Observational limit on gravitational waves from binary neutron stars in the Galaxy

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- Analyze 15.8 hours of data from the November 1994 LIGO 40-meter prototype.
- Instrument sensitive enough to detect the gravitational-wave chirps from coalescing compact binary systems within our Galaxy.
- Data stream searched using matched filtering.
- Upper limit on the rate R of neutron star binary inspirals in our Galaxy:

$$R_{90\%} < 1.0/\mathrm{hour}.$$

- Full-scale LIGO will constrain population of tight binary neutron star systems in Universe.

PHOTO OF THE 40-METER LAB FROM 1994

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NOISE POWER SPECTRUM OF 40-METER INSTRUMENT FROM 1990-1994

This is Figure 2 on page 159 of

A. Abramovici *et al.*, Phys. Lett. A **218**, 157 (1996)

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OPTICAL TOPOLOGY OF THE 40-METER INSTRUMENT IN 1994

This is Figure 1 on page 158 of

A. Abramovici *et al.*, Phys. Lett. A **218**, 157 (1996)

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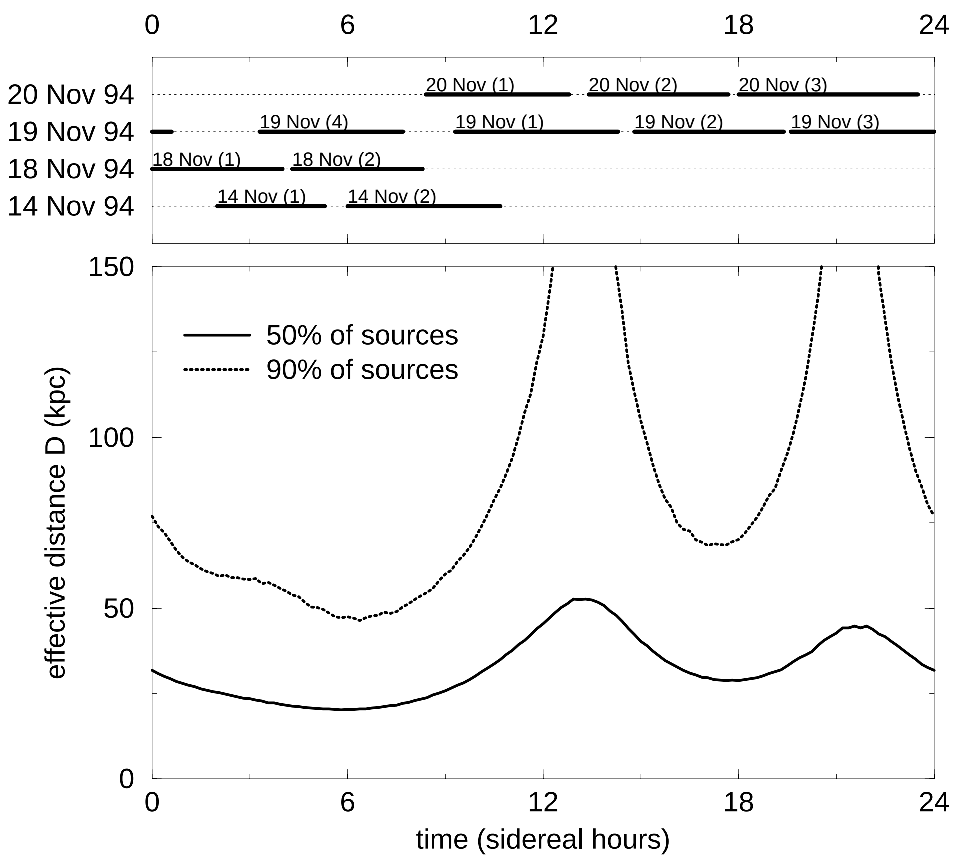
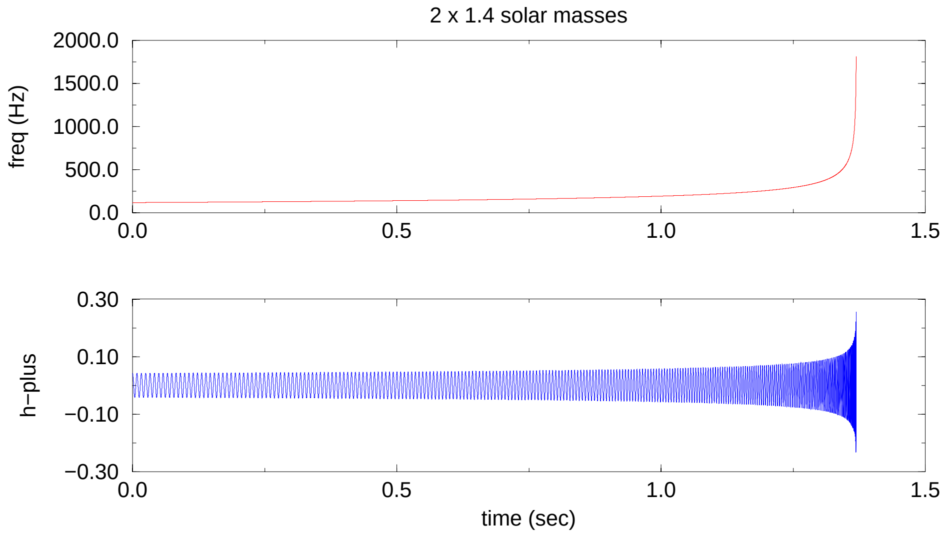
Data Collection Times



- 11 runs, 44.8 hours of raw data
- Goal: understand time-domain performance
- Arms in optical resonance (lock) 82% of the time
- Effective distance D to 50% and 90% of sources in Galactic model shown.
- Time variation: antenna pattern sweeping past Galactic bulge.

Inspiral Chirp Signals



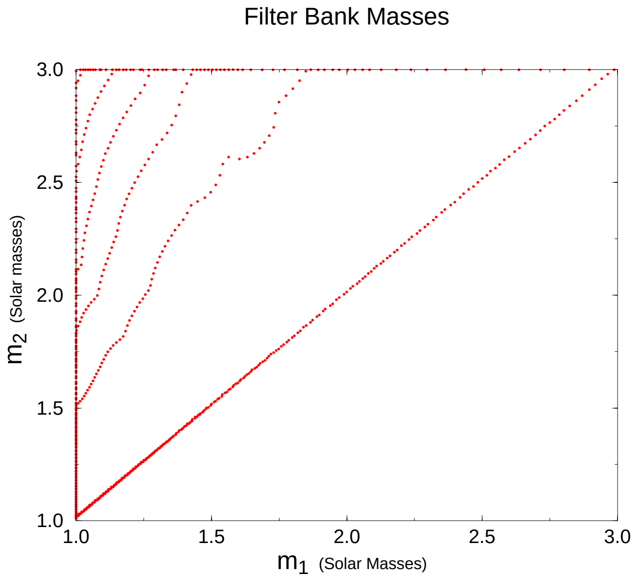
- Calculated in 2nd-order post-Newtonian approximation (2 independent groups).
- Approximations result in $< 10\%$ loss of SNR
- Typical signal enters bandpass at 120 Hz, does 255 cycles, cut off by merger after 1.35 secs.
- Mass range: $M_k = (m_1, m_2)_k$ with $1M_\odot < m_1 \leq m_2 < 3M_\odot$.
- *Effective distance D*: distance at which system must be located directly above plane of IFO arms, with orbital plane parallel to IFO arms, to produce the same strain in IFO.

Detector's Output

- 11 or 13 control/environment channels.
- Most interest: voltage signal $v(t)$ derived from feedback force to hold IFO in resonance. $v(t) \propto h(t) = \Delta L/L$, filtered to attenuate low freq (seismic) noise and to prevent aliasing.
- Recorded with 12-bit ADC at 9868.42 Hz sample rate.
- Loss of SNR from quantization $< 0.9\%$.
- Instrument's transfer function $R(f)$ determined by applying known forces at start of each data run; calibration errors affect SNR by $< 0.3\%$.
- Voltage that would be produced by binary inspiral:

$$\begin{aligned} v_h(t) &= \int_{-\infty}^{t} R(t-t')h(t')dt' \\ &= \int_{-\infty}^{\infty} \tilde{h}(f)\tilde{R}^*(f)\mathrm{e}^{-2\pi ift}df \end{aligned}$$

Search Method: Digital Matched Filtering



- Use bank of 687 mass-pairs. Covers mass range $1M_\odot \rightarrow 3M_\odot$ with $< 2\%$ loss of SNR.
- Construct two signals for each mass-pair:

$$X_k^{s,c}(t) = N_k{}^{s,c} \int_{-\infty}^{\infty} df \, \frac{\tilde{v}(f)\tilde{h}^{*}_{s,c}{}^{M_k}(f)\tilde{R}(f)}{S_v(|f|)} e^{-2\pi i f t}$$

- $S_v(|f|)$: voltage noise power spectrum.
- Normalization $N_k{}^{s,c}$: in absence of sources mean values of $[X_k^{s,c}(t)]^2$ are 1.
- SNR in k'th template (maximized over phase) is

$$\rho_k(t) = \sqrt{[X_k^s(t)]^2 + [X_k^c(t)]^2}.$$

Data Processing/Filtering

UWM LSC Group Beowulf

- FFT methods
- Segments 26.6 sec = 2^{18} samples
  Overlap 6.6 sec = 2^{16} samples
- Skip 180 s after lock (let mechanical modes damp)
- Estimate $S_v(f)$ with 8 segments centered about data
- 24 hours on 48 node DEC Alpha Beowulf. Each node: 600 double-precision Mflops - max throughput 29 GFlops

Time/Frequency Discriminator (χ^2 test)

Problem: transients (glitches)

Galactic inspiral $\Rightarrow$ large filter output ρ

Noise glitch $\Rightarrow$ large filter output ρ

Solution: time/frequency discriminator

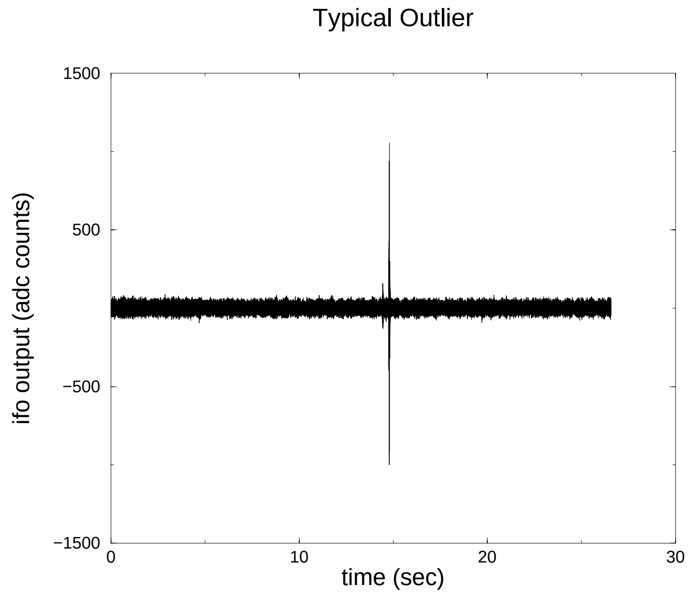
- Break frequency band into $p = 8$ subintervals, with equal SNR contributions from inspiral (but *different* SNR contributions from glitch).
- Form statistic χ^2 by summing squares of deviations from mean.
- For Gaussian noise, statistic has χ^2 distribution with $2p - 2 = 14$ degrees of freedom.

Galactic inspiral $\Rightarrow$ large filter output ρ, small χ^2

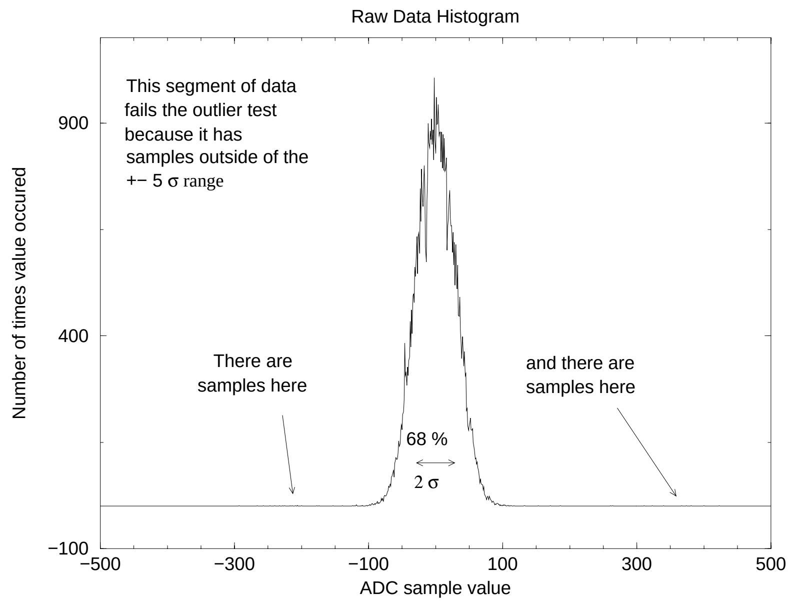
Noise glitch $\Rightarrow$ large filter output ρ, large χ^2

Removal of Outliers

Problem: Large transients (rejected by the time/freq discriminator) bias the instrument's noise power spectrum.



Solution: We *prefilter* and remove data segments with obvious outlier points.

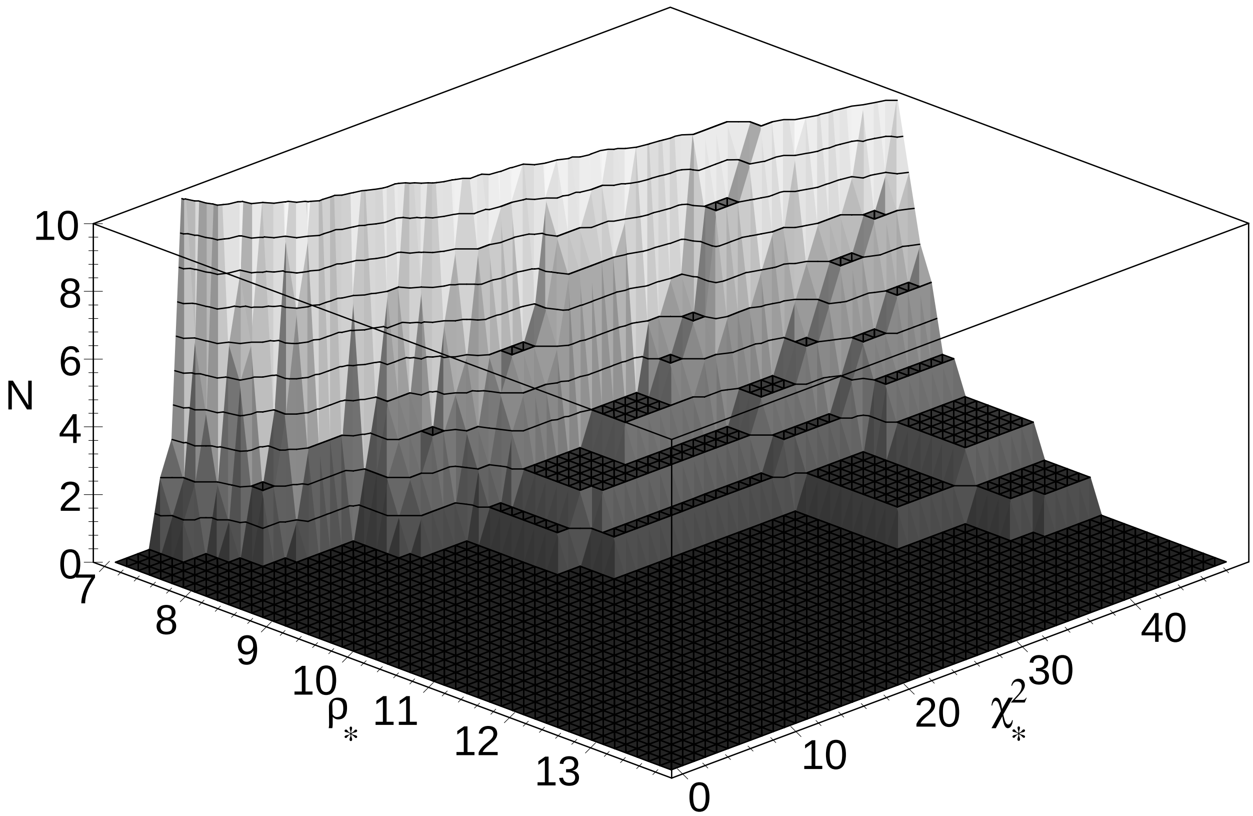


Summary of filtering process

- Pre-filter data, let mechanical modes damp, obtain 2852 segments (time T = 15.8 hours).
- Record, for each data segment, and for each of 687 filters:
  1. Maximum SNR ρ in filter.
  2. Time/freq statistic χ^2 (if SNR $\rho > 5$).
  3. Arrival time of maximum.
  4. Normalization $N^{s,c}$ of filter (gives effective distance to “source”).

Results of filtering

Event: In a data segment, there is a filter for which ρ satisfies $\rho > \rho_*$ and $\chi^2 < \chi^2_*$.



This graph shows the number N of *Events* as a function of the thresholds ρ_* and χ^2_*.

Setting a limit on the rate R of Galactic inspiral

Assumptions:

- IFO responds linearly to gravitational wave strain
- Inspiral waveforms are correct
- Spatial distribution of Galactic binaries is:

$$dN \propto e^{-\mathcal{D}^2/2\mathcal{D}_0^2}\mathcal{D}\, d\mathcal{D} \times e^{-|Z|/h_Z}\, dZ$$

  $\mathcal{D} =$ Galactocentric radius
  $\mathcal{D}_0 = 4.8$ kpc $=$ Galactic bulge radius
  $Z =$ height off the Galactic plane
  $h_Z = 1$ kpc $=$ Galactic disk thickness
  Distance to center of galaxy: 8.5 kpc

- Time-distribution of inspirals is Poisson process

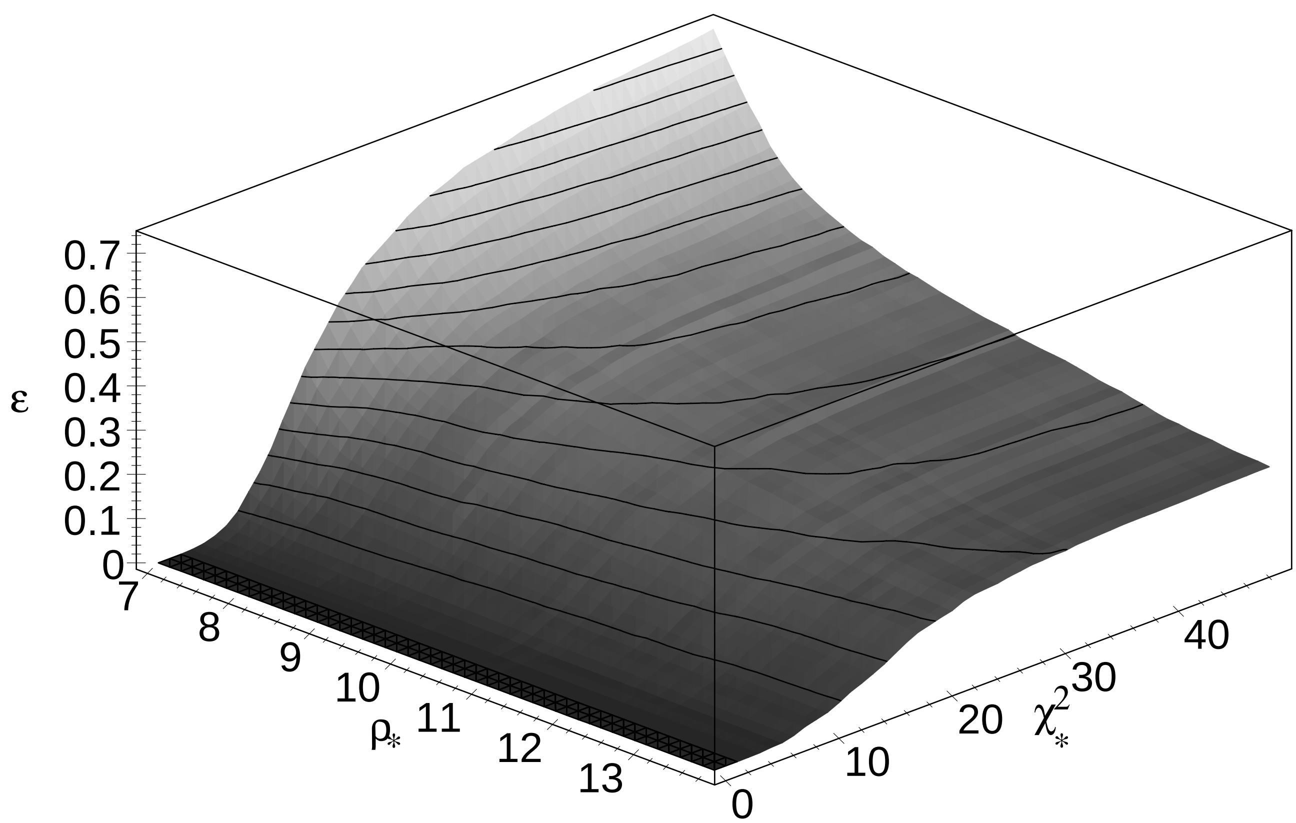
Caveat:

Antenna pattern vanishes along line between arms. If no IFO noise, and nothing seem, we *can't* conclude "no inspirals took place in Galaxy". We can only make statistical statement about R.

Galactic Inspiral Detection Efficiency $\epsilon(\rho_*, \chi^2_*)$

Need to know how efficiently IFO/analysis pipeline would identify inspiral events.

- Used Monte-Carlo simulations (additional runs through the data set)
- Add thousands of simulated Galactic inspiral waveforms drawn from distribution dN



Shown is $\epsilon(\rho_*, \chi^2_*)$ the fraction of simulated Galactic inspirals which give rise to detected "Events".

Setting 90% confidence limit

Our method makes minimal assumptions about noise in detector. We obtain the event rate bound from the probability that a neutron-star binary event would be as "loud" (SNR as big) as the "loudest" observed event.

- Use threshold $\chi^2_* = 21.06$ chosen to reject only 10% of events in stationary Gaussian noise
- Compute Baysian 90% confidence limit using uniform priors for the event rate

Get limit:

$$R_{90\%} = \frac{3.89}{T\epsilon(\rho_{\rm max} = 10.4, \chi^2 = 21)} = 1.0/\text{hour}$$

If loudest event inspiral $\Rightarrow$ 90% confidence
If loudest event detector noise $\Rightarrow$ confidence $> 90\%$
$R_{90\%}$ is a conservative upper limit on Galactic inspiral rate when detector noise poorly understood.

Comments

- An ideal detector (efficiency = 1) would give limit $R_{90\%} = 0.23/\mathrm{hour}$
- No surprise: stellar population studies indicate expected rates $\approx 10^{-6}$/year
- Previous (published) searches:
  1. Glasgow/Garching: upper limit on burst sources
  2. Resonant mass detectors: upper limits on monochromatic signals and on stochastic background (but *not* on binary inspiral)
- Coincidence analysis of bar data might be able to set comparable or better upper limits than $R_{90\%} = 1.0/\mathrm{hour}$.
- If loudest event in first-generation LIGO has $SNR = 8$, similar analysis gives

$$\mathcal{R}_{90\%} = \frac{1.9 \times 10^{-4}}{\mathrm{Mpc}^3\mathrm{yr}} \left(\frac{38\mathrm{Mpc}}{r_{\mathrm{max}}} \right)^3 \left(\frac{1\mathrm{yr}}{T_{\mathrm{obs}}} \right) ,$$

Note 1, Linda Turner, 11/02/98 11:42:12 AM
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