Analysis of Data from LIGO and GEO

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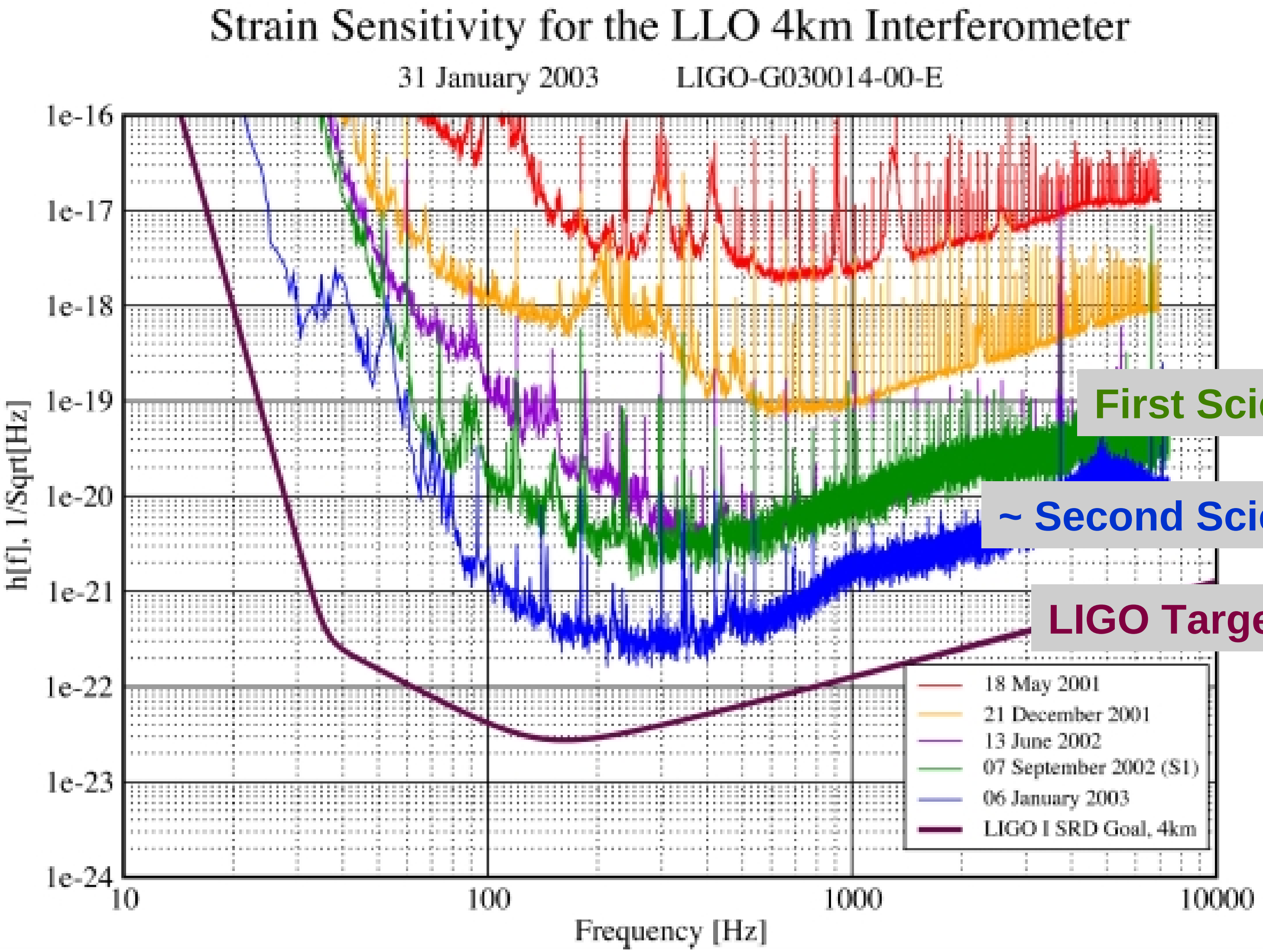
On behalf of the LIGO Scientific Collaboration

Amaldi Meeting, 7 July 2003

Outline of talk

- The first two science runs (S1 and S2)
- Analysis Tools & Facilities
- Overview of S1 analysis:
  - Binary Coalescence
    - Details: **Gonzalez**, 14:15 on July 9th
    - Poster**: Brown, "***Testing the LIGO Inspiral Analysis with Hardware Injections*"
    - Paper approved by LSC; will be posted on gr-qc after some editorial changes.
  - Pulsars and CW Sources
    - Details: **Allen** & **Woan**, 14:30 on July 9th
    - Paper approved by LSC; will be posted on gr-qc after some editorial changes.
  - Stochastic Background
    - Details: **Whelan**, 14:00 on July 9th
    - Paper approved by LSC; will be posted on gr-qc after some editorial changes.
  - Unmodeled Burst Sources
    - Details: **Weinstein**, 13:45 on July 9th
    - Results: *PRELIMINARY*
- Plans for S2 and beyond

Sensitivity Improvements



First Science Run S1

~ Second Science Run S2

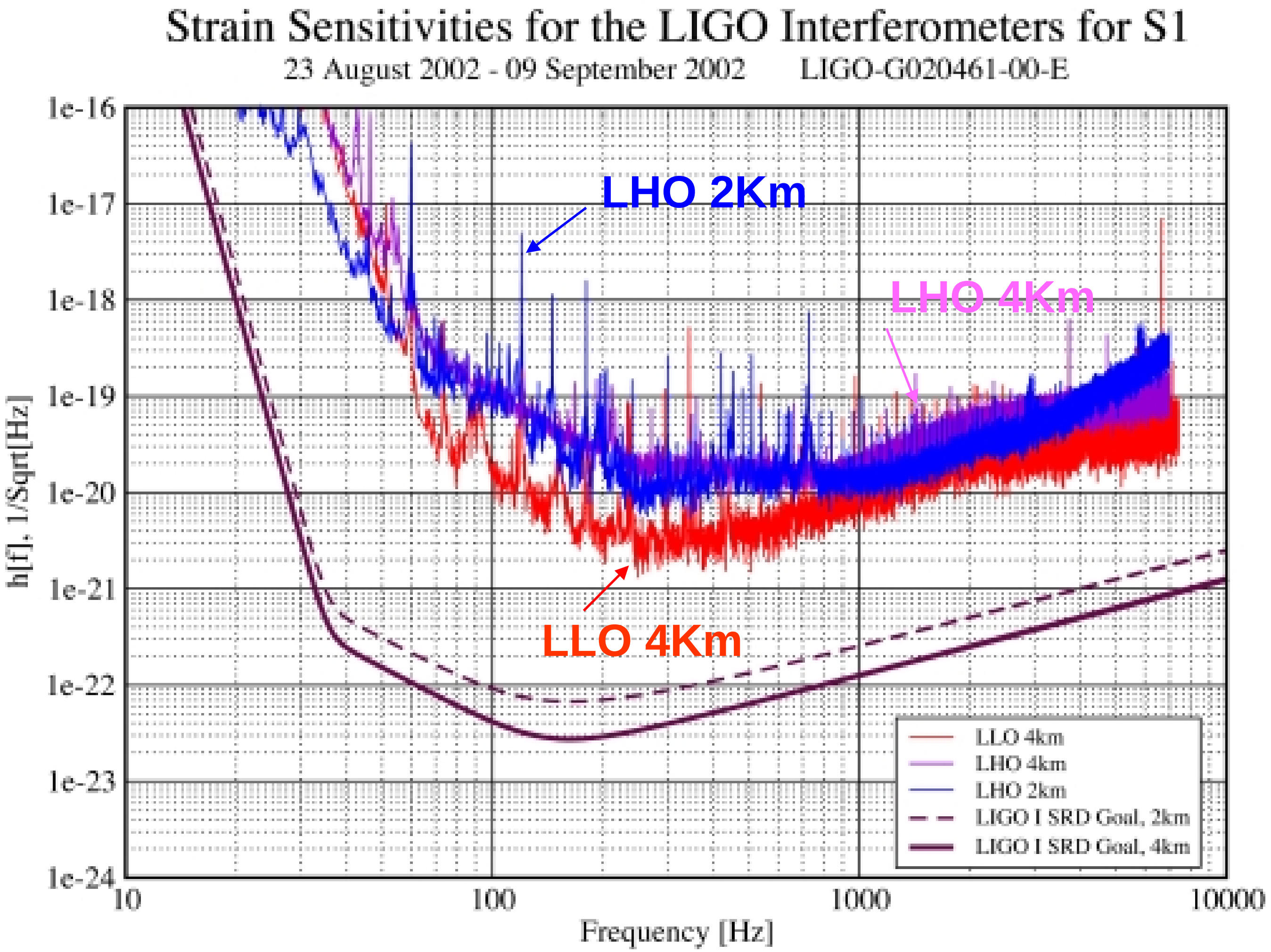
LIGO Target Sensitivity

Lock Summaries S1/S2

	S1	S2
Dates	23/8-9/9/02	14/2-14/4/03
	Hours	Hours
Runtime	408 (100%)	1415 (100%)
Single IFO statistics:		
GEO:	400 (98%)	
H1 (4km):	235 (58%)	1040 (74%)
H2 (2km):	298 (73%)	818 (58%)
L1 (4km):	170 (42%)	523 (37%)
Double coincidence:		
L1 && H1 :	116 (28%)	431 (31%)
L1 && H2 :	131 (32%)	351 (25%)
H1 && H2 :	188 (46%)	699 (49%)
Triple coincidence:		
L1, H1, and H2 :	96 (23%)	312 (22%)

Sensitivities: GEO << H2 < H1 < L1

Sensitivity in S1



LSC Data Analysis Organization

- LSC data analysis is organized in four working groups. Each has two co-chairs:

» **Binary inspiral**:	Patrick Brady [UWM], Gabriela Gonzalez [LSU]
» **Pulsars/CW**:	Maria Alessandra Papa [AEI], Mike Landry [LHO]
» **Stochastic BG**:	Joe Romano [UTB], Peter Fritschel [MIT]
» **Burst**:	Erik Katsavounidis [MIT], Stan Whitcomb [CIT]

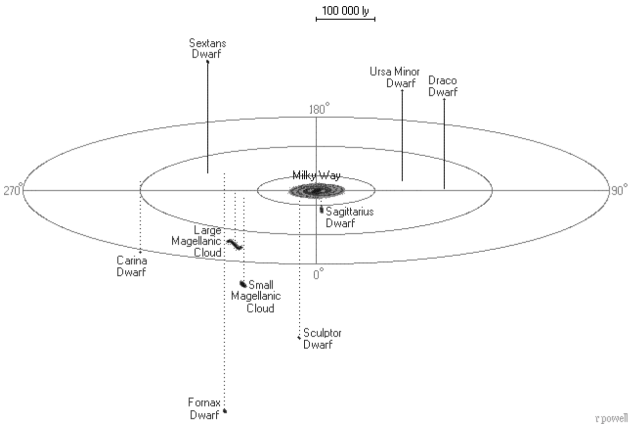
- Each group has had dozens of weekly teleconferences, face-to-face meetings, presentations to the LSC, etc.
- LSC LIGO-I author list has ~300 individuals and ~30 institutions from the USA, Europe, and Asia

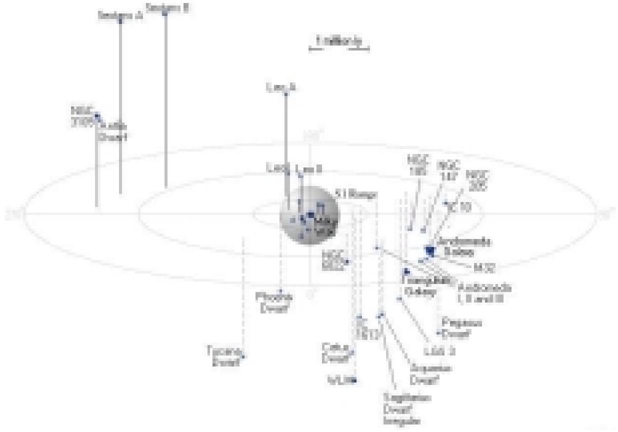
LSC Data Analysis Tools and Facilities

- Data Analysis Tools:
  - » Software Libraries: LAL, LALAPPS, DMT, Frame, FFTW, …
  - » LIGO Data Analysis System (LDAS)
  - » Data Monitor Tool (DMT)
  - » Condor (for standalone jobs on clusters)
  - » Matlab (graphical/analytical analysis)
- Large Data Analysis Facilities (main S1):
  - » Sites: LLO (70 dual nodes), LHO (140 dual nodes), CIT (210 dual nodes)
  - » Tier I Center: Caltech (210 dual cpu nodes + all level 1 data in SAN-QFS system)
  - » Tier II Centers: UWM (Medusa, 300 nodes), PSU (under design)
  - » Other LSC Resources: AEI (Merlin, 180 dual cpu nodes), UTB (Lobizon, 128 nodes), MIT (112 nodes), Cardiff (80 dual cpu nodes)

Search for Inspirals

- **Sources:**
  - » Compact neutron star binaries undergoing orbital decay and coalescence.
  - » Masses, positions, orbital parameters, distances: unknown
- **Analysis goals:**
  - » Develop and test an inspiral detection pipeline incorporating instrumental vetos and multi-instrument coincidence
  - » Obtain upper limit on the NS-NS inspiral rate
    - – For setting upper limits, need a source distribution model:
      - S1 range included Milky Way (our Galaxy) and LMC and SMC
      - S2 range includes Andromeda





Search for Inspirals

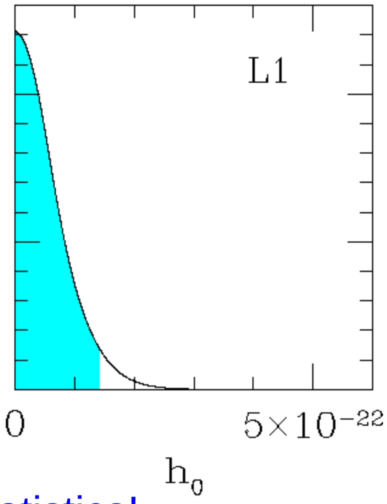
- **S1 Search method:**
  - Optimal Filtering used within LDAS to generate “triggers”
    - Used only most sensitive two IFOs: H1 and L1. Distance to an optimally-oriented SNR=8 source is L1: 176 kpc, H1: 46 kpc.
    - Bank of 2110 second post-Newtonian stationary-phase templates for $1 < m1 \leq m2 < 3$ solar masses with 3% maximum mismatch for total mass < 4 solar masses
    - Threshold on $\rho > 6.5$ and $\chi^2 < 5(8 + 0.03\,\rho^2)$ [8 frequency bins]
  - DMT used to generate “vetoes” and select data. Criteria established with playground dataset:
    - Eliminate contiguous science-mode intervals with large band-limited GW noise (6 minute stretch with 3σ or 10σ compared to average for the entire run).
    - H1: vetoed ±1 second windows from reflected port PD (avg arm length), eliminating 0.2% of data.
  - Require coincidence in time (11 msec) and chirp mass (1%) for triggers which are strong enough to be seen in both detectors
  - Upper limit set by measured detection efficiency at highest SNR event
- **S1 results:**
  - **No event candidates found in coincidence**
  - 90% confidence upper limit: **inspiral rate < 170/year** per Milky-way equivalent galaxy, in the (m1, m2) range of 1 to 3 solar masses.

Search for Continuous Waves

- **Source:** PSR J1939+2134 (fastest known rotating neutron star) located 3.6 kpc from us.
  - » **Frequency** of source: known
  - » **Rate of change of frequency (spindown)**: known
  - » **Sky coordinates** (α, δ) of source: known
  - » **Amplitude** h_0: unknown (though spindown implies $h_0 < 10^{-27}$)
  - » **Orientation** ι: unknown
  - » **Phase, polarization** φ, ψ: unknown
- **S1 Analysis goals:**
  - » Search for emission at 1283.86 Hz (twice the pulsar rotation frequency). Set upper limits on strain amplitude h_0.
  - » Develop and test an efficient analysis pipeline that can be used for blind searches (**frequency domain method**)
  - » Develop and test an analysis pipeline optimized for efficient "known target parameter" searches (**time domain method**)

Search for Continuous Waves

- **S1 Search Methods:**
  - » done for all four detectors: L1, H1, H2, G with standalone codes running under Condor.
  - » No joint IFO result (timing problems, L1 best anyway)
  - » **Frequency-domain method** (optimal for detection, frequentist UL):
    - – Take SFTs of (high-pass filtered) 1-minute stretches of GW channel
    - – Calibrate in the frequency domain, weight by average noise in narrow band
    - – Compute F = likelihood ratio (analytically maximized over ι, φ, ψ)
    - – Obtain upper limit using Monte-Carlo simulations, by injecting large numbers of simulated signals at nearby frequencies
  - » **Time-domain method** (sets Bayesian upper limit):
    - – Heterodyne data (with fixed freq) to 4 samples/second
    - – Heterodyne data (with doppler/spindown) to 1 sample/minute
    - – Calculate $\chi^2(h_0, \iota, \varphi, \psi)$ for source model
      Easily related to probability (noise Gaussian)
    - – Marginalize over ι, φ, ψ to get PDF for (and upper limit on) h_0



- **S1 results:**
  - » h_o**<1.4x10**$^{-22}$ (from L1). Constrains **ellipticity < 2.7x10**$^{-4}$
  - » **Beautiful** agreement between theoretical and actual noise statistics!

Stochastic Radiation

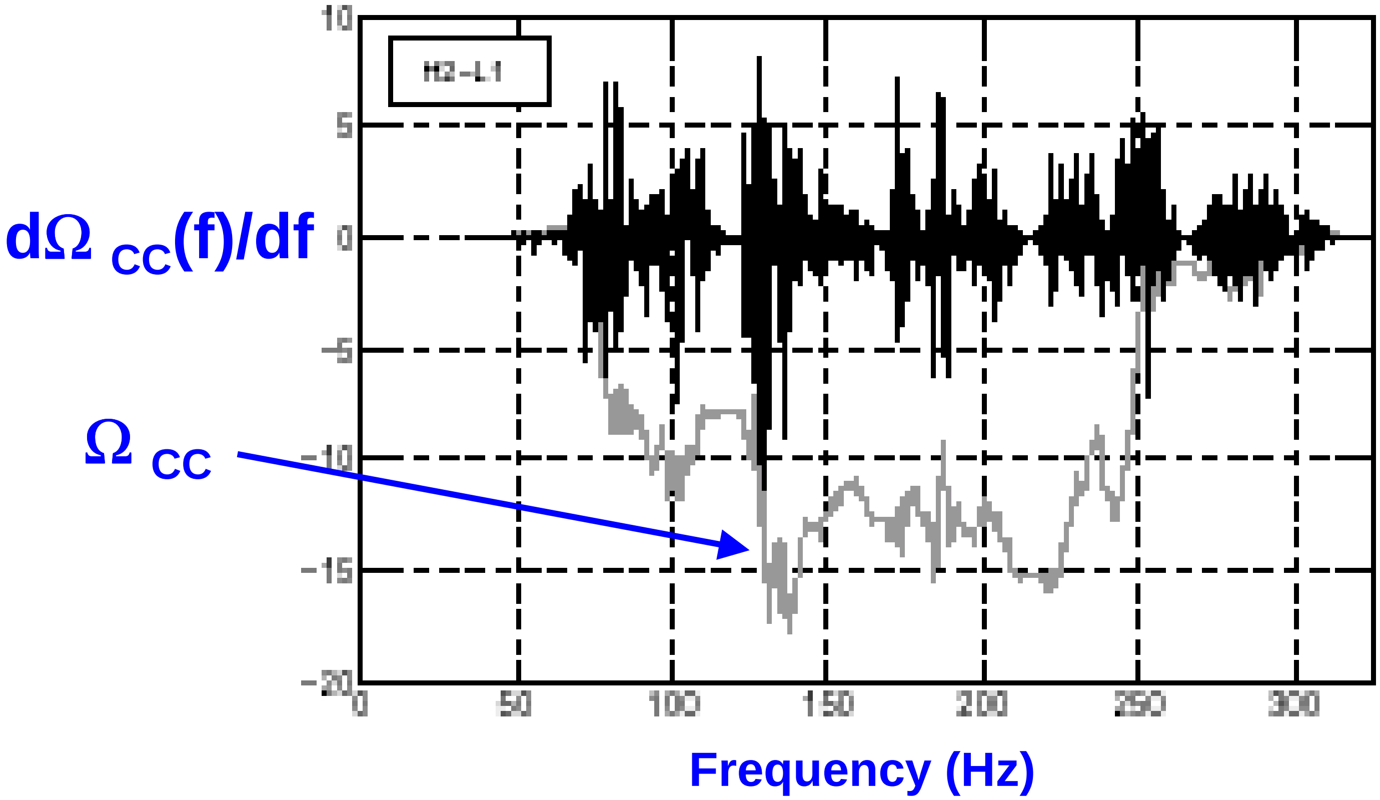
- **Sources**
  - » Early universe sources (inflation, cosmic strings, etc) produce very weak, non-thermal unpolarized, isotropic, incoherent background spectrum
  - » Contemporary sources (unresolved SN & inspiral sources) produce power-law spectrum
  - » Indirect constraints on fractional energy density $\Omega_{GW}(f) < 10^{-5}$
- **Analysis goals:**
  - » Directly constrain $\Omega_{GW}(f)$ for 40 Hz < f < 314 Hz
  - » Investigate instrumental correlations

Stochastic Radiation

- **S1 search method**
  - Done within LDAS
  - Look for correlations between pairs of detectors
  - Break data into (2-detector coincident) 900-second stretches
  - Break each of these into 90-second stretches
  - Window, zero pad, FFT, estimate power spectrum for 900 sec
  - Remove ¼ Hz bins at $n \cdot 16$ Hz, $n \cdot 60$ Hz, 168.25 Hz, 168.5 Hz, 250 Hz
  - Find cross-correlation with filter optimal for $\Omega_{GW}(f) \propto f^0$
  - Extensive statistical analysis to set 90% confidence upper limit
- **S1 search results:**
  - H1-H2 cross-correlation contaminated by environmental noise (corresponding to $\Omega_{GW} < 0$)
  - **Limit from H2-L1 (with 90% confidence):**
    Ω_{GW} (40Hz - 314 Hz) < 23±4.6

Stochastic Radiation

How does the H2-L1 Cross Correlation Statistic behave as a function of frequency?



Limit from H2-L1: Ω_{GW} (40Hz - 314 Hz) < 23±4.6

Bursts

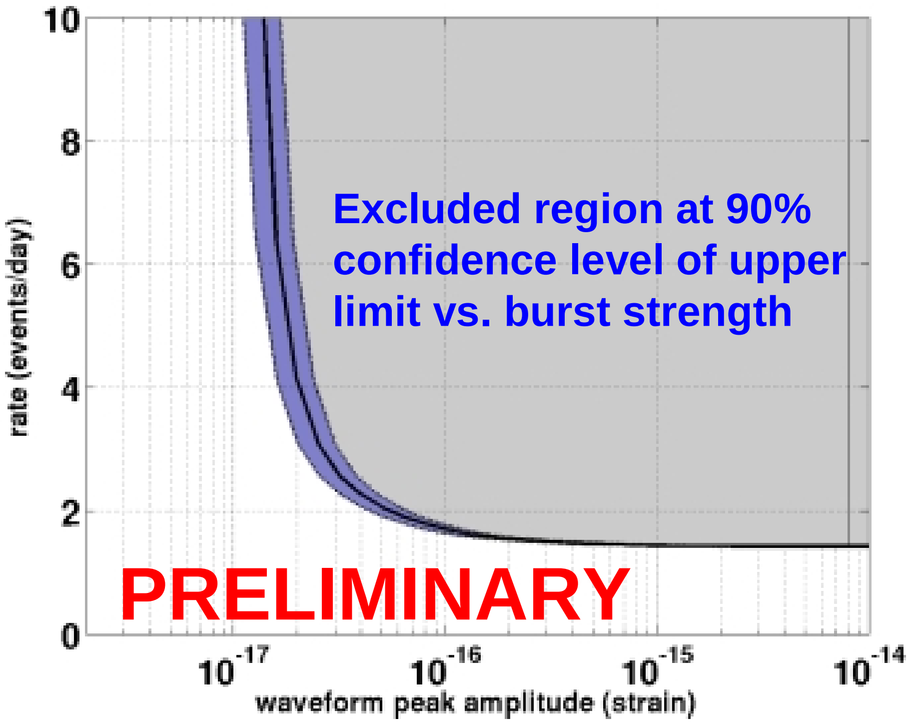
- **Sources:** phenomena emitting short transients of gravitational radiation of unknown waveform (supernovae, black hole mergers).
- **Analysis goals:**
    - Don’t bias search in favor of particular signal model(s)
    - Search in a broad frequency band
    - Establish bound on rate of (uncalibrated) instrumental events using [triple] coincidence techniques
    - Interpret these bounds in terms of source/population models in rate versus strength plots

Bursts

- **S1 Search methods:**
  - » Create database of instrumental monitor triggers using DMT
  - » Create database of GW triggers using LDAS
    - – **"SLOPE"** algorithm (time domain) is an optimal filter for a linear function of time with a 610 μsec rise-time.
    - – **"TF-Clusters"** algorithm identifies regions in the time-frequency plane with excess power (threshold on pixel power and cluster size).
  - » Veto GW trigger events by using instrumental monitors. (Thresholds set with playground data.)
  - » Use time-shift analysis to estimate background rates, and Feldman-Cousins to set upper limits or confidence belts
  - » Use Monte-Carlo studies to determine detection efficiency as a function of signal strength and model

Bursts

- **PRELIMINARY S1 Search results:**
  - » (for 1ms Gaussian pulses):**1.6** events/day rising up as the detection efficiency reduces (50% efficiency point is at **h~3x10^{-17}**).



Excluded region at 90% confidence level of upper limit vs. burst strength

PRELIMINARY

Plans for S2 and beyond

- Inspiral
  - (If no detections) get better upper limit, making use of longer observation time, additional sources in Andromeda
  - Improved data quality cuts and statistical testing; coherent analysis
  - Search for non-spinning BHs up to ~20 solar masses (or UL)
  - Search for MACHO binaries (low mass BHs) in Galactic Halo
- Burst
  - “Eyes wide open” search for signals in the 1-100 msec range
  - Triggered search for correlations with GRBs
  - Modeled search for
    - Black hole ringdown
    - Supernovae waveform catalog
  - Four-way coincidence with TAMA
- Pulsar Time domain method:
  - Upper limits on all known pulsars > 50 Hz
  - Search for Crab
  - Develop specialized statistical methods (Metropolis-Hastings Markov Chain) to characterize PDF in parameter space
- Pulsar Frequency domain method
  - Search parameter space (nearby all-sky broadband + deeper small-area)
  - Specialized search for SCO-X1 (pulsar in binary)
  - Incoherent searches: Hough, unbiased, stack-slide
- Stochastic
  - May optimally filter for power-law spectra: $\Omega_{GW}(f) \propto f^{\beta}$
  - Correlate ALLEGRO-LLO
  - Technical improvements: apply calibration data once/minute, overlapping lower-leakage windows, study H1-H2 correlations in more detail.