is fairly robust across the wide range of signals considered
  - Effective SNR between 7.5 and 10.0 for matched filtering SNR of 10
- Work in progress on further improvements
  - Improving the non-linear optimization phase (currently using PSO with minimal modifications)
  - Instantaneous frequency models that show smoother time evolution.