Continuous wave parameter estimation and non-standard signal follow up

Greg Ashton

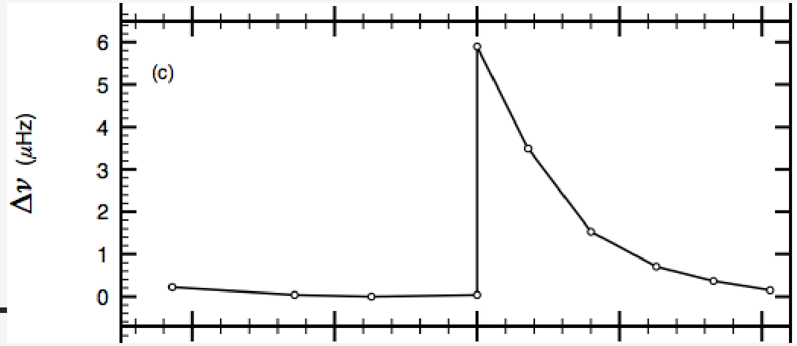
Reinhard Prix & Ian Jones

Monash Centre for Astrophysics

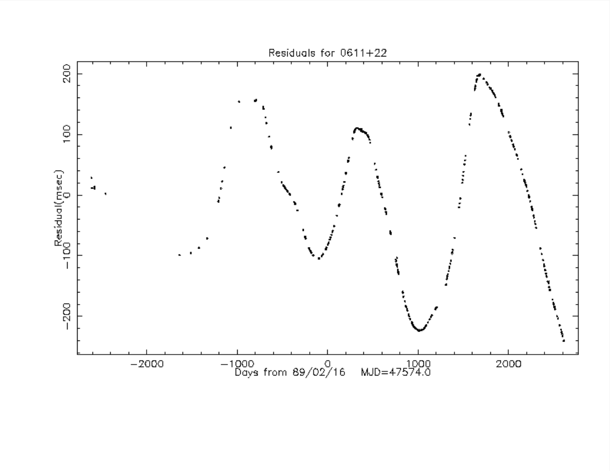
Motivation

- Searches for signals from neutron stars are designed for detection
- The same methods are not best suited when one has a candidate
- Parameter estimation (PE) can help in understanding candidates
- Parameter estimation can be modified to allow for alternative signal models

Pulsar glitch: [Espinoza et al. (2011)]



Pulsar timing noise: [www.jb.man.ac.uk]



Search basics I

- For a signal from an isolated neutron star we have a source model

$$h(t; \boldsymbol{\theta}) \qquad \text{where, e.g.,} \quad \boldsymbol{\theta} = \{f, \dot{f}, RA, DEC, h_0, \cos\iota, \psi, \phi\}$$

- Then, given some data $d(\mathrm{t})$, we can compute a *likelihood*

$$P(d(t)|H_s, \boldsymbol{\theta}) \propto \mathrm{e}^{-\frac{1}{2}\langle d-h)|d-h\rangle}$$

- More details:
  - Prix (2009) "Gravitational Waves from Spinning Neutron Stars"
  - Riles (2013) "Gravitational waves: Sources, detectors and searches"

Search basics II

- Often, searches use a *likelihood ratio* or *Bayes factor*

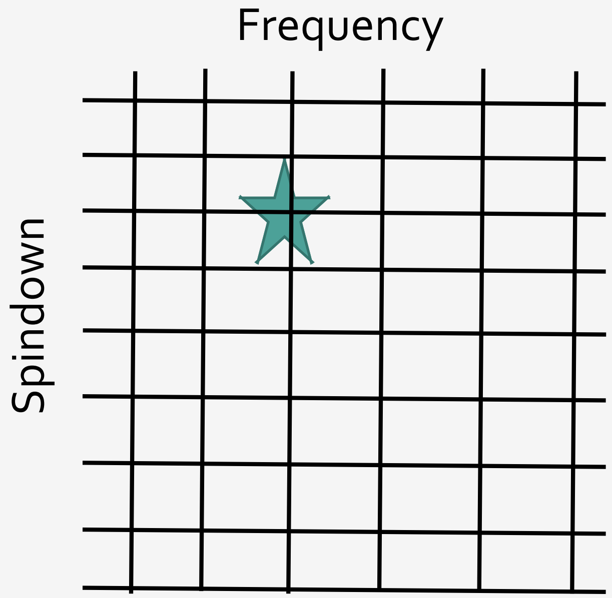
$$\Lambda(d(t);\boldsymbol{\theta}) = \frac{P(d(t)|\boldsymbol{\theta},H_S)}{P(d(t)|H_N)} = B_{S/N}(d(t);\boldsymbol{\theta})$$

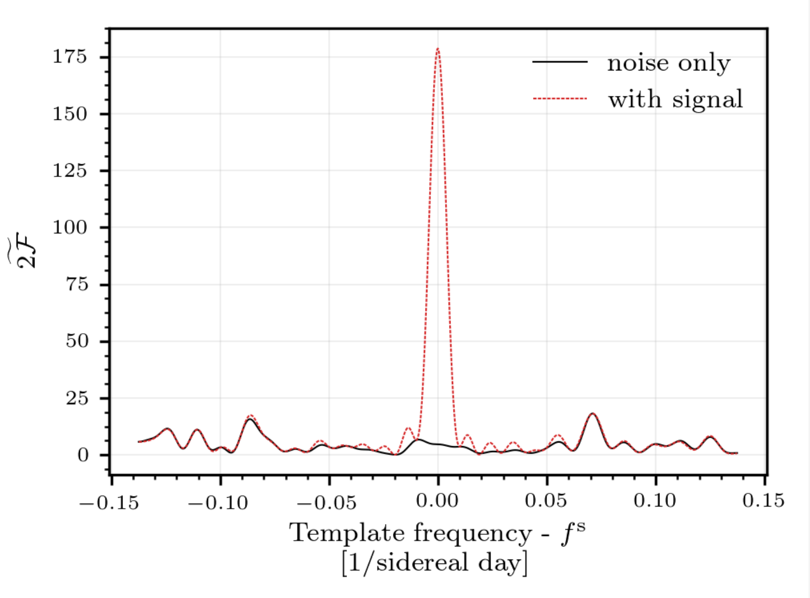
- All of the following can often be used interchangeably
  - Log-likelihood ratio
  - Log-Bayes factor
  - Matched filtering amplitude
  - Detection statistic

- Large values $\Rightarrow$ more likely
- Above some threshold $\Rightarrow$ "detected"

PE: Grid based approaches

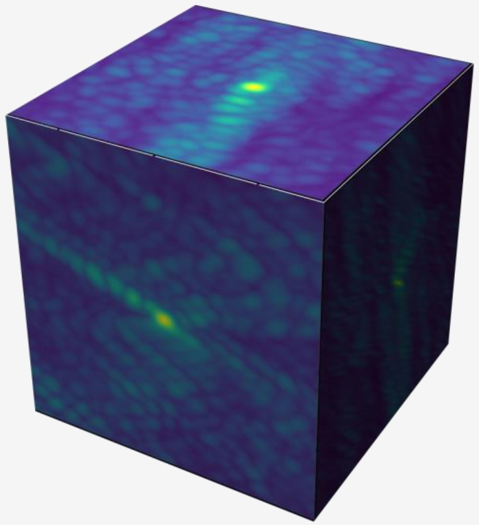
- Compute likelihood ratio over a grid of points
- Maximum is best estimate for the signal parameters
- If grid spacing ~ "signal size": uncertainty dominated by grid setup
- Else error reflects intrinsic uncertainty of data about the signal
- Grid based approaches best applied in initial search
  - Able to set robust upper limits – sometimes analytically

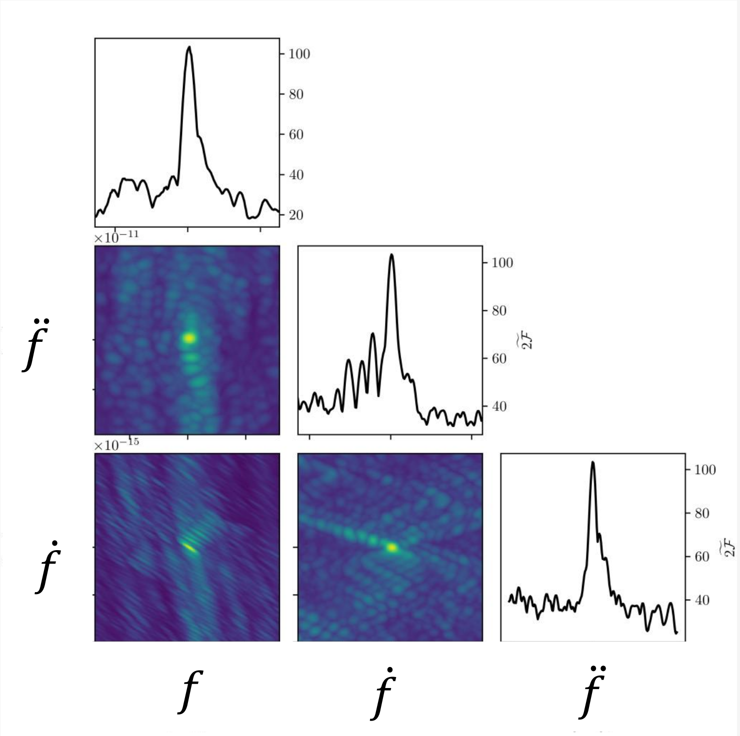




PE: Grid based approaches

- However, grid based approaches become inefficient for parameter estimation
- Need grid spacing less than the “size of the signal”
- Multiple dimensions





- Lots of grid points searched where there is no signal!

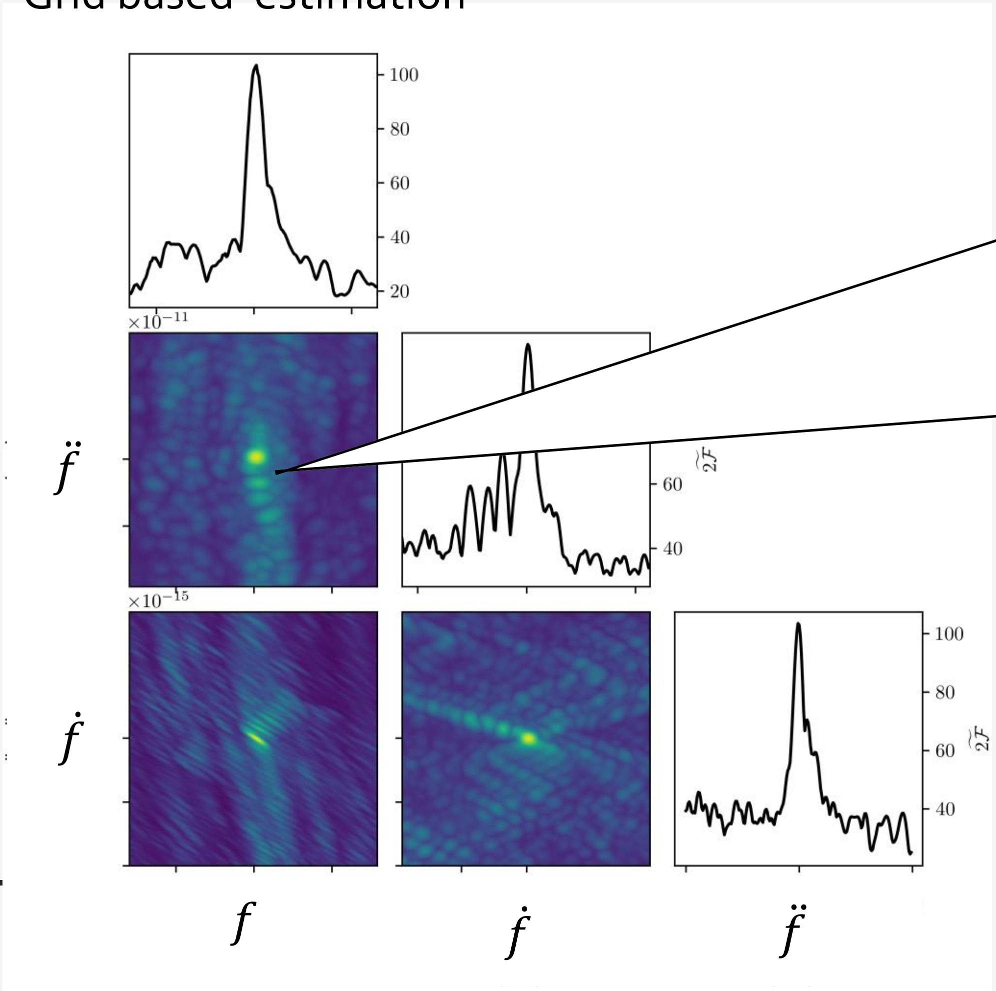
PE: MCMC/Nested sampling

- Solutions to the problem of estimating a high-dimension posterior distribution
- Can be viewed as 'optimization' routines, but fundamentally built around Bayesian data analysis
- Ideal for non-standard signal searches as no grid required
- Nested sampling already used in the known pulsar searches
  - see talk by Matt Pitkin and, e.g. Pitkin et al (2012)

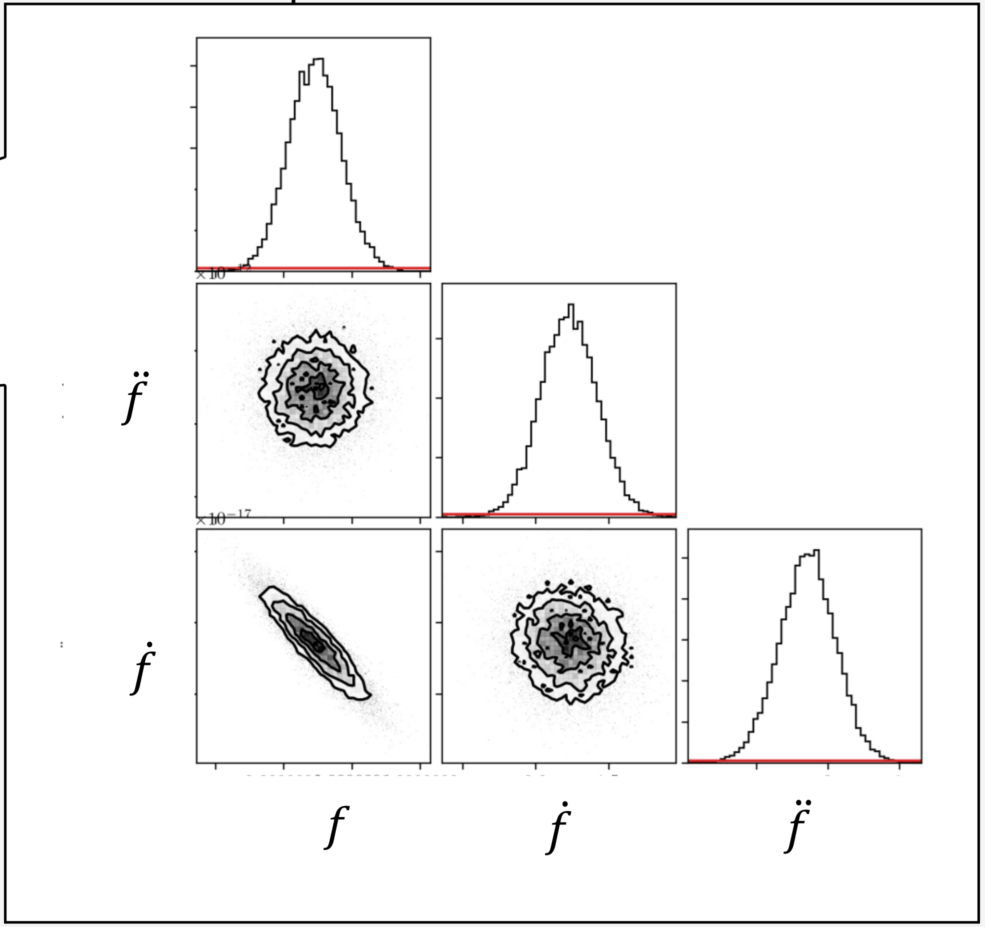
Basic PE: Demo

Same computation time

Grid based estimation



MCMC-based parameter estimation



[GA & Prix (2018)]

“How do you sensitively search for systems that may have unknown (spin) glitches?”

Glitch-robust searches I

- Glitches could reduce detectability if using standard search techniques
- Glitch-robust detection statistic:

$$h(t; f, \dot{f}, \ldots) \rightarrow h(t; f, \delta f, \dot{f}, \delta\dot{f}, t^{g}, \ldots)$$

$$\varphi(t) = 2\pi \sum_{k=0}^{s_{\max}} f^{(k)} \frac{(t - t_{\mathrm{ref}})^{k+1}}{(k+1)!} \rightarrow \varphi'(t) = \varphi(t) + 2\pi \sum_{\ell=0}^{N_{\mathrm{g}}} H(t - t_{\ell}^{\mathrm{g}}) \sum_{k=0}^{s_{\max}} \delta f_{\ell}^{(k)} \frac{(t - t_{\ell}^{\mathrm{g}})^{k+1}}{(k+1)!}$$

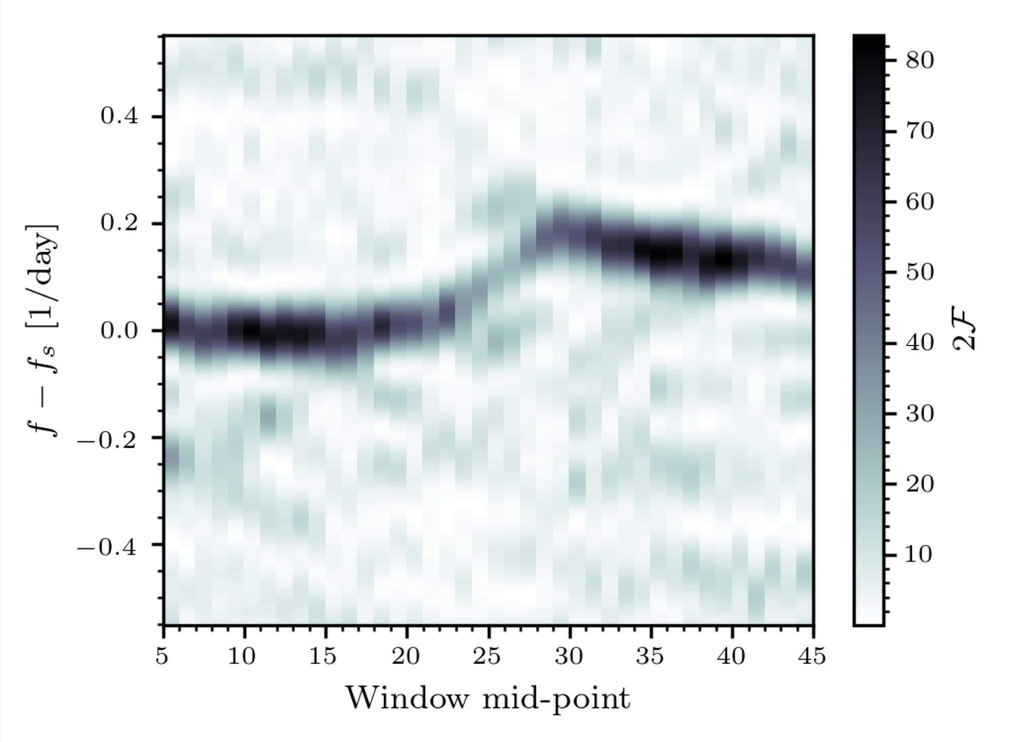
See Edwards, Hobbs, & Manchester (2006) for the pulsar equivalent

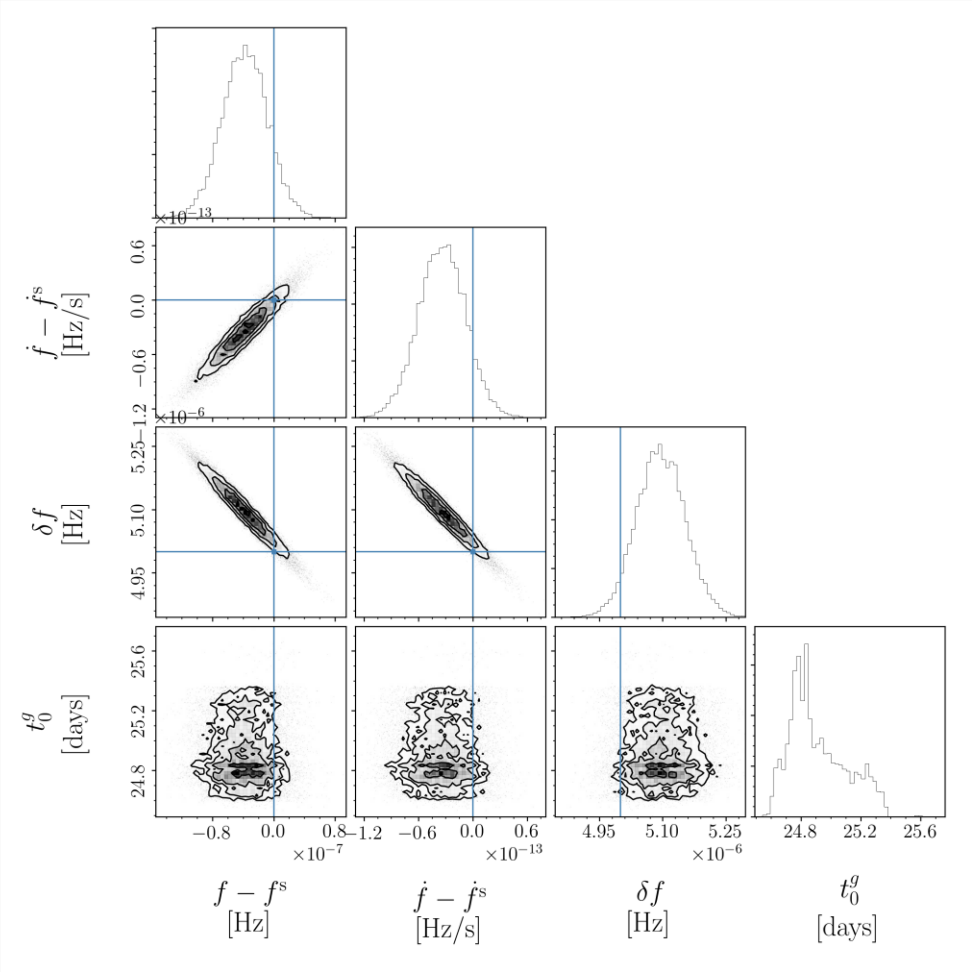
- Can be applied to any standard search algorithm
- Glitch-robust ≠ search for CWs following a glitch

Glitch-robust searches II

- One *could* perform glitch-robust (all-sky/directed/targeted search)
  - A version already applied in the known pulsar (targeted) searches
  - Adding extra parameters to all-sky/directed searches is difficult to justify
  - Semi-coherent wide parameter space searches are already less sensitive to glitch (GA, Prix & Jones (2017))
- MCMC/Nested Sampling methods ideally suited for glitch follow-up
  - No metric required to set up a grid
  - Natural priors based on astrophysics

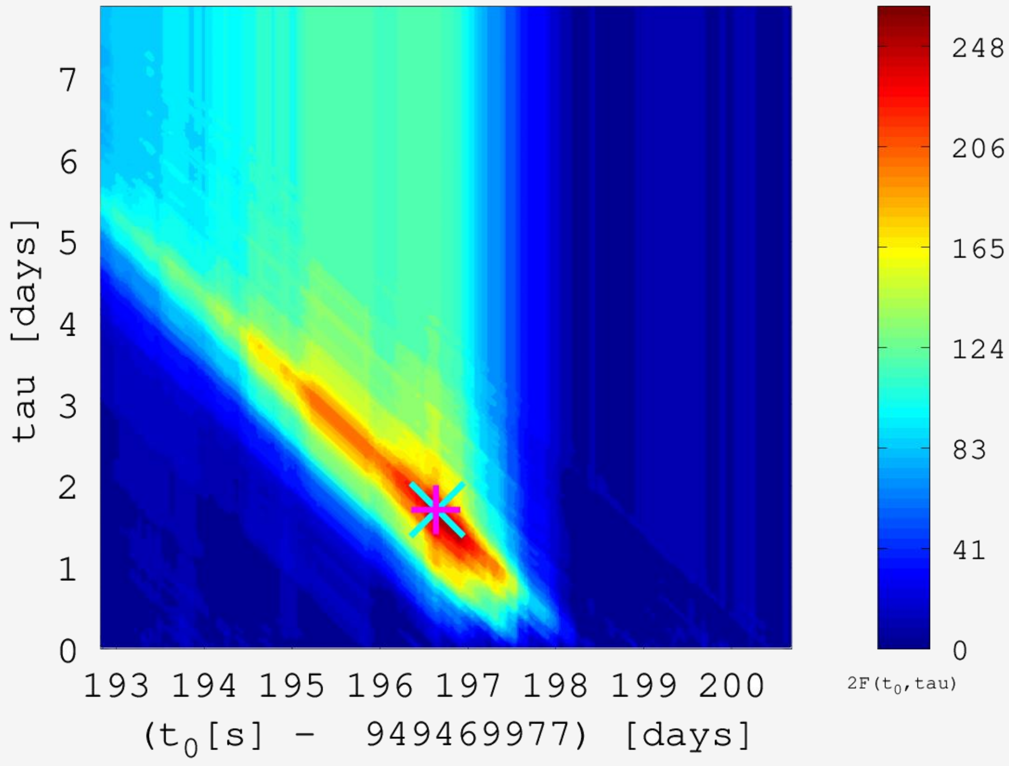
Glitch-robust searches III: Example

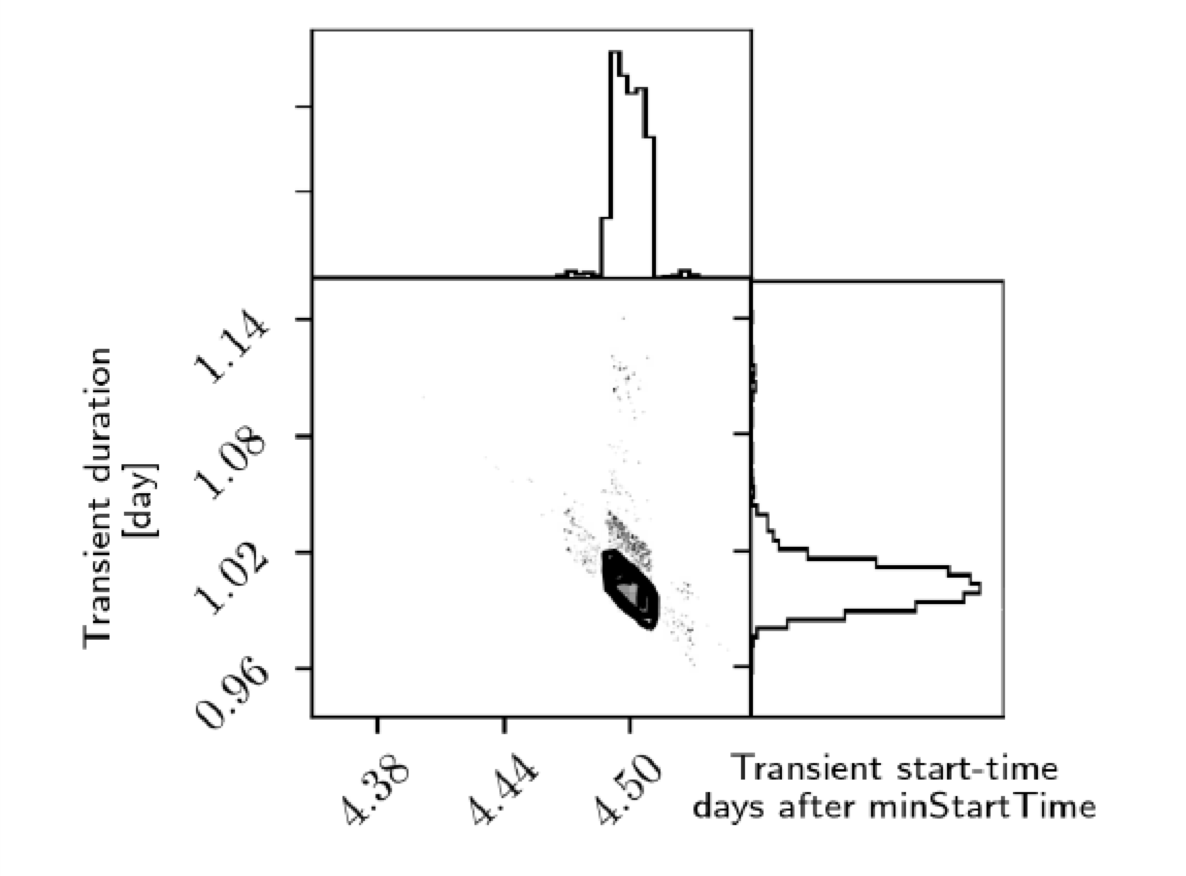




Transient CW

Credit: David Keitel

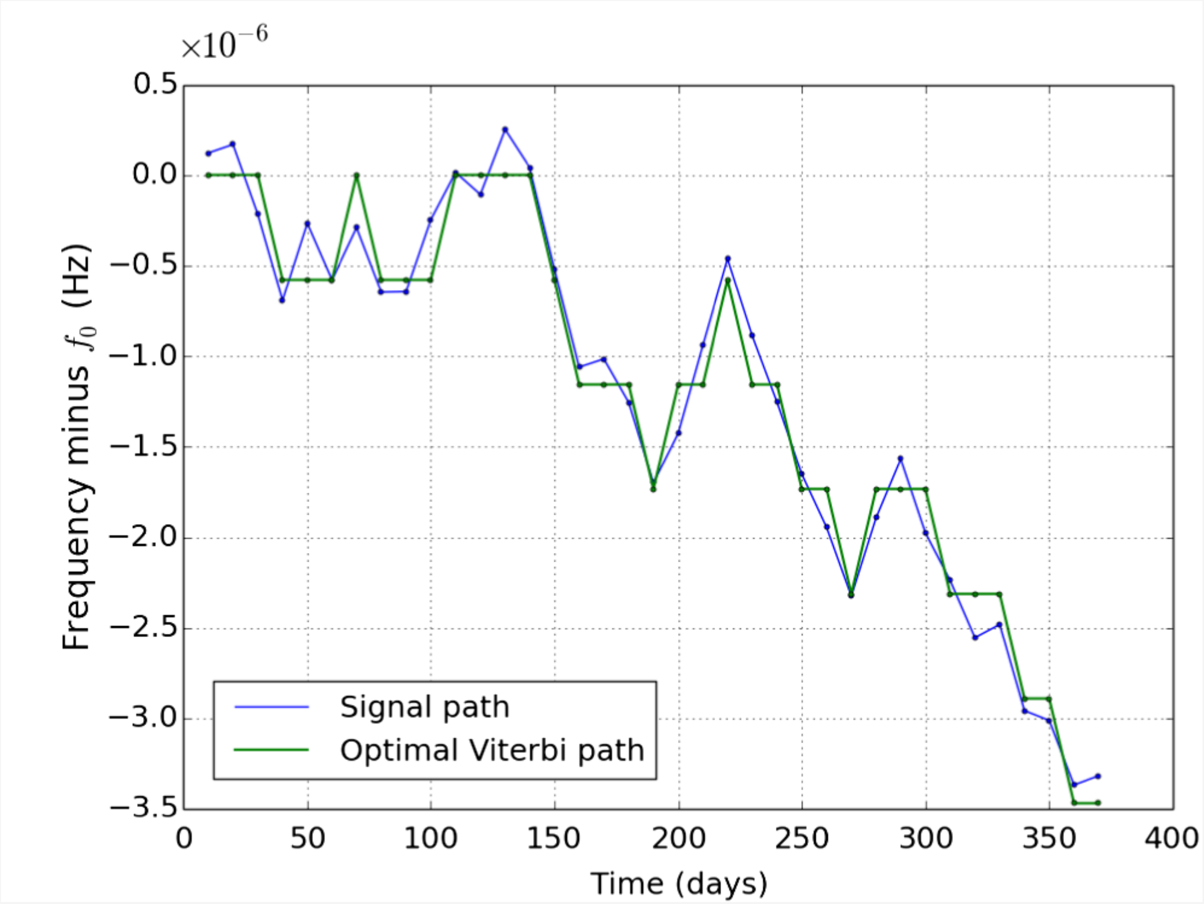




Tracking the signal

- Hidden Markov model tracking (Vitirbi)
- Currently applied to the problem of "spin-wandering"
- Useful for getting the physics from any detection
  - Timing noise
  - Glitches
  - Unexpected behaviour

- [Sun et al., Phys Rev D 97,043013 (2018)]
- [Suvarova, Sun, Melatos et al PRD 93 123009 (2016)]



Overview

- In the detection era parameter estimation will play a key role
- Inference algorithms (i.e. MCMC, Nested sampling) can greatly improve PE accuracy (at fixed computational cost)
- Easy to generalise to non-standard signals i.e. glitches, transients
- Get Bayes factors/odds-ratios which allow model selection
- Glitch-robust/PE methods implemented in PyFstat