Improved all-sky Hough search for continuous gravitational waves

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Continuous gravitational waves from neutron stars

There are probably ~10^8-10^9 neutron stars in the galaxy

~10^5 are radio pulsars (we know of ~ 2500)
~10^7 are (unseen) dead magnetars
~10^8 are totally unknown

We will see GWs from any neutron star that is

sufficiently lumpy
sufficiently close
spinning at a rate that will appear in our band

We focus on the development of algorithms for the analysis of continuous waves signals from isolated unknown neutron stars for LIGO and Virgo data.

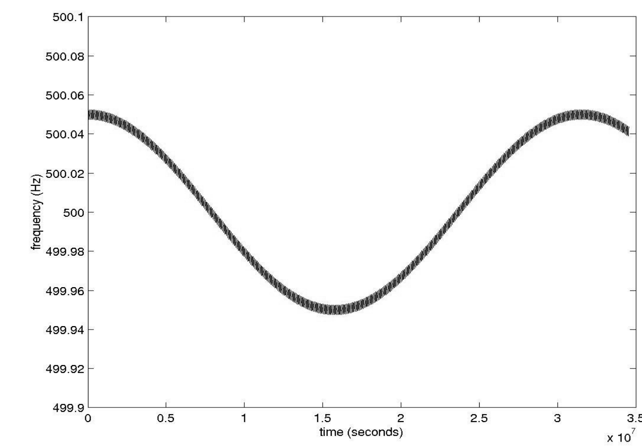
Unlike searches for gravitational waves from pulsars (whose location, gravitational wave emission frequencies, and spin-down rates are well known), searches for electromagnetically quiet sources require algorithms which look at vastly larger parameter spaces.

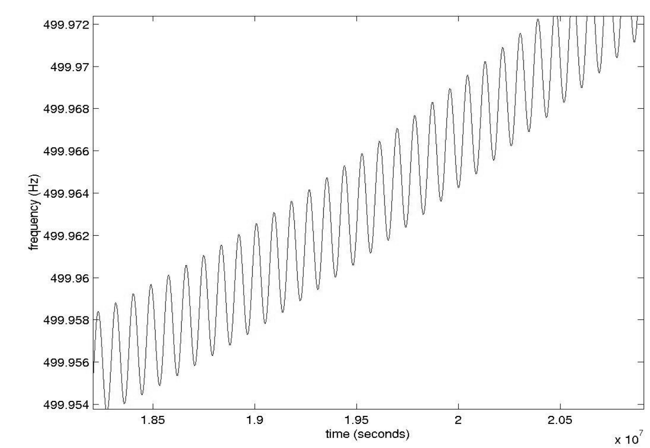
The algorithms have to account for 'rapid' modulation due to earth rotation (both Doppler modulation of the frequency and amplitude modulation due to the diurnal changes in detector antenna pattern) and the slower modulation due to the earth's orbit around the sun.

All-sky searches for continuous waves from isolated stars

- **Long integration times are necessary** since the gravitational wave amplitude is very low.

- **The signal is not truly monochromatic:**
  - Unknown source **spin-down** (frequency derivatives)
  - **Doppler** modulation of the apparent source frequency in the interferometer rest frame
  - **Antenna pattern** modulation due to daily rotation





- The **frequency and amplitude modulations** depend on the source's unknown sky location, and the amplitude modulation also depends on the source's unknown **orientation angles**.

- As a **result** of these complications, it is **not feasible**, even using all the computational power now available on Earth, to carry out an all-sky, broadband, year-long search for a gravitational wave signals that exploits the set fully via **coherent integration**

Alternative approaches need to be exploited -> semi-coherent methods

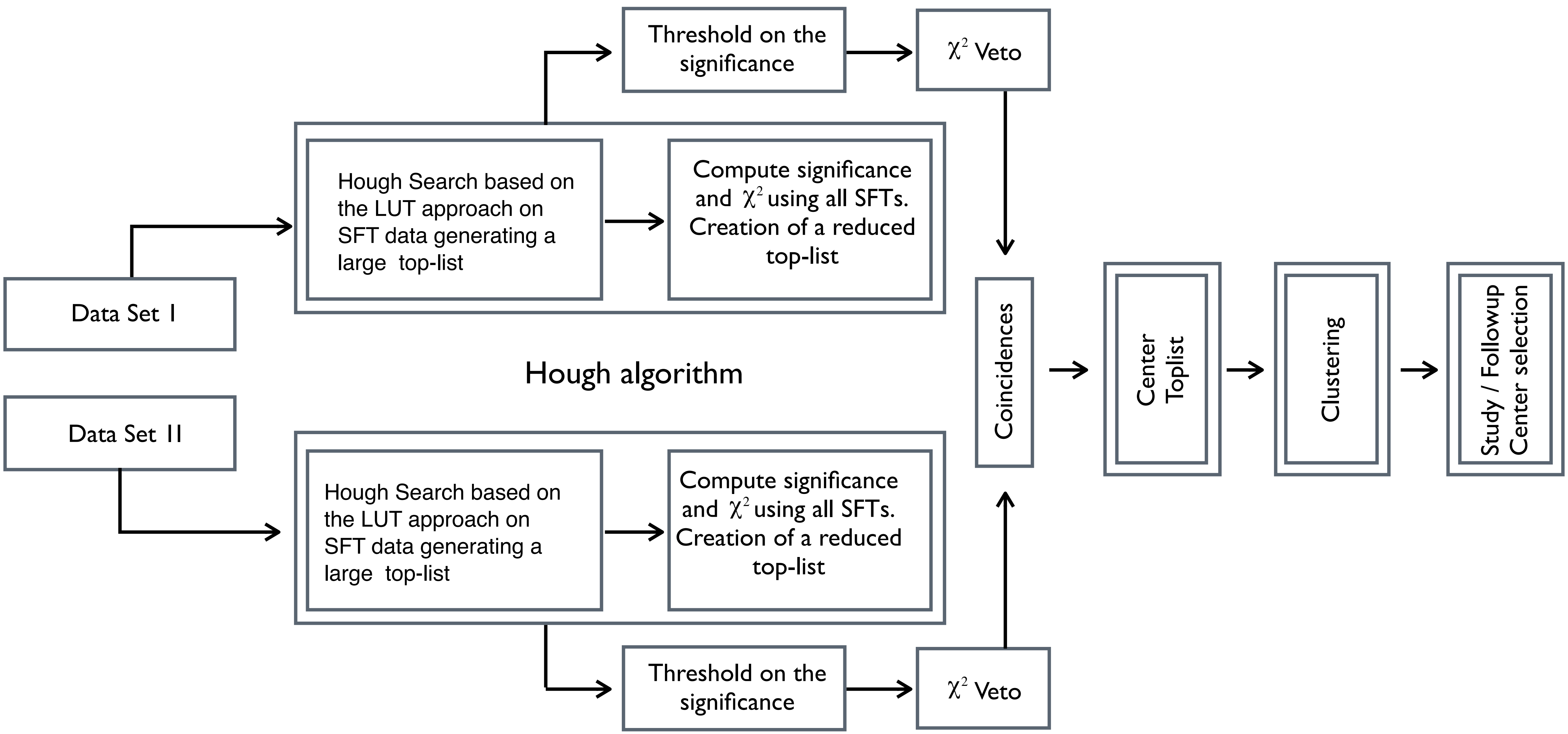
Quick-Look Search Pipelines:

The data is split into shorter segments which are searched separately with a coherent method using a coarse grid in parameter space. The results of the coherent search in each segment are then combined incoherently on a finer search grid.

Pipeline	**Published observational results to date**
PowerFlux	**PRD 77 (2008) 022001 (S4)** **PRL 102 (2009) 111102 (S5)** **PRD 85 (2012) 022001 (S5)** **(arXiv:1605:03233 - May 2016)(S6)**
Einstein@home	**PRD 79 (2009) 022001 (S4)** **PRD 80 (2009) 042003 (S5)** **PRD 87 (2013) 042001 (S5)**
Sky Hough	**PRD 72 (2005) 102004 (S2)** **PRD 77 (2008 022001 (S4)** **CQG 31 (2014) 08501414 (S5)**
Frequency Hough	**PRD 93 (2016) 042007 (VSR2/4)**
Time Domain $\mathcal{F}$-statistic	**CQG 31 (2014) 165014 (VSR1)**

Description of the Sky Hough search

Pipeline Scheme:



Hough algorithm

arXiv:gr-qc/0407001 arXiv:gr-qc/0601081

Input data are 1800s SFTs . That input corresponds to the **coherent step** (although other coherent integrations can be used if one increases the length of the segments).

Hough -> Hough sums Weighted binary counts (0/1 = normalized power below/above SNR), with weighting based on antenna pattern and detector noise to **track the frequency drifts** due to **Doppler** modulations and **df/dt** as the **incoherent step**.

The grid

$$\delta f = \frac{1}{T_{coh}} \qquad \delta sky = \frac{10^4 \delta f}{f\, PixelFactor} \qquad \delta \dot{f} = \frac{1}{T_{coh} T_{obs}}$$

Frequency band — We divide the full frequency range of the search into small pieces of 0.1Hz

Sky patches — The main idea is to split up the sky into smaller patches, that will allow us to use the look up table approach to compute the Hough transform. We collect 300 candidates for each sky patch and frequency band.

Output / Toplist — We generate two different top-lists containing the 1000 more significant candidates per frequency band

Candidate postprocessing

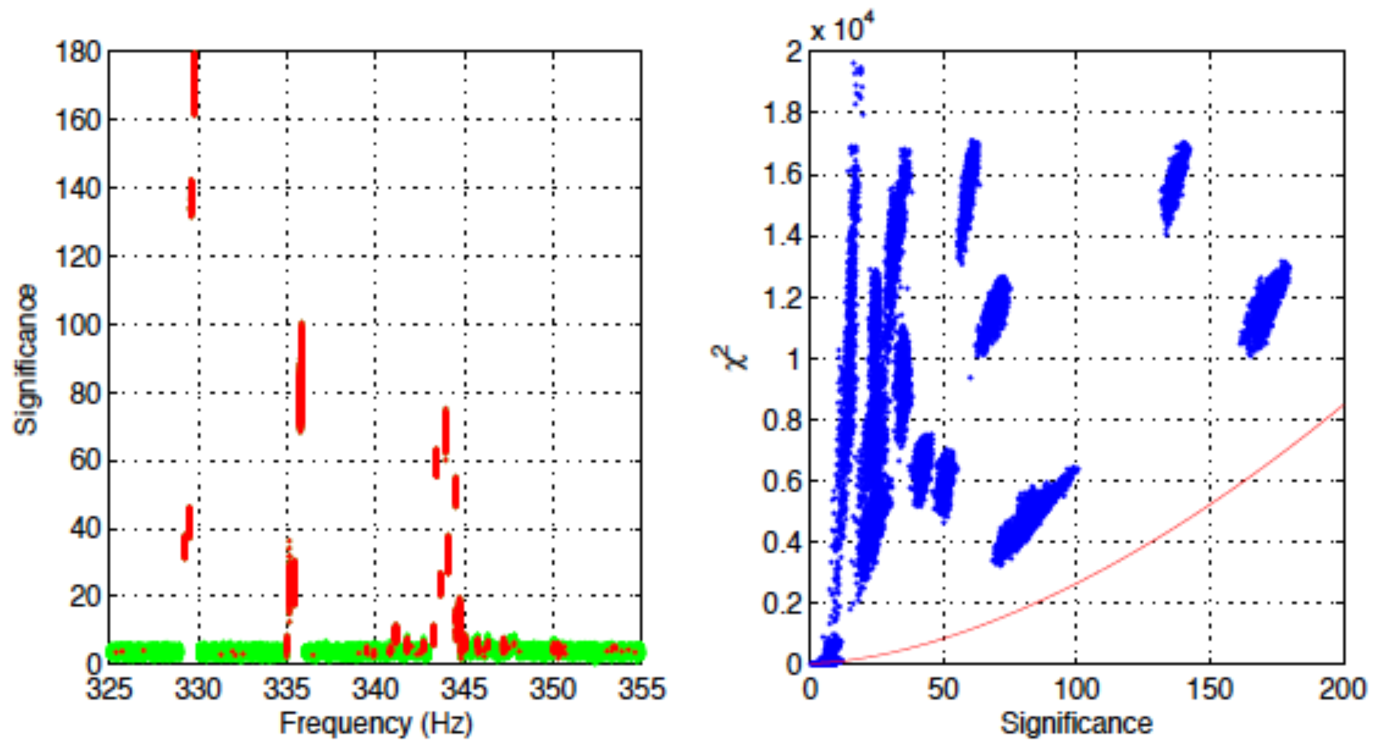
Threshold on Significance

The first step is to set a threshold on significance according to a certain FAP in both top-list.

$$s = \sqrt{2}\,\mathrm{erfcinv}(2\alpha)$$

Chi2 Veto

This veto will eliminate candidates that are not consistent with our hypothesis of a signal and Gaussian noise.



arXiv:1311.2409v3

The χ^2 veto is able to veto the violin modes present in the data and many other narrow instrumental artifacts.

Candidate postprocessing

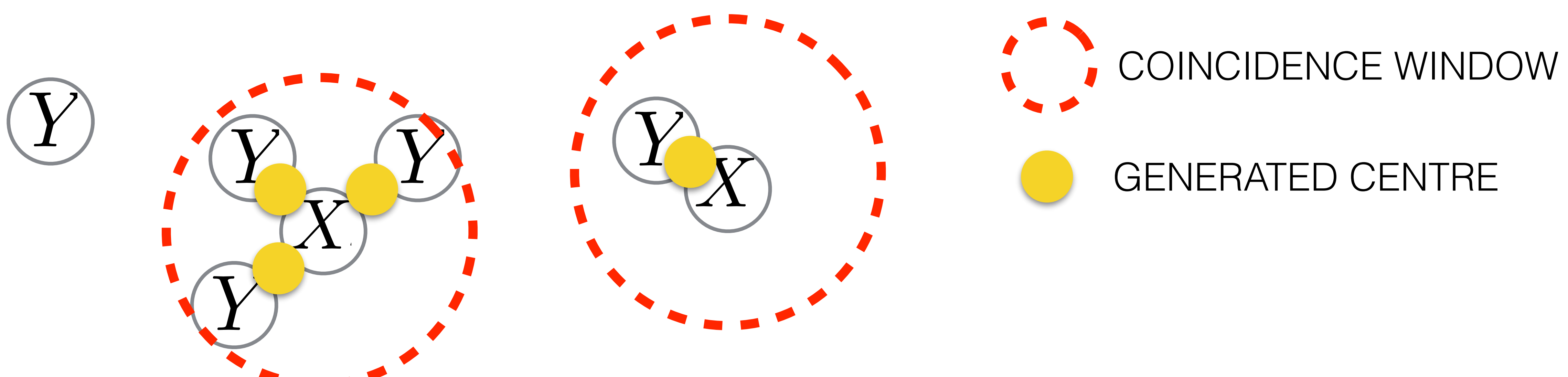
Search for coincidental candidates in the two data sets

We can define two candidates to be coincident if

- all the different parameters (sky location, frequency and spin-down) are within a pre-defined window
- or if the total distance in a 4-dimensional parameter space is smaller than a certain predetermined value.

Coincidental Toplist generation i.e. Center points

For each coincident pair we generate a centre.
In other to avoid excessively large lists, we only keep Nc centres with the highest mean significance.



Candidate postprocessing

Clustering method

We study the topology of the reduced set of centres by analysing the distance between them. With that information we split the centres into different clusters and identify a nucleus that will be the centre of a follow-up search in case of being selected.

Population Threshold

We only accept a cluster if the population is higher that a certain value.

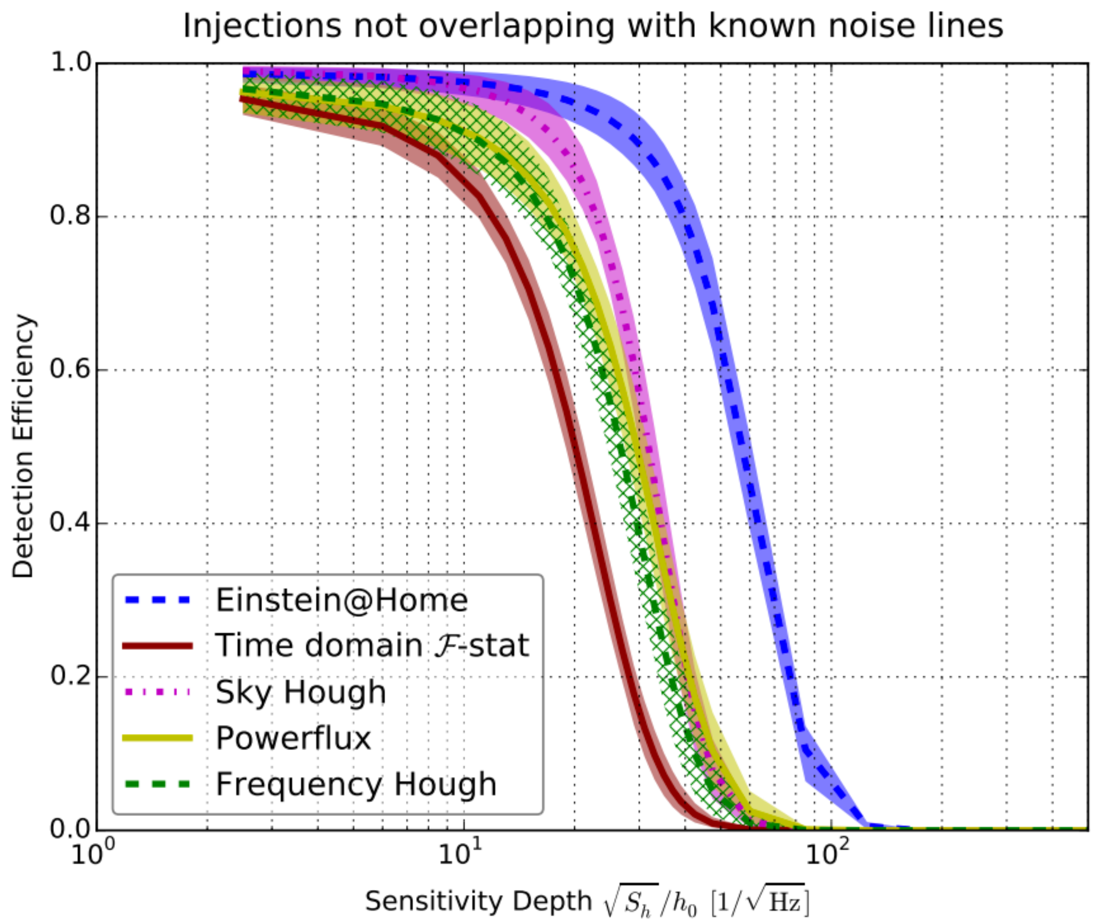
Selection

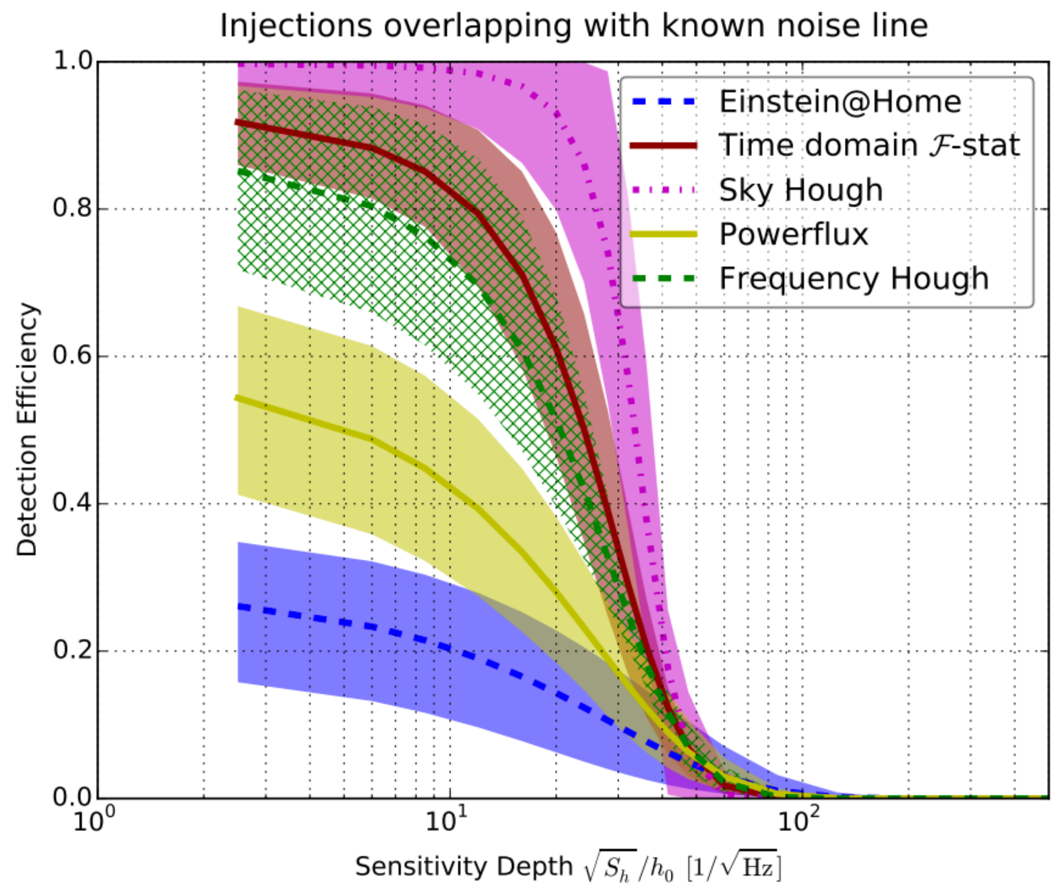
For each search band we select a maximum of 1 cluster: the cluster that has the largest population and significance simultaneously.

The Mock Data Challenge

An all-sky MDC was set up using LIGO S6 science run data to compare the different search pipelines. It consisted of 3110 injected random signals between 40–1550 Hz.

Efficiency

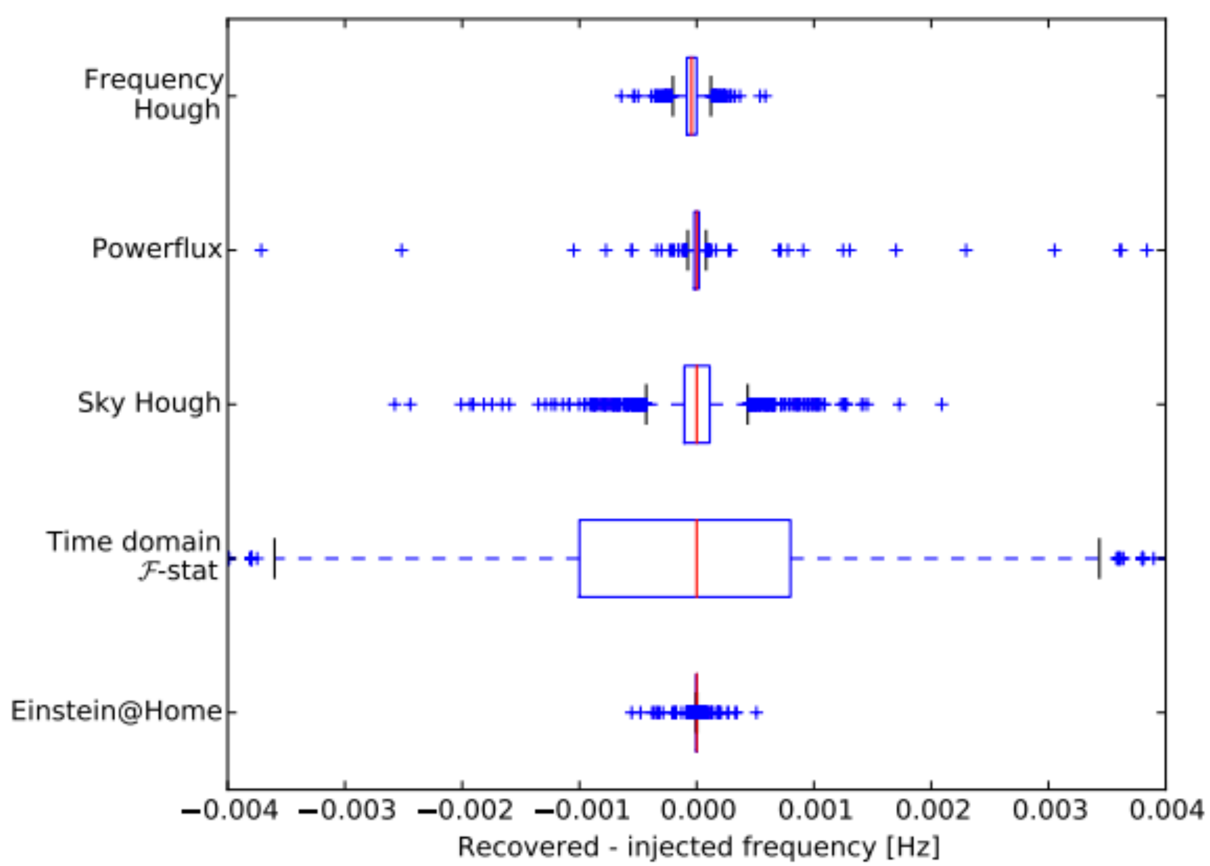


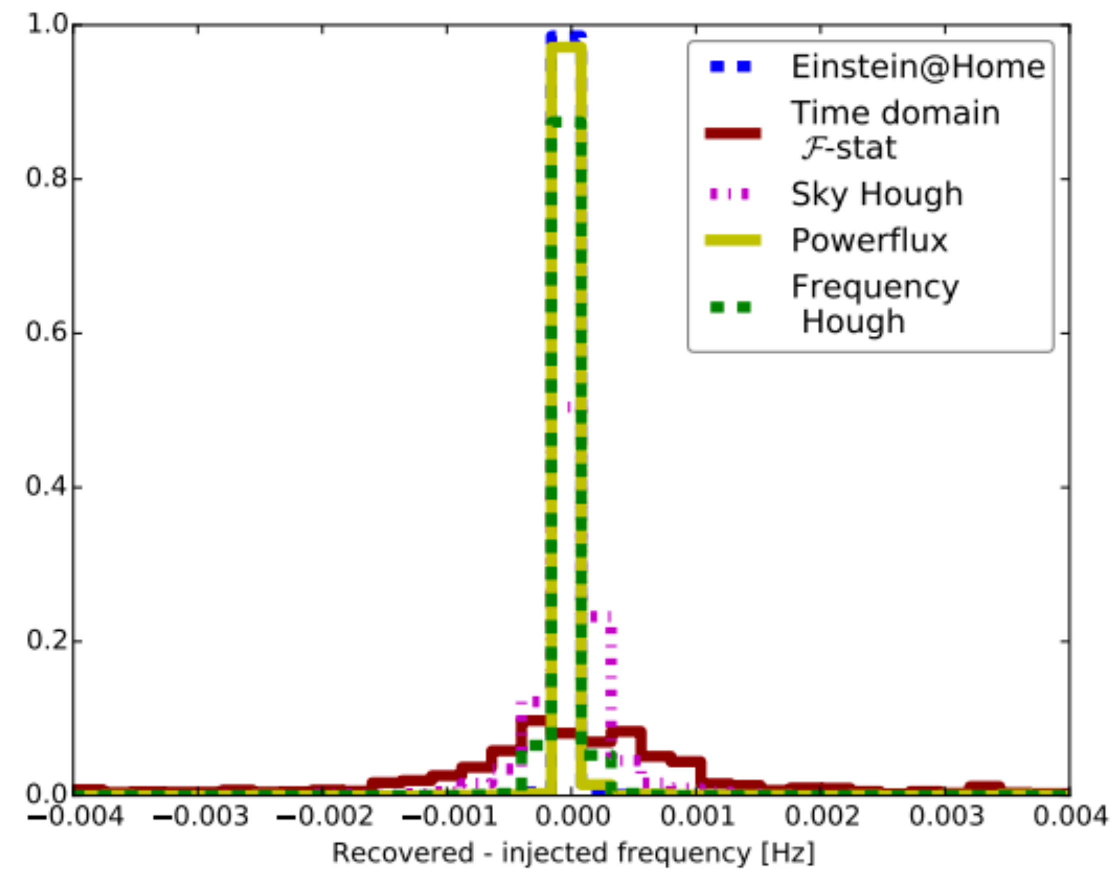


arXiv:1606.00660

The Mock Data Challenge

Parameter Estimation





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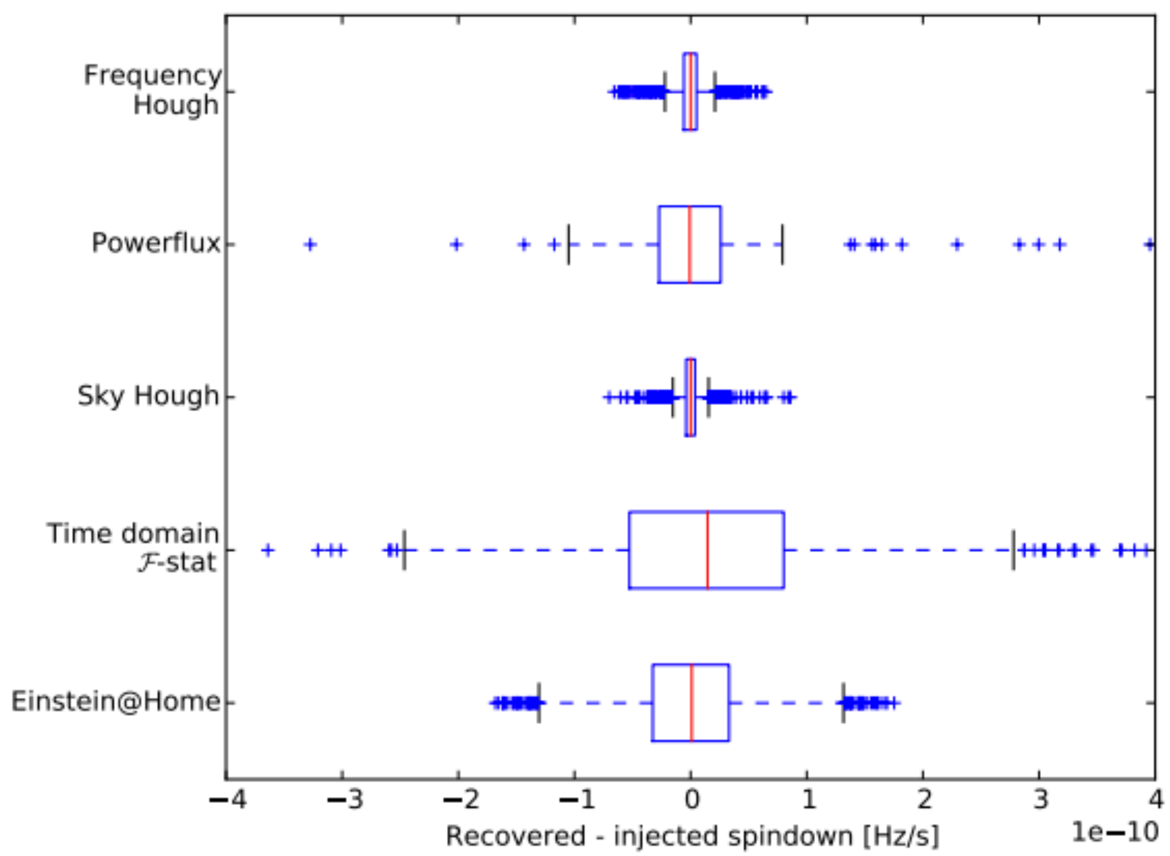
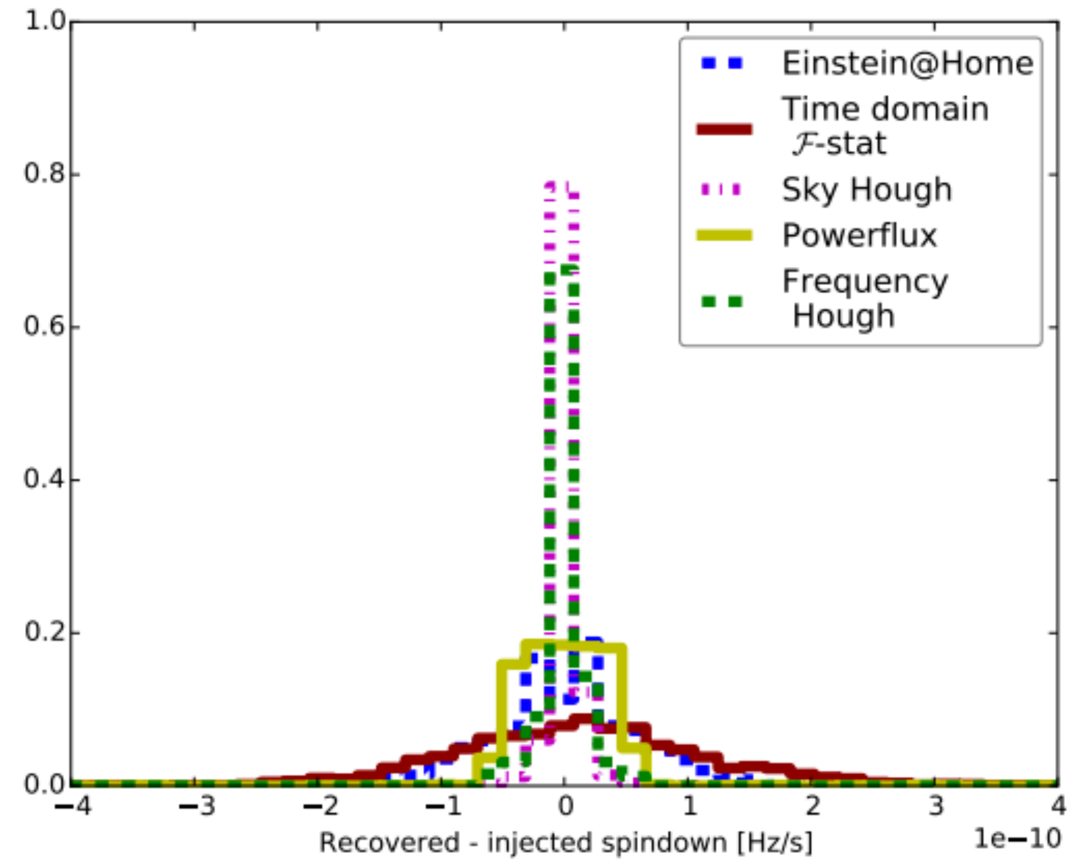
The Mock Data Challenge

Parameter Estimation





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The Mock Data Challenge

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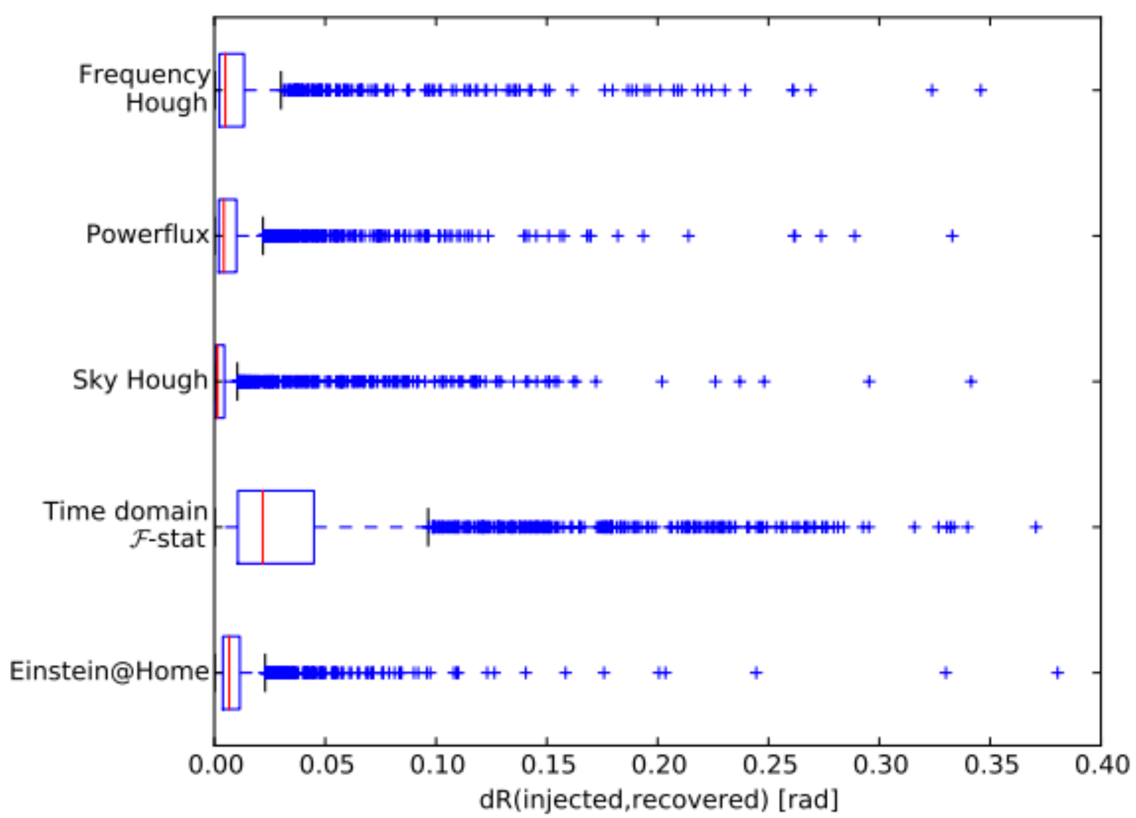

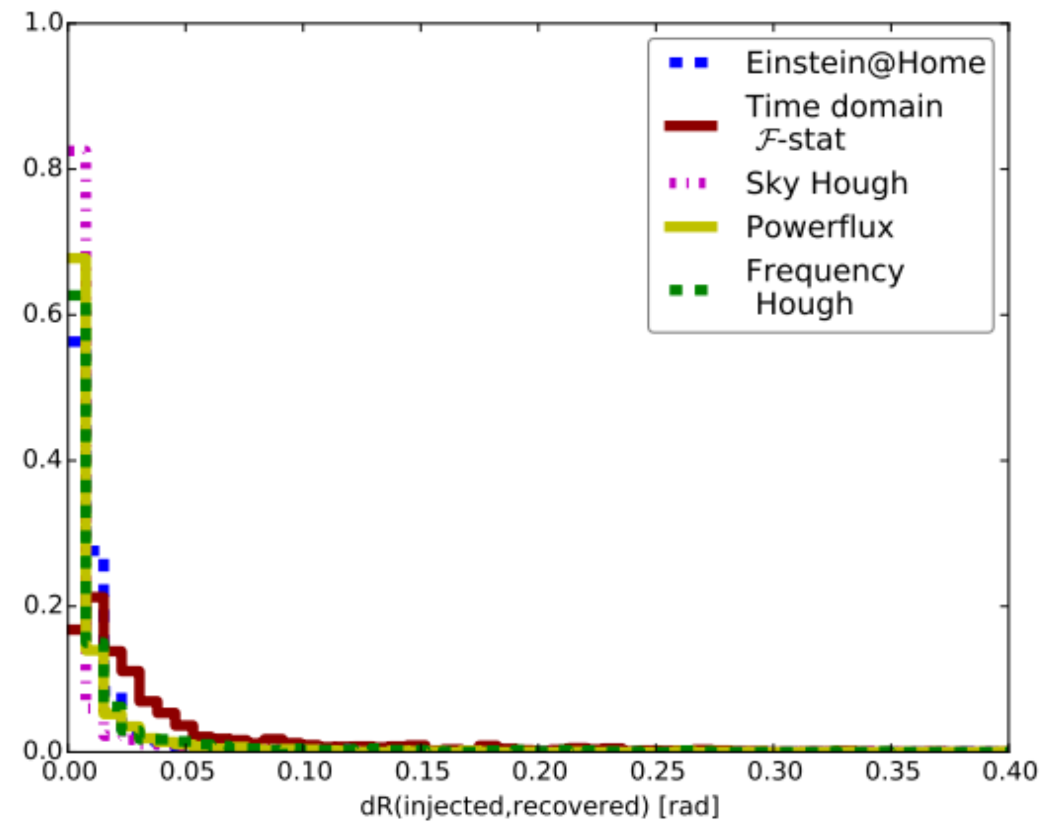

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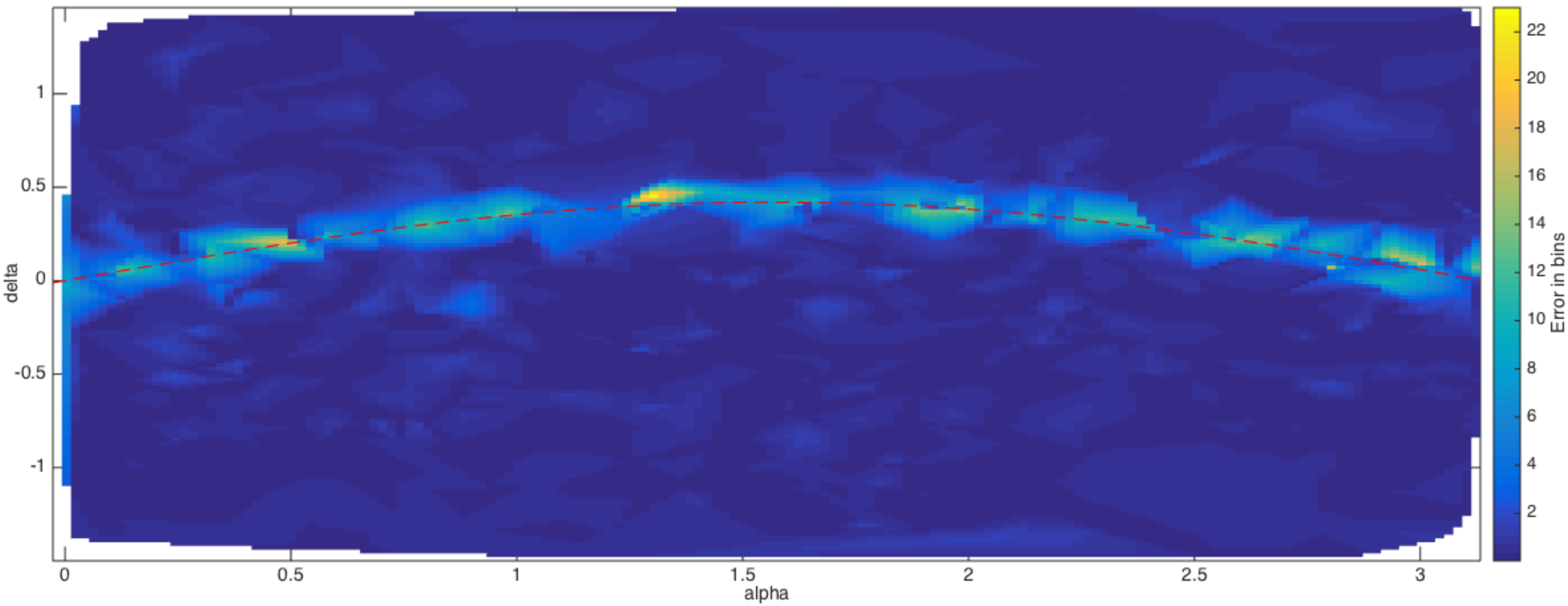
The sky parameter estimation issues



This figure shows that the error over the sky location is predominantly larger over the great circle in red, the figure is been generated using the 1561 injections from the MDC stage 3 and interpolating the selected followup points error with respect to the injected value. The parameters used to generate the followup points are the optimal selection from the previous section and the total number of defined followup points is 1031.

Conclusions

- The Sky Hough method is robust over noise artefacts, second frequency derivatives.
- The new clustering method allows us to use lower thresholds in significance, it results in an increase of efficiency and a better parameter estimation.
- Expected increase in sensitivity for O1
- Sky-Hough all-sky method paper on the way
- O1 investigation from 50-2000Hz is being done at this moment, spin down range [-1.0e-8 ,1.0e-9]Hz/s
- RDC compare efficiency between bands 50-100Hz 150-200Hz 1050-1100Hz
- Tuning of the pipeline and UL is being done over the RDC band set
- Further improvements will be considered for O2.