Searching for continuous gravitational wave signals

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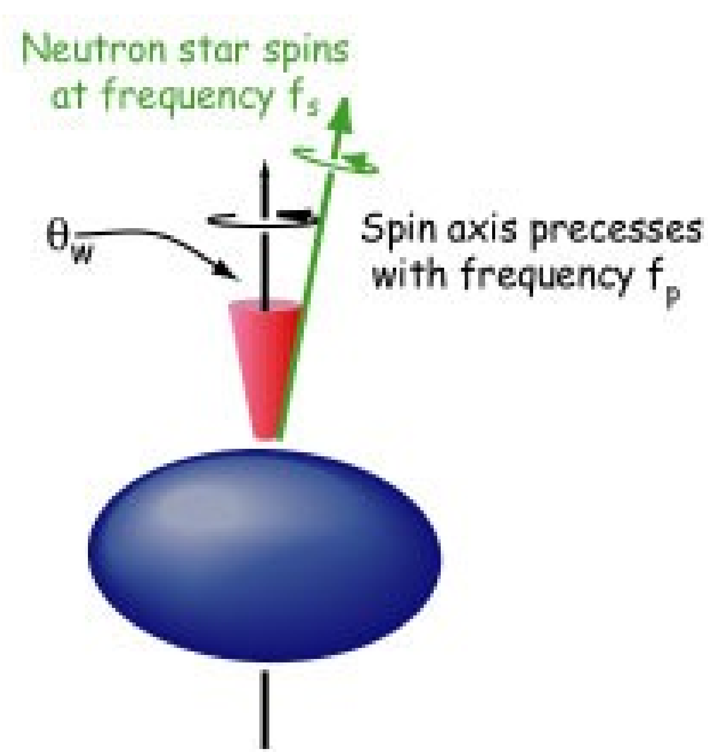
Plan

to be brief

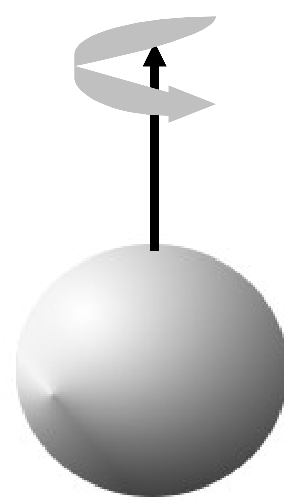
- Basics about CW searches from the GW data-analysis perspective
- Brief overview of our searches
- Some recent (released) results and perspectives
- Proposals for discussion

Gravitational waves from pulsars: brief overview of emission circumstances

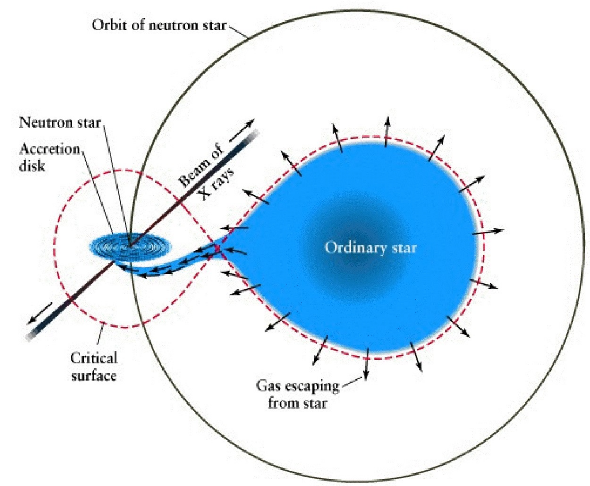
- Pulsars (spinning neutron stars) are known to exist!
- Emit gravitational waves if they are non-axisymmetric:



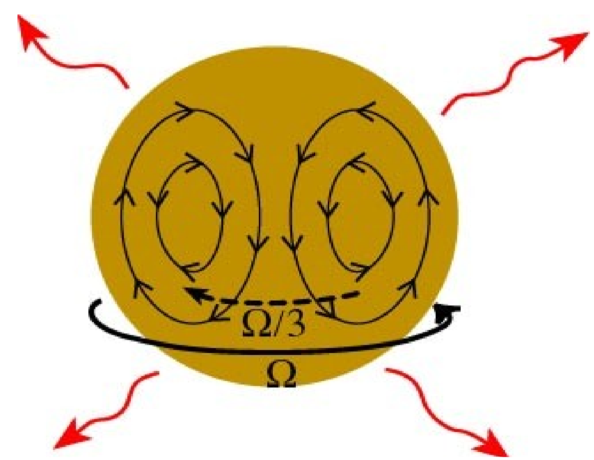
Wobbling Neutron Star



Bumpy Neutron Star

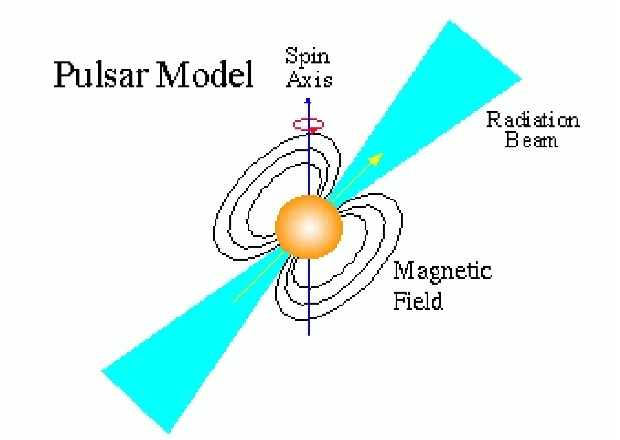


Low Mass X-Ray Binaries



Young Neutron Stars

The signal frequency



- Nearly-monochromatic continuous signal at a frequency:
  - spin precession at $\sim f_{rot}$
  - excited oscillatory modes such as the r-mode at 4/3* f_{rot}

h

  - non-axisymmetric distortion of crystalline structure, at $2f_{rot}$ (for known objects, up to now, we have assumed $f_{gw}=2f_{rot}$)

The expected signal waveform on Earth

- For a observer at rest w.r.t. to the source the waveform is sinusoidal with small spin-down, i.e. a phase evolution of this type:

$$\Phi(T(t)) = \Phi_0 + 2\pi \sum_{n=0}^{\infty} \frac{f_n}{(n+1)!} (T(t) - T(t_0))^{n+1}$$

T is the time at the SSB, t the time at the detector.
$T(t) = T(t; \alpha, \delta)$

- Due to the relative motion between the detector and the source we receive a signal whose frequency is Doppler modulated.
- Due to the motion of Earth and to the non-uniform antenna sensitivity pattern, the signal is also amplitude modulated

The expected signal waveform on Earth

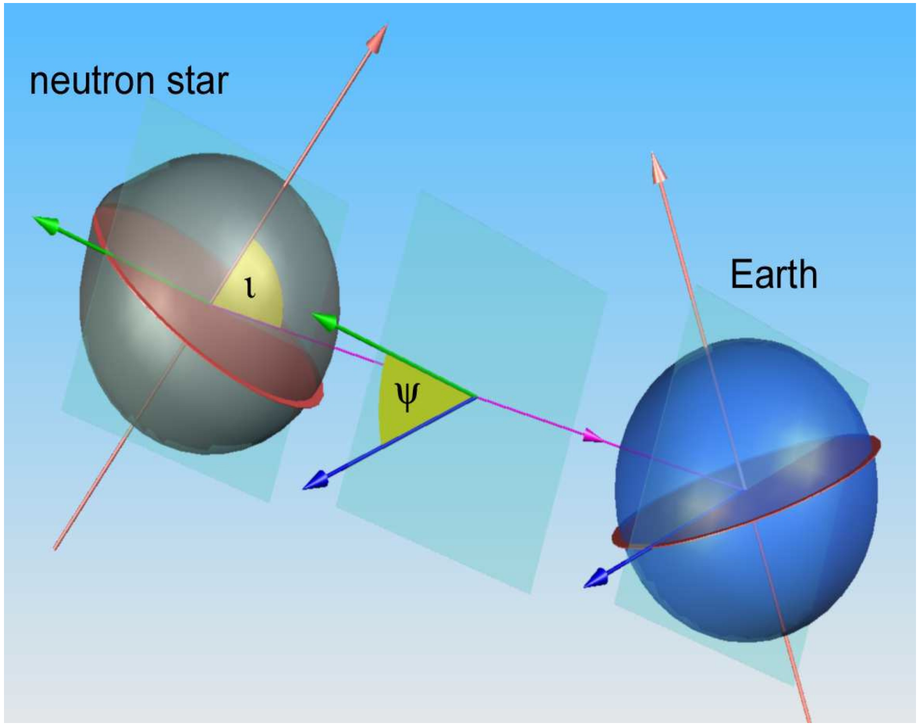
$$h(t) = F_+(t,\psi)h_+(t) + F_\times(t,\psi)h_\times(t)$$

$$h_+ = A_+ \cos\Phi(t) \qquad A_+ = \frac{1}{2}h_0(1+\cos^2\iota)$$

$$h_\times = A_\times \sin\Phi(t) \qquad A_\times = h_0 \cos\iota$$

$$h_0 = \frac{16\pi^2 G}{c^4}\frac{I_{zz}\varepsilon f_r^2}{d}$$

- *i* is the inclination angle of the pulsar axis w.r.t. the line of sight
- Ψ is the polarization angle
- d the distance of the source
- + and x are the 2 polarizations of the gravitational wave



The searches

- Signal parameters: position (may be known), inclination angle, polarization, amplitude, frequency (may be known), frequency derivative(s) (may be known), initial phase.

- Most sensitive method: coherently correlate the data with the expected signal (if the signal were monochromatic an FFT):
  - Templates: we assume various sets of the unknown parameters and correlate the data against these different wave-forms.
  - Good news: we do not have to search explicitly over polarization, inclination, initial phase and amplitude.

- We have no “pointing control” : our data stream has signals from all over the sky all at once. However: low signal-to-noise is expected, unfortunately. Hence confusion from many sources overlapping on each over is not a concern (unlike for LISA).

- Input data to our analyses:
  - a calibrated data stream which with a better than 10% accuracy, is a measure of the GW excitation on the detector
  - Sampling rate: 16kHz, but since the high sensitivity range is 40-1500Hz we can downsample at 3 kHz.

What searches ?

Show you now some recent preliminary results

- Signals for signals from known pulsars
- Targeted searches
- Blind searches of previously unknown objects
  - Coherent methods (require prediction of the phase evolution of the signal)
  - Semi-coherent methods (require prediction of frequency evolution of the signal)

What drives the choice ?

The computational expense of the search

4 Nov-31 Dec 2005 S5 data: known pulsars, 95% upper limits

h_0	Pulsars
$1\times10^{-25} < h_0 < 5\times10^{-25}$	44
$5\times10^{-25} < h_0 < 1\times10^{-24}$	24
$h_0 > 1\times10^{-24}$	5

Lowest h_0 upper limit:

PSR J1603-7202 (f_{gw} = 134.8 Hz, r = 1.6kpc) $h_0 = 1.6\times10^{-25}$

Lowest ellipticity upper limit:

PSR J2124-3358 (f_{gw} = 405.6Hz, r = 0.25kpc) $\varepsilon = 4.0\times10^{-7}$

All values assume $I = 10^{38}$ kgm^2 and no error on distance

Ellipticity	Pulsars
$\varepsilon < 1\times10^{-6}$	6
$1\times10^{-6} < \varepsilon < 5\times10^{-6}$	28
$5\times10^{-6} < \varepsilon < 1\times10^{-5}$	13
$\varepsilon > 1\times10^{-5}$	26

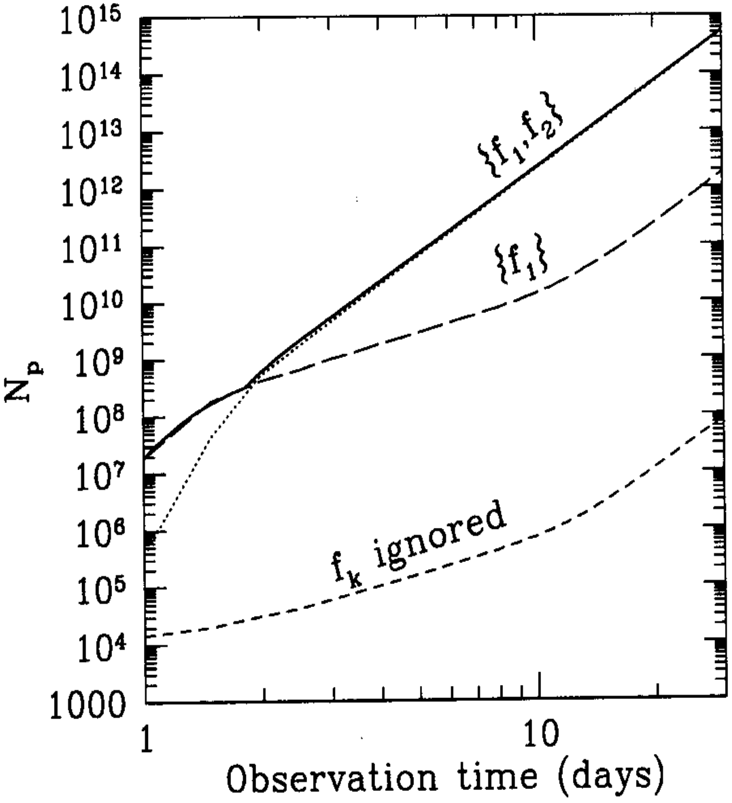
PRELIMINARY

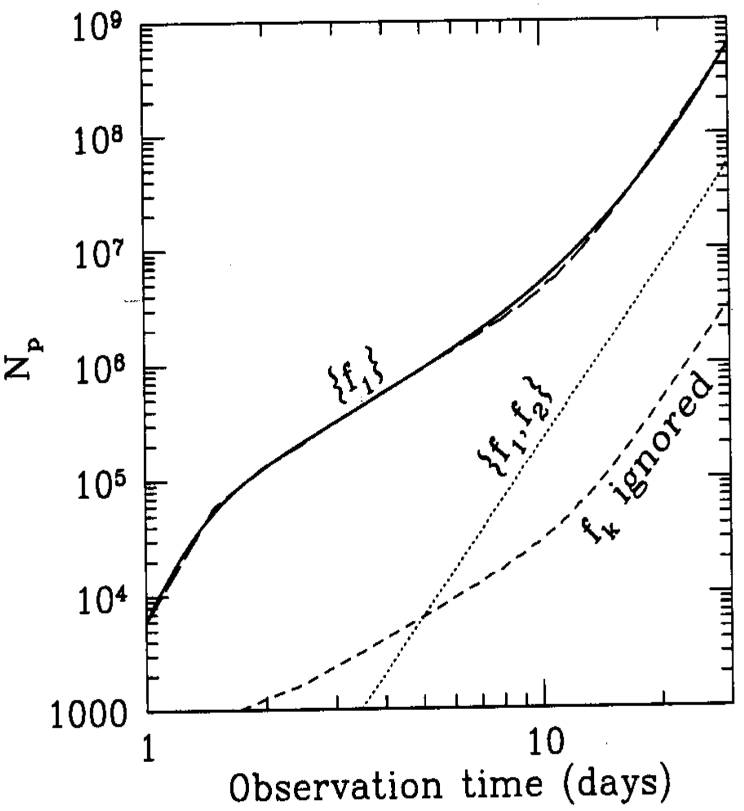
Blind searches and coherent detection methods

- Coherent methods are the most sensitive methods (amplitude SNR increases with sqrt of observation time) but they are the most computationally expensive, why ?

  - Our templates are constructed based on different values of the signal parameters (e.g. position and spindown).
  - The parameter resolution increases with longer observations
  - Sensitivity also increases with longer observations
  - As one increases the sensitivity of the search, one also increases the number of templates one needs to use.

the number of templates grows dramatically with the coherent integration time baseline and the computational requirements become prohibitive





[*Brady et al., Phys.Rev.D57 (1998)2101*]:

Blind searches: how many templates

It is necessary to search for every signal template distinguishable in parameter space. Number of parameter points required for a coherent $T=10^7$s search

[*Brady et al., Phys.Rev.D57 (1998)2101*]:

Class	f (Hz)	τ (Yrs)	N_s	Directed	All-sky
Slow-old	<200	>1000	1	**3.7×10^{6}**	**1.1×10^{10}**
Fast-old	<1000	>1000	1	**1.2×10^{8}**	**1.3×10^{16}**
Slow-young	<200	>40	3	**8.5×10^{12}**	**1.7×10^{18}**
Fast-young	<1000	>40	3	**1.4×10^{15}**	**8×10^{21}**

Number of templates grows dramatically with the integration time. To search this many parameter space coherently, with the optimum sensitivity that can be achieved by matched filtering, is computationally prohibitive.

Hierarchical searches are the best techniques when the parameter space is large and when there exist computing power constraints:

- The smallest signal detectable with a given confidence becomes larger as the parameter space increases. Thus it makes no sense to use techniques that ``dig out of the noise’’ signals that are too small to be significant.
- We use methods that are less computationally intensive and not as sensitive in order to narrow down the parameter space to the final sensitivity level.
- This is a better use of computational resources because no calculations are lost to search regions of the parameter space where, if present, a signal would be to small to be confidently detected.
- Hierarchy of coherent and non-coherent searches

Coherent detection methods

- There are essentially two types of coherent searches that are performed:
  - Matched-filtering methods. Aimed at computing a detection statistic. These methods have been implemented in the frequency domain (although this is not necessary) and are very computationally efficient. Einstein@Home uses such a method.

    Phys. Rev. D69 (2004), Phys. Rev. Lett. 94 (2005) 181103.

  - Standard Bayesian analysis, as fast numerically but provides natural parameter estimation. It has been used for targeting known objects.

    Phys. Rev. D69 (2004), Phys. Rev. Lett. 94 (2005) 181103.

Incoherent detection methods

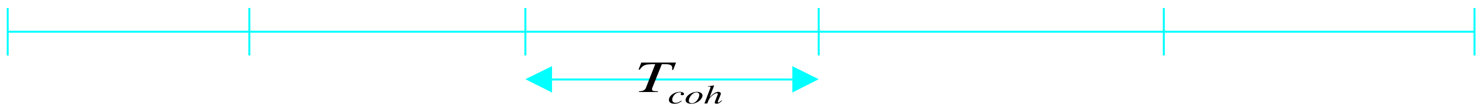
- The alternative to coherent methods is incoherent methods. These are very much less computationally intensive and a little less sensitive.

  - In the past 5 years several we have developed several semi-coherent methods based on different techniques:

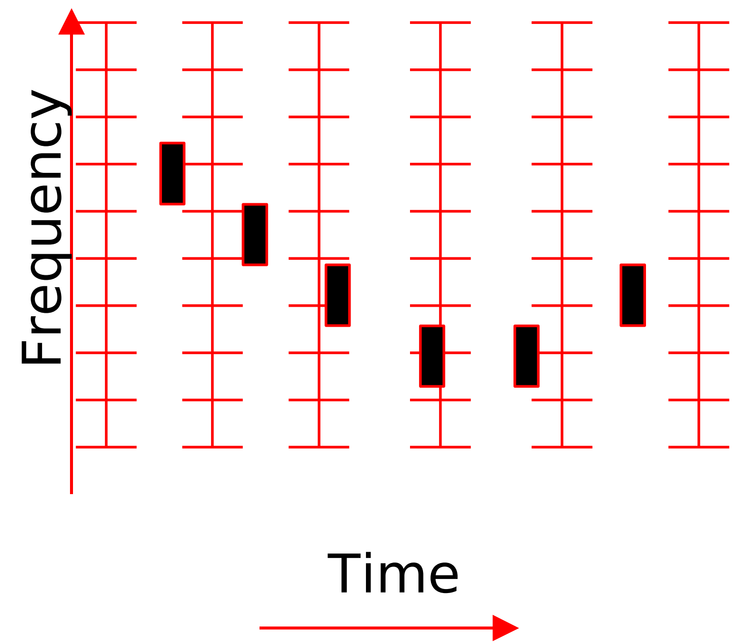
    - Stack-slide of power spectra (Radon transform)
    - Hough transform on time-frequency maps Phys. Rev. D70 (2004) 082001 and Phys. Rev. D72 (2005) 102004.
    - Powerflux analysis from spectra

  - We use this type of method for fast, blind large parameter space scans of the data

Incoherent searches

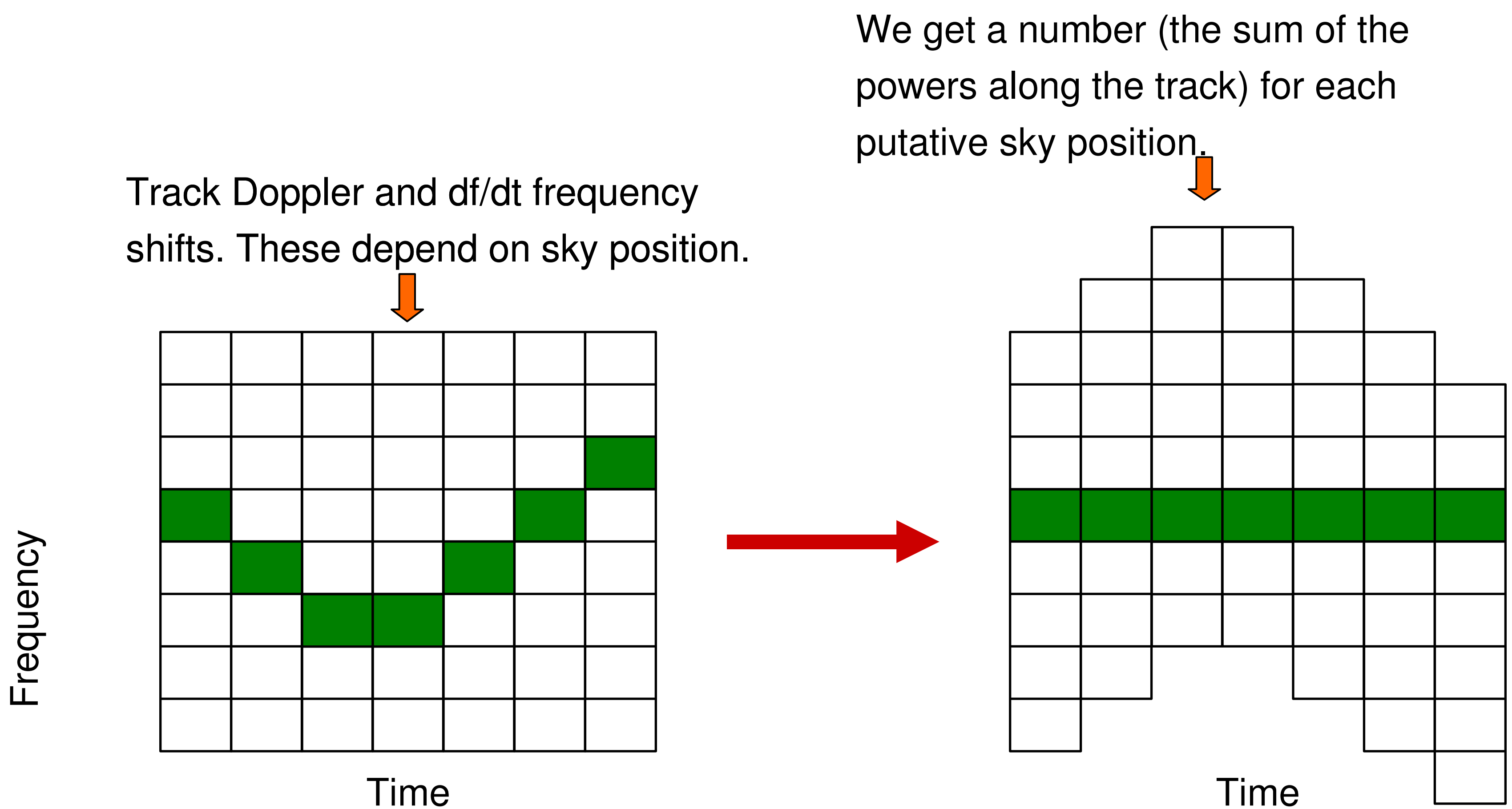


- The idea is to perform a search over the total observation time by piecing together *incoherently* the information from shorter time-baseline coherent searches.

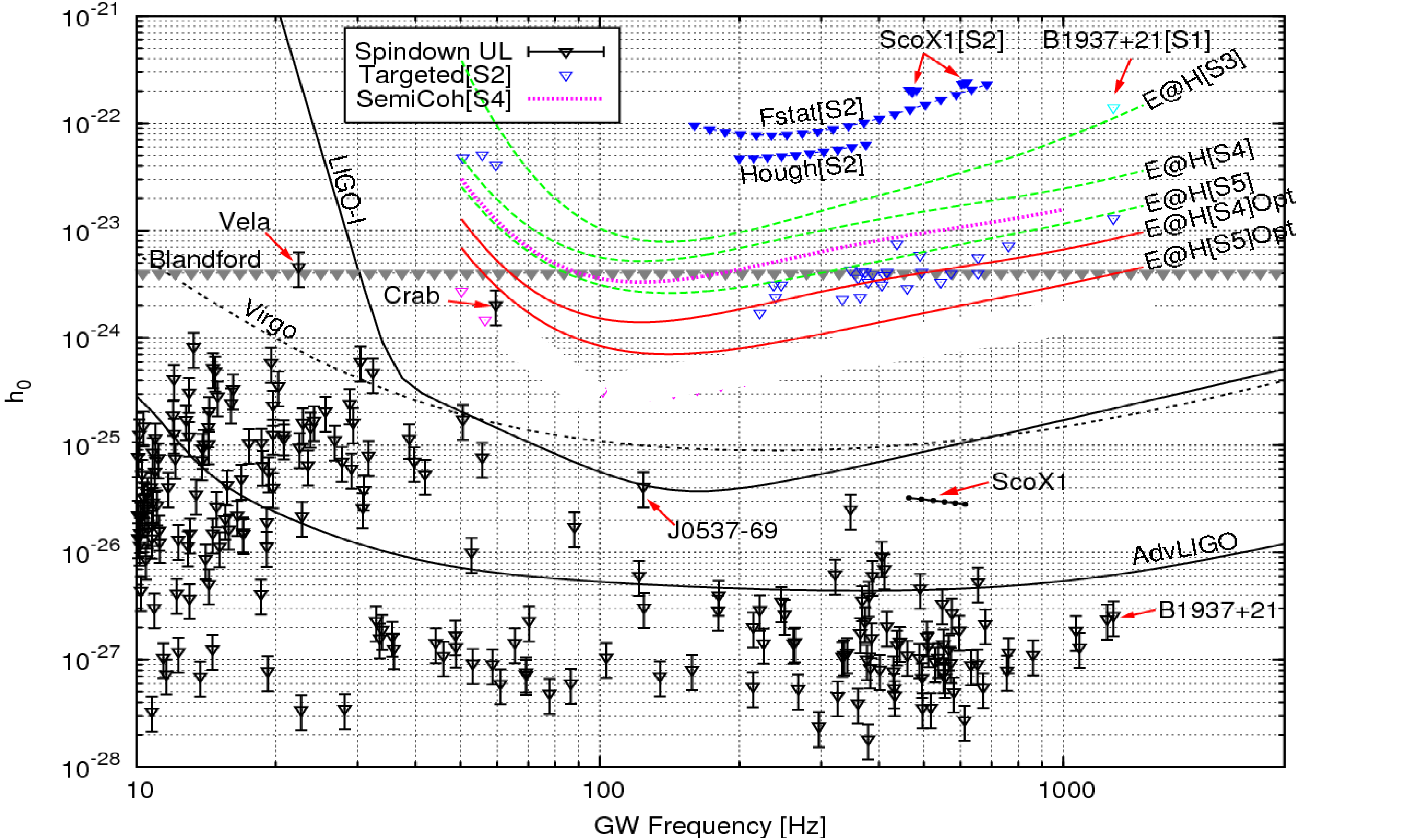


The StackSlide Method

- **Break up data into segments and perform a coherent search over each segment.**
- **StackSlide: stack these segments tracking residual frequency change, slide to line up & add the power weighted by noise inverse -- incoherent step.**



Summary of released results and prospects



Questions for our neutron-star expert colleagues

- We are carrying out searches for all known pulsars in our band for which we have accurate enough timing to perform a coherent search, but:

  - Can we get timing on more objects ?
  - Can we improve our phase modeling ? are there are more uncertainties that we should take into account ?

- How should we spend our compute cycles for blind searches ? What frequencies/spin-down parameters ?

- What targeted searches should we do first (RXJ1856, SN1987A, towards the Galactic Center, Cas A ?)