Astrophysical Source Identification and Signature (ASIS) Group: Implementation for LIGO-I

Bruce Allen
Chair, LSC ASIS working group
University of Wisconsin - Milwaukee

LIGO-G000333-00-D

What Is **ASIS**?

- Subgroup of the **L**IGO **S**cientific **C**ollaboration (**LSC**)
- Formed: March 1998. One of three LSC “data” groups.
- Meets about once/month (typically 30 people).
- Mailing list:110 members of whom >25 actively doing ASIS coordinated-work

    Chair: Bruce Allen

    Webmaster: Patrick Brady

    Meeting Organizer: Alan Wiseman

    Secretary: Alberto Vecchio

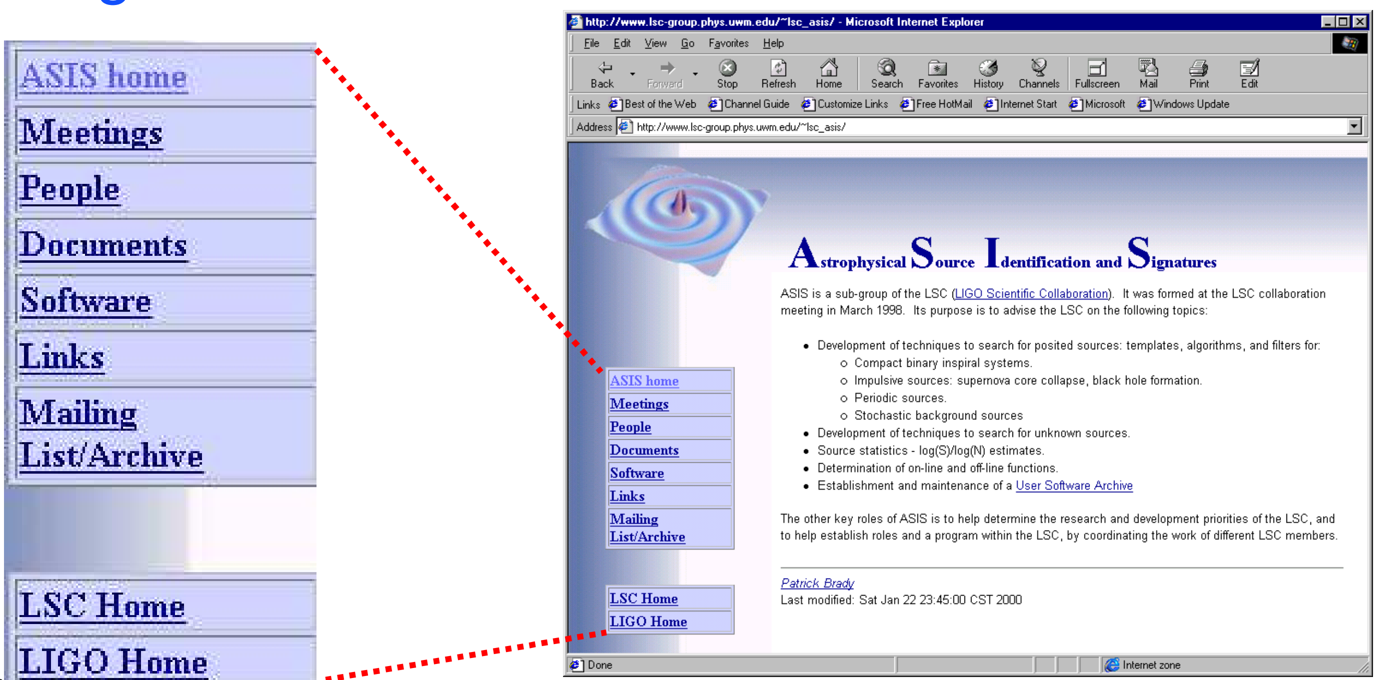
    LIGO Laboratory Liaison: Barry Barish

Purpose of ASIS

- Development of techniques to search for proposed sources: templates, algorithms and filters for
  - » Inspiral of compact objects
  - » Periodic sources
  - » Stochastic backgrounds
  - » Impulsive sources
- Blind search methods (unknown sources)

ASIS Web Site: www.lsc-group.phys.uwm.edu/~lsc_asis/

- Documents, software, & links
- Meetings announcements, agendas & minutes
- Mailing list & archives



LIGO-G000333-00-D

Organization of ASIS Work

- Priorities set in "LSC Data Analysis White Paper"
- Identified lead groups for different software development/coding tasks
- Analysis codes collected in public LAL Library
  - » current release 0.4 (last week)
  - » code and documentation available for public examination
  - » easy interface to the LIGO Data Analysis System
- The ASIS group could use additional help:
  if you or your research group has something to contribute, please consider joining the LSC.

LIGO-G000333-00-D

Science Goals & Assumptions

- LIGO,GEO & VIRGO bring GW detection into region where it's plausible to detect astrophysical sources. Compared to previous detectors, they will extend:
  - » amplitude sensitivity by factor 100-1000 (space volume 10^6 - 10^9)
  - » bandwidth by factor of 100
- *However:* no known sources with rates/amplitudes large enough to guarantee detection with LIGO-I,
- "Well understood" sources are probably too weak for LIGO-I
- Large uncertainties in rate/amplitude estimates, and no body of prior knowledge/best practice (as in HEP).

Hence: "Opportunistic" Data Analysis Strategy for LIGO-I

- Initial emphasis is breadth (not depth)
  - » Instrument "broadband", not tuned for particular source type
  - » Computing resources shared between different GW source types, not targeted at a particular type
- Maintain ability to recognize unanticipated sources
- Search for (and set upper limits on)
  - » NS/NS, NS/BH, BH/BH binary coalescence (rate)
  - » Correlated GW emission by Gamma Ray Bursts (energy)
  - » GW emission by known pulsars (amplitude)
  - » GW stochastic background (energy-density)
  - » Nearby strongly GW-emitting pulsars (spatial density)
  - » Generic "burst" sources (rate & amplitude)

LIGO

LSC ASIS

Essential GW Searches...

- Binary Inspiral (pair of compact stars): either observe, or place upper limit on the rate in the Universe
  - » NS/NS well understood (a premiere LIGO design goal)
    - – Waveform can be calculated very accurately
    - – Hulse-Taylor binary (wrong freq for LIGO) is canonical example
    - – Hundreds of NS pulsars are cataloged
  - » NS/BH might offer much stronger signals for 20 solar-mass BH, but
    - – Rate “more” uncertain
    - – Waveform not calculable analytically (or numerically, currently)
    - – Signal processing strategy less certain
  - » BH/BH even more speculative
- Approach: parallel MPI-based hierarchical search: 10-100 Gflops drives LIGO computing requirements

…essential GW Searches...

- Continuous wave sources (e.g., rapidly rotating neutron stars with bumps on them)
  - » Known neutron stars probably too weak to observe with LIGO-I
  - » Data analysis "easy" for observed pulsars with known periods, spin-downs
  - » Data analysis "difficult" for full-sky or partial-sky survey
    - – source waveform not single frequency (spindown)
    - – waveform modulated by earth's spin, motion around sun, and Jupiter-induced perturbations
  - » Detector-limited search: Petaflops
  - » Practical search (factor of 2 less sensitive in amplitude): Teraflops
- Approach: hierarchical search, using off-site supercomputers and large beowulf clusters

…essential GW Searches...

- Stochastic background signals
  - » Produced by early-universe processes (speculative) or unresolved “contemporary” phenomena
  - » A factor of 100 (or more!) smaller in amplitude than detector noise
  - » Analysis method: correlate signals from separated detectors
  - » Approach: “Easy” low bandwidth data analysis problem
- Gamma-Ray Bursts (poorly understood)
  - » At cosmological distances. Release huge amounts of energy
  - » Approach: correlate GRB catalog with GW burst catalog & h data
- Black hole formation
  - » Search for characteristic “ringdown” signal emitted by the perturbed horizon when BH is formed or enlarged by merger
  - » Tests Einstein’s theory of GR
  - » Approach: trivial flops - use inspiral search code

…essential GW Searches.

- Close SN (Feeling lucky today? One/30-100 years.)
  » Approach: plan duty cycle so one IFO is always in operation
  » Join the neutrino SN watch
- Optically observed supernovae
  » Place limits on in-band signal
- Neutron stars formed in SN
  » Rapidly rotating stars may have GW driven instability that spins them up and carries away large angular momentum in first year
- Unknown signals - for example previously undetected supernovae (unmodeled waveforms)
  » Use time/frequency methods to add “events” to database
  » Eventual early-warning for electromagnetic & neutrino observatories
  » Approach: search for correlation between 2 or more sites

Organization of ASIS Work

- Current Lead groups for coding/development work:
  - » **Albert Einstein Institute** (MPG - Potsdam): hierarchical pulsar search
  - » **Caltech**: directed pulsar search
  - » **Cardiff**: (1) binary inspiral search - template generation & placement
    (2) "blind" line-tracking time-frequency search
  - » **Cornell**: (1) transient source search with power statistic
    (2) robust stochastic background search
  - » **U. Michigan**: amplitude-modulation discriminator (antenna pattern)
  - » **U. Texas - Brownsville**: stochastic background search
  - » **U. Wisconsin - Milwaukee**: (1) binary inspiral search - hierarchical filtering code (2) hierarchical stack-slide pulsar search
- Other groups actively participating in ASIS include: CFA, CIT-TAPIR, LLO, Stanford, TAMA, UFG

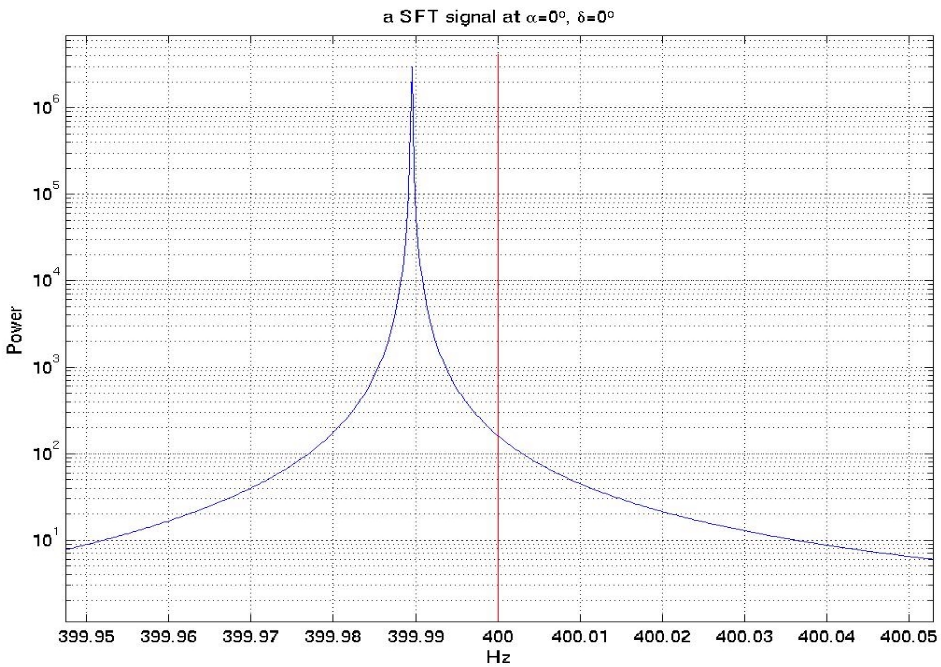
LIGO-G000333-00-D

Pulsar Search: Albert Einstein Institute (Potsdam)

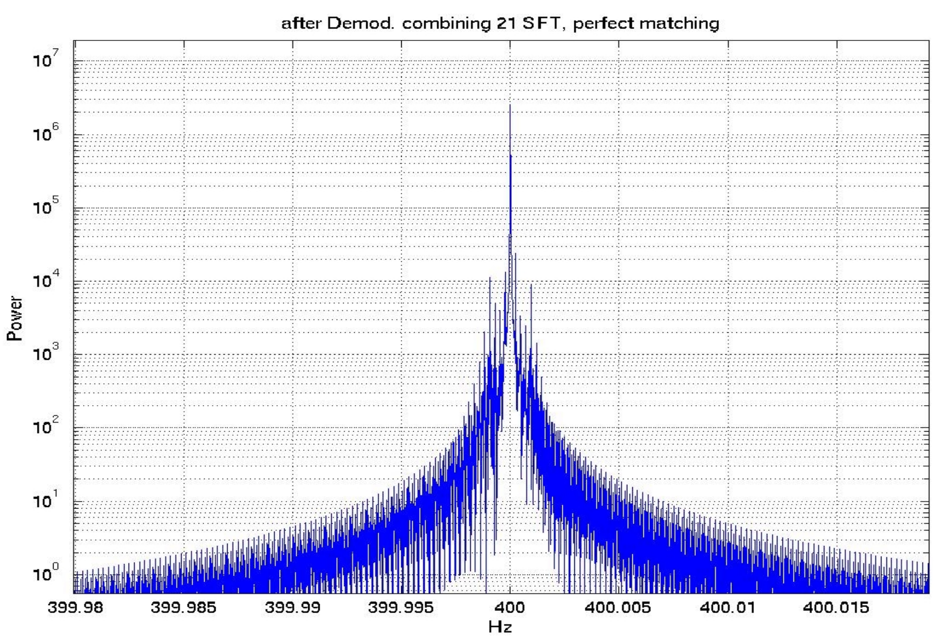
- Entire AEI gravitational-wave group
- General-purpose code for targeted or area searches
- Expected sensitivity:
  - » Infinite CPU: detector-limited sensitivity $h \sim 10^{-25} \cos(\phi(t))$
  - » 100 Gflops: 4-month equally-sensitive search of Galaxy with no spindown (pulsars > 10^7 years old) in frequency range 500-1000 Hz
- Area search method: three-step hierarchical
  1. Start with database of short (~1 hour-long) FFTs. Combine (with demodulation) 24 of these to make ~1-day long demodulated FFT for large sky-position/spindown “patch”. Identify frequency-space “peaks”.
  2. Use Hough transform to look for pattern of peaks consistent with small sky-position/spindown “patch”.
  3. If threshold exceeded, follow up with coherent demodulation.

Pulsar Search: Albert Einstein Institute (Potsdam)

- Current status:
  - » Source database code completed for several source types, from NASA ADC, Princeton Pulsar Group, and Parkes multi-beam survey catalogs.
  - » Earth GPS time to solar-system barycenter time conversion code completed.
  - » Demodulation code completed and tested (used in stages 1 & 3).
  - » Coarse parameter space gridding code now undergoing testing. Fine gridding code now underway
  - » Hough transform code (used in stage 2) coding underway, currently several implementations. Working with VIRGO-Rome group.
- Open problems:
  - » How to take full advantage of correlations in source-parameter space
  - » Finding a very efficient implementation of the Hough transform



Spectrum from one of the SFTs, with time baseline Tc ~ 1 hour. The signal has f0 = 400Hz, the peak appears at a different freq. because of the Doppler modulation.



Spectrum of one of the demodulated FFTs with time baseline Tc ~ 21 hours. Since in this case there is perfect signal-template match there is no power loss and perfect shift of the peak to f0 = 400Hz.

- AEI continuous signals search -

Pulsar Search: Caltech

- Stuart Anderson
- Search for GW emission from known (radio) pulsars.
- Will obtain detector-limited sensitivity $h \sim 10^{-25} \cos(\phi(t))$ using insignificant computational resources.
- Method: for each known pulsar, fold (add together) time-series GW data using correct period pre-determined from radio data.

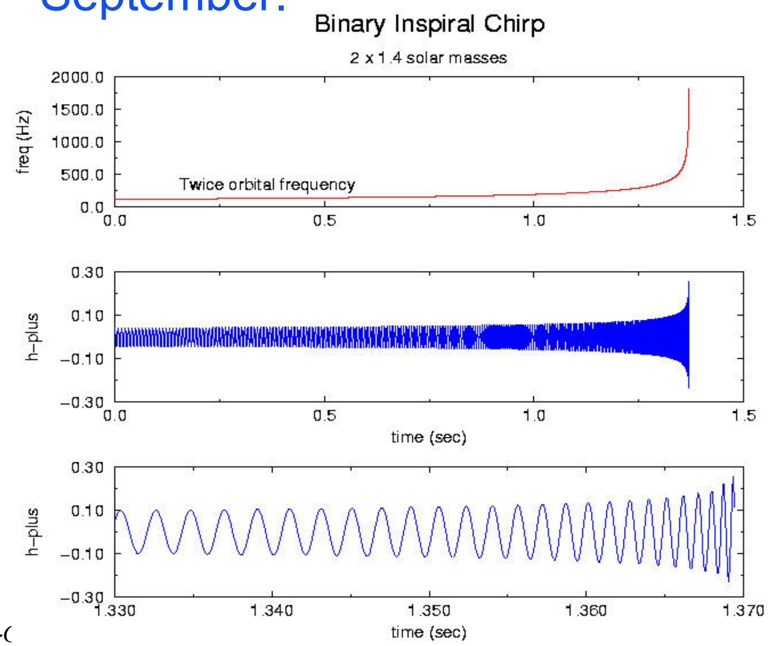
LIGO-G000333-00-D

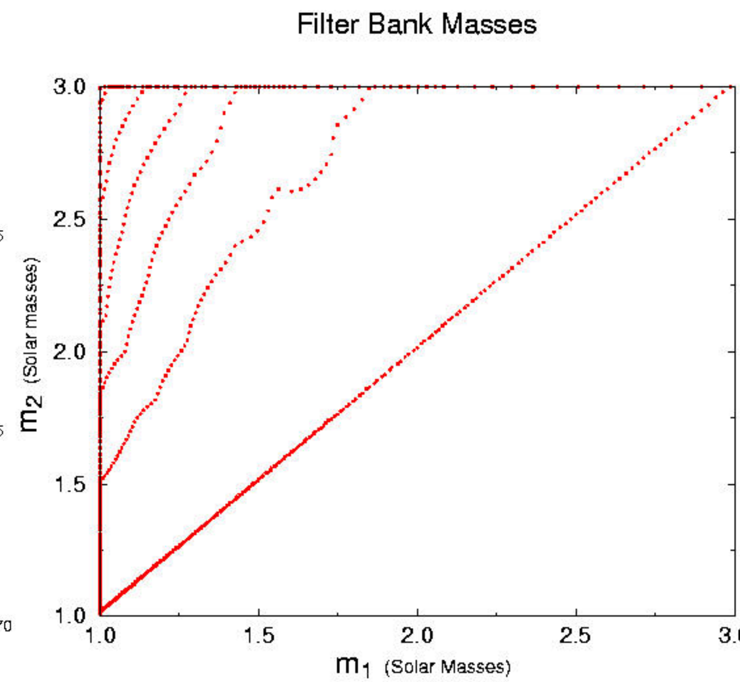
Binary Inspiral Search: Cardiff

- D. Churches and B.S. Sathyaprakash
- Inspiral waveform template generation and parameter-space gridding.
- “Half” of binary inspiral search code (filtering “half” from UWM)
- Produce accurate or “best” waveforms:
  - » 2.5 post-Newtonian order
  - » systems from 0.1 to 30 solar masses
  - » Taylor and Pade approximation methods
  - » time-domain & stationary-phase in frequency-domain.

Binary Inspiral Search: Cardiff

- Current status
  - » time and frequency domain Taylor & Pade approximant code complete for spinless zero-eccentricity systems.
  - » Coding for template placement now underway - should be completed by September.





Line-Tracking Time-Frequency Search: Cardiff

- R. Balasubramanian, W. Anderson, E. Chassande-Mottin
- Method looks for “curves” in time-frequency diagram
- Useful technique for unmodeled sources, such as high-mass binary systems
- Current status: time-frequency transform code complete:
  - » Wigner-Ville
  - » Windowed FFT
  - » Reassigned Spectrogram
- Steger’s line-tracking algorithm complete
- Currently being tested on LIGO engineering data

Power Statistic: Cornell

- E. Flanagan, P. Brady, J. Creighton
- Method looks for “rectangles” in time-frequency diagram with excess energy
- Useful technique for unmodeled sources
- Code complete
- Paper documenting method “in preparation”

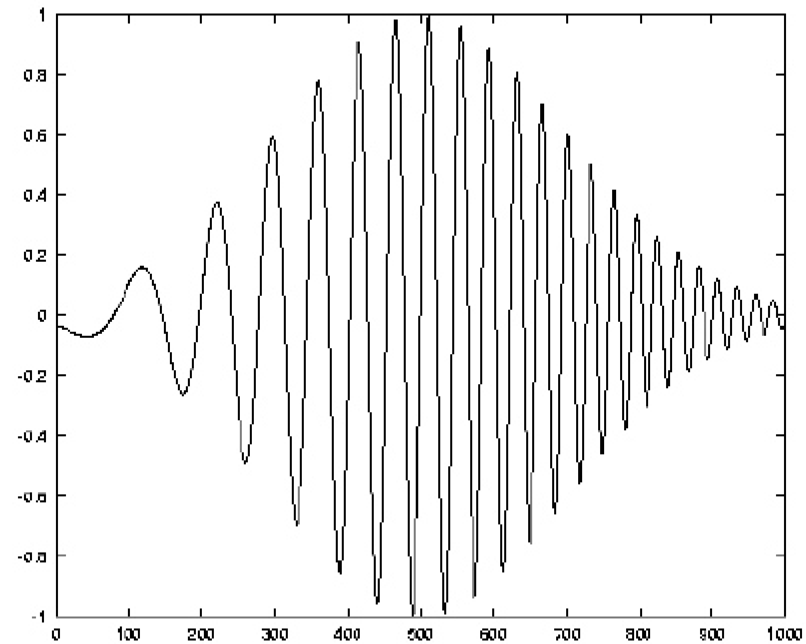


FIG. 1. Waveform in the time domain.

LIGO-G000333-00-D

Robust Stochastic Background Detection: Cornell

- E. Flanagan, S. Drasco
- Method to search for stochastic background by correlating two or more detectors
- Generalization of the “traditional” two-detector correlation method, which gives optimal treatment of some types of non-Gaussian detector noise, in weak signal limit
- Code being written in collaboration with UTB group and others

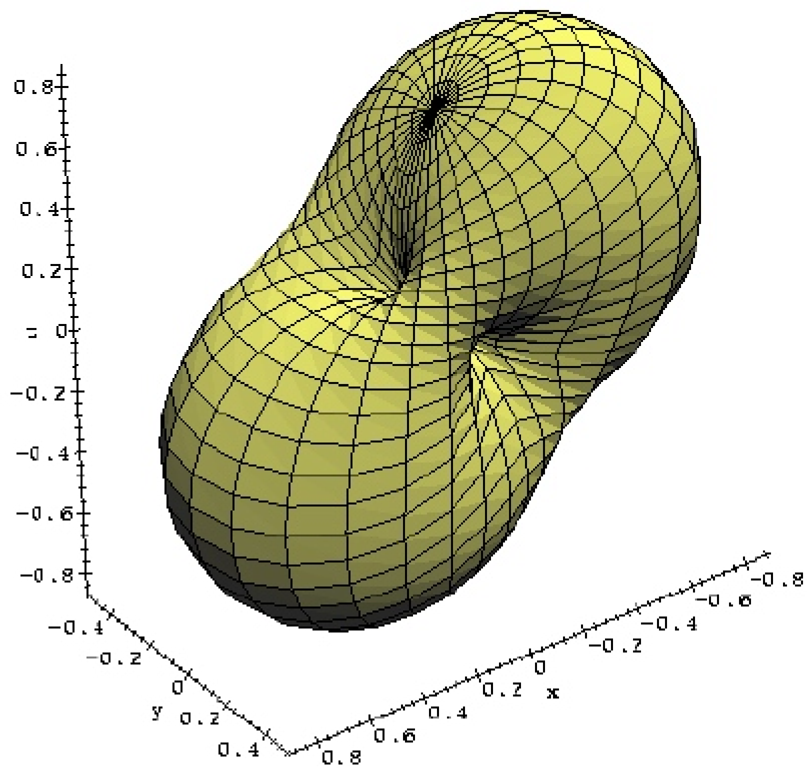
Amplitude Modulation Discriminator: U. of Michigan

- D. Chin, K. Riles
- Tools to see if the amplitude of a posited source (for example a pulsar) exhibits an amplitude modulation consistent with it's inferred position.
- First version is completed, and in LAL library.
- Testing revealed errors in literature.
- Next version will:
  - » examine change in antenna pattern when period of wave comparable to storage time in interferometer
  - » take account of variable earth rotation, precession, nutation, oblateness, etc.

LSC ASIS

Amplitude Modulation Discriminator: U. of Michigan

Here is a typical antenna pattern (average sensitivity to both source polarizations):



Stochastic Background Detection: U. Texas - Brownsville

- J. Romano, M. Diaz, E. Flanagan, A. Vecchio, C. Ungarelli
- Method to search for stochastic background by correlating two or more detectors
- Tool-kit for two-detector correlation
- Filter bank will search for $\Omega(f)$ of "broken power law" form
- Should enable detector-limited sensitivity of $\Omega(f\sim100\text{ Hz})\sim10^{-6}$ in four months of integration with the two LIGO detectors.

Hierarchical Binary Inspiral Search: U. Wisconsin - Milwaukee

- B. Allen, P. Brady, D. Brown, J. Creighton, A. Wiseman
- The “filtering half” of the binary inspiral search code (Cardiff doing templates, template placement)
- Implements general N-level hierarchical search through arbitrary set of templates
  - » Family of post-Newtonian binary inspiral waveforms
  - » Black hole horizon-formation ringdown
- Code now complete.
  - » Being used as example for building/testing LIGO Data Analysis System “Wrapper API” interface
  - » Undergoing first stage of testing (simulated Gaussian noise)

Hierarchical Stack-Slide Pulsar Search: U. Wisconsin - Milwaukee

- P. Brady, T. Creighton
- General-purpose code for area or targeted searches. Uses a two-step hierarchy:
  - » On coarse grid:
    - – Demodulate short time-series for given source parameters (sky position & spindown)
    - – Combine resulting FFTs by sliding (depending on source parameters) and adding power.
  - » For grid points exceeding threshold, repeat on (selected) fine grid
- Expected sensitivity: similar to Hough-transform search (details in papers by Brady & T. Creighton).

Hierarchical Stack-Slide Pulsar Search: U. Wisconsin - Milwaukee

- Current status:
  - » low-pass filtering code completed
  - » time series resampling completed
  - » power spectrum sliding completed
  - » power spectrum summing completed
  - » Currently at work on fine template bank