Searching for Gravitational Waves from Binary Inspirals with LIGO: Current Status and Future Plans

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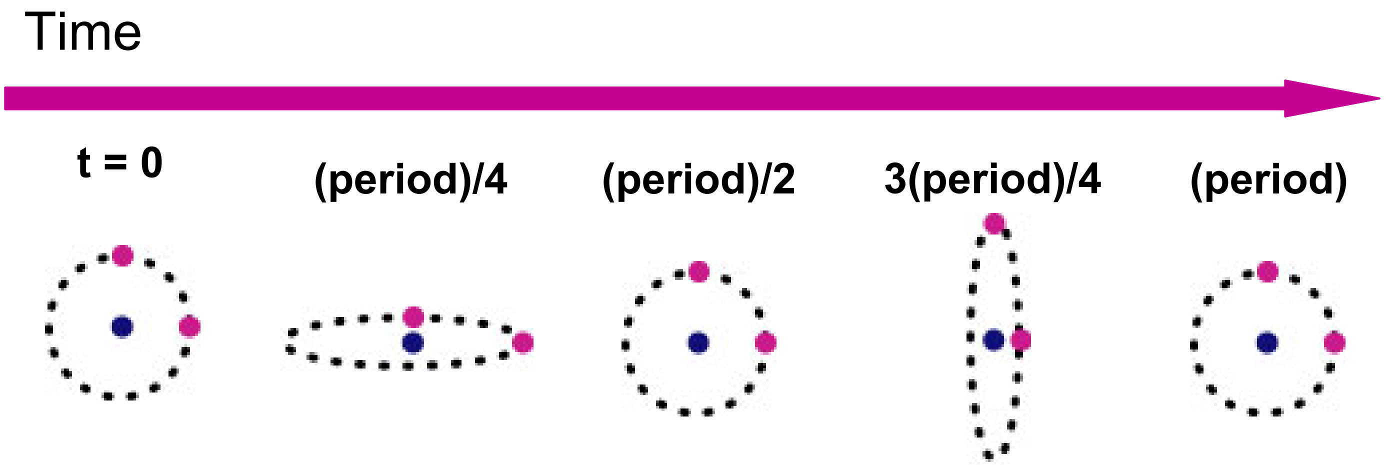
Overview

- Gravitational Waves and Binary Inspirals
- Data Analysis Methods
- Results from the First LIGO Science Run (S1)
- Second LIGO Science Run (S2)
  - Pipeline and Current Status
  - Background Studies
- Searching for MACHO binaries in S2

Gravitational Waves

- As gravitational waves pass, they change the distance between neighboring bodies

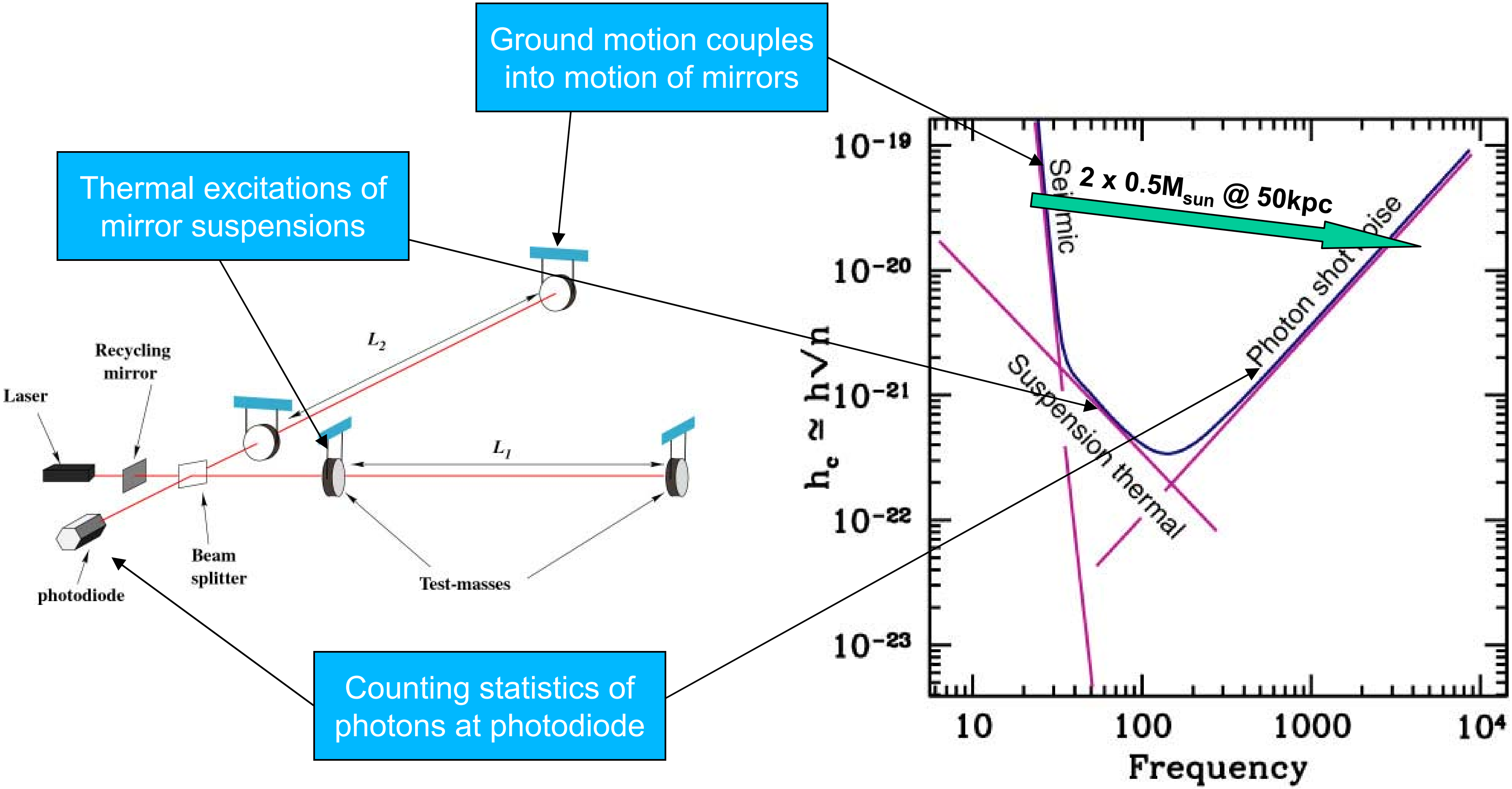


Time

t = 0 **(period)/4** **(period)/2** **3(period)/4** **(period)**

- Change in distance is proportional to gravitational wave strain: $dL / L = 2\, h(t) \sim 10^{-22}$

The LIGO Interferometers



Ground motion couples into motion of mirrors

Thermal excitations of mirror suspensions

Counting statistics of photons at photodiode

Gravitational Waves from Inspirals

- Binary neutron star systems (BNS) are known to exist
  - PSR 1913+16 (Hulse-Taylor)
  - PSR J0737-3039 will merge in ~ 85 Myr (Burgay et. al.)

- BNS emits gravitational waves due to a time changing quadrupole moment

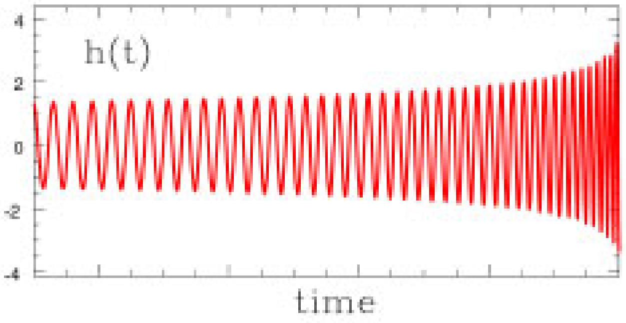
$$h(t) = \frac{1Mpc}{D}\left[\sin\alpha h_s(t - t_c) + \cos\alpha h_c(t - t_c)\right]$$

- Energy is lost as gravitational waves so the system becomes more tightly bound
  - As radius decreases, orbital period decreases

- Decrease in radius causes increase in GW flux and frequency

Binary Inspiral Waveforms

- Last few minutes of BNS inspiral signal has a “chirp” waveform in frequency range 40 Hz ~ 2 kHz



- Well modeled by post-Newtonian approximation
  - We use restricted 2 pN stationary phase waveforms:

$$\tilde{h}_c(f) = \left(\frac{5\mu}{96\ M_\odot}\right)^{\frac{1}{2}} \left(\frac{M}{\pi^2\ M_\odot}\right)^{\frac{1}{3}} t_\odot^{-\frac{1}{6}}\ f^{-7/6} \exp\left[i\Psi(f; M, \eta)\right]$$

Matched Filtering

- The waveform is known well so use matched filtering
  - Correlate the chirp with the data stream weighed by the average power spectrum $S_h(f)$
  - Have two filters for each phase of the chirp

$$S_{[c|s]}(t; M, \eta) = \frac{2}{\sigma} \int_{-\infty}^{\infty} df\, e^{-2\pi i f t} \frac{\tilde{h}(f) \tilde{h}^*_{[c|s]}(f; M, \eta)}{S_h(f)}$$

  - Combine these into by exploiting symmetry of stationary phase chirp

$$\tilde{h}_s(f) = i \tilde{h}_c(f)$$

- Construct a signal-to-noise squared ratio from the two filters

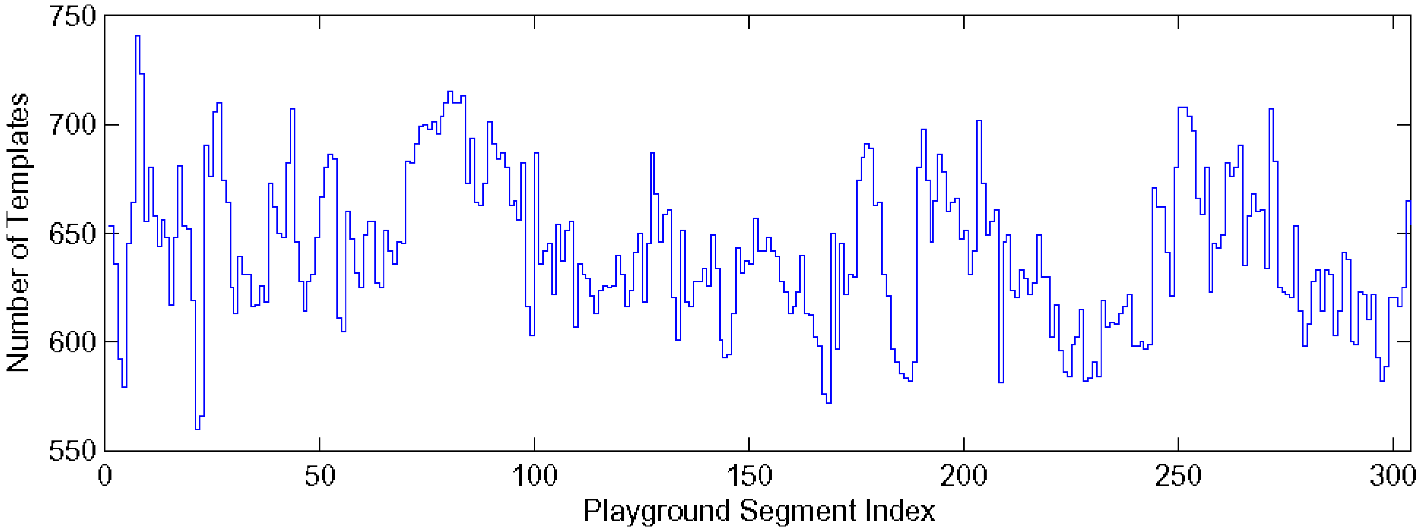
$$\rho^2(t; M, \eta) = S_c^2(t; M, \eta) + S_s^2(t; M, \eta)$$

- Threshold on $r^2(t)$ and look for maxima: inspiral triggers

Inspiral Template Banks

- We want to search for a population of neutron stars
  - Matched filter computes a signal-to-noise ratio for one waveform

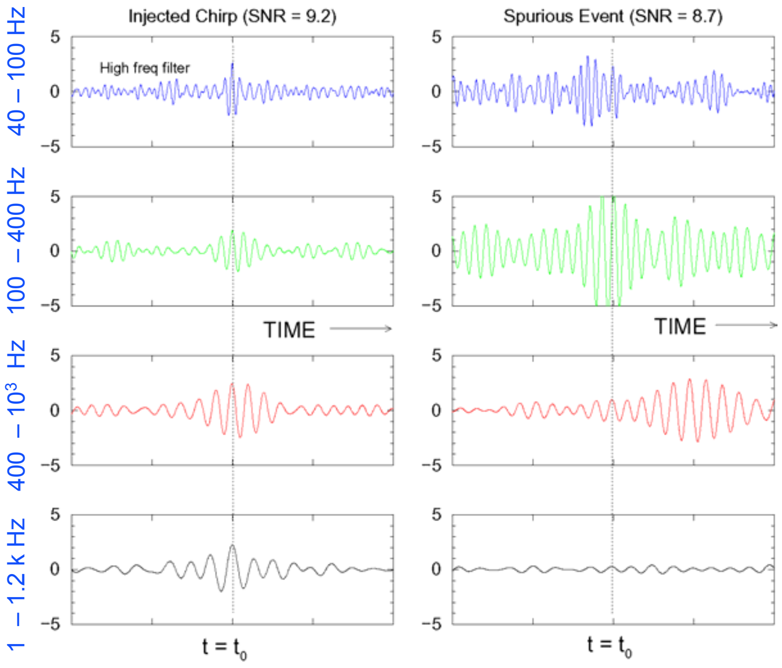
- Construct a bank of templates and compute matched filter for each bank
  - For BNS: $1.0 < (m_1,m_2) < 3.0\ M_{sun}$
  - Generate bank for each chunk with maximum 3% loss in signal-to-noise
  - Size of bank depends on the shape of the interferometer power spectrum



The x^2 Veto

- Any loud transient in the data can cause the filter to have a large r^2
- The x^2 veto checks that the SNR is consistent with an inspiral signal
  - Split the chirp into p frequency bands with equal power in each band
  - Subtract the expected contribution of filter in each band from the actual contribution

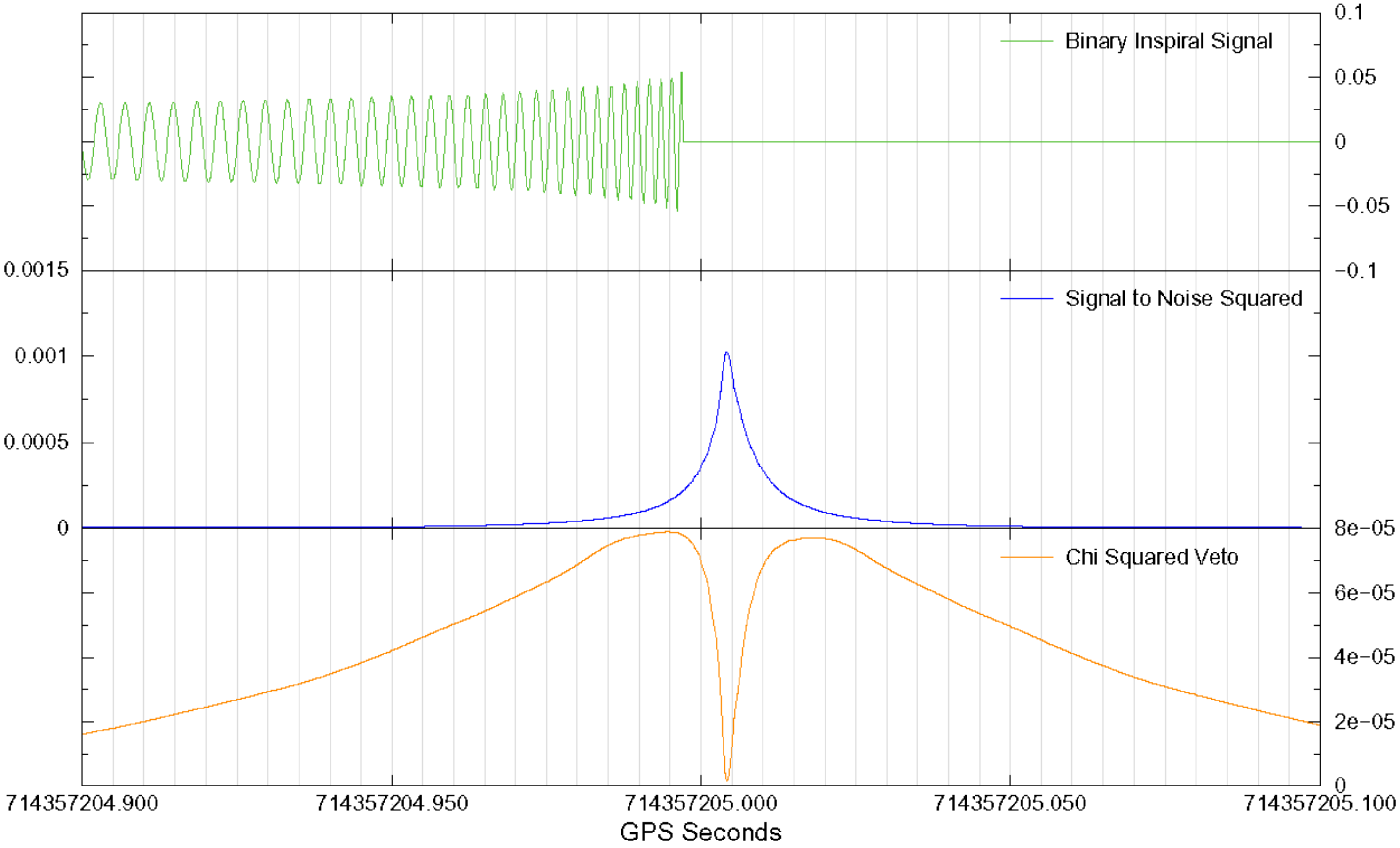
$$\chi^2 = \frac{p}{\sigma^2}\sum_{l=1}^{p}\left([S_c]_l - \frac{S_c}{p}\right)^2 + \left([S_s]_l - \frac{S_s}{p}\right)^2$$



  - x^2 distributed with 2p-2 degrees of freedom
  - Allow for the mismatch of the bank by thresholding on

$$\frac{\chi^2}{(p+\delta^2\rho^2)} < \text{threshold}$$

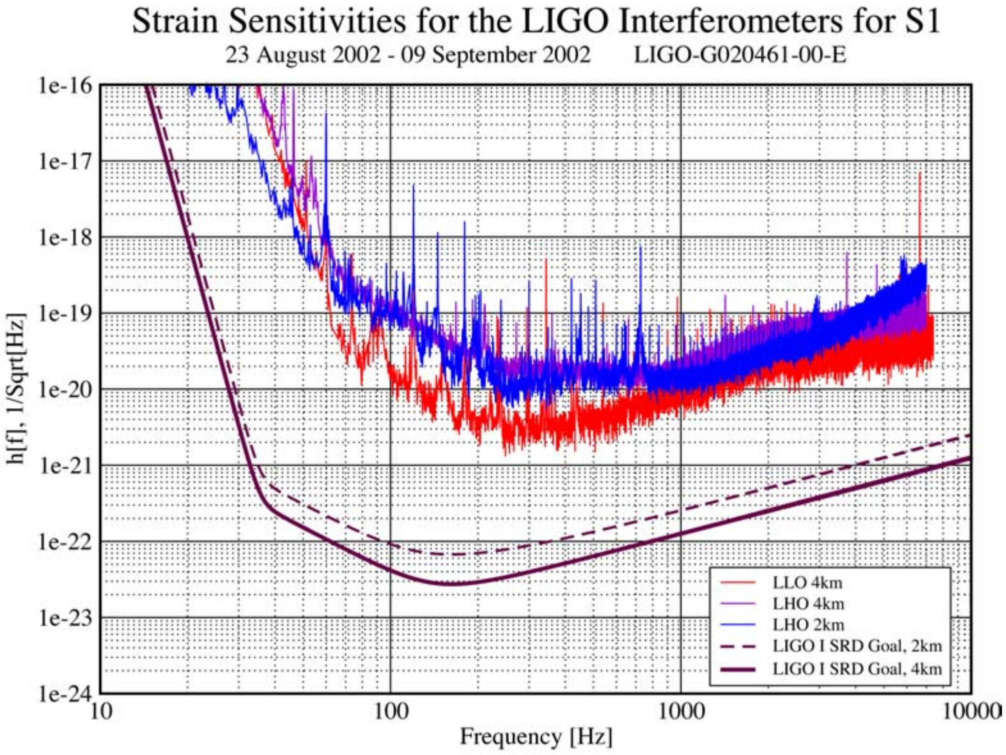
Testing With An Injected Chirp



S1 Inspiral Sensitivity

- Average sensitivity to optimally oriented 2 x 1.4 M_{sun} neutron star binary at r = 8:
  - » LLO 4k 176 kpc
  - » LHO 4k 36 kpc

- During S1 LIGO was sensitive to inspirals in
  - » Milky Way
  - » Magellanic Clouds



S1 Binary Neutron Star Search Results

- B. Abbott et. al. “Analysis of LIGO Data for Gravitational Waves from Binary Neutron Stars” gr-qc/0308069, submitted to PRD

- Searched total of 236 hours of LIGO data
    - » Used LHO 4k and LLO 4k single IFO and double coincident data

- No double coincident inspiral signals were found

- Loudest event found at r = 15.9 in LLO 4k
    - » Not an inspiral signal: due to a photodiode saturation in the interferometer

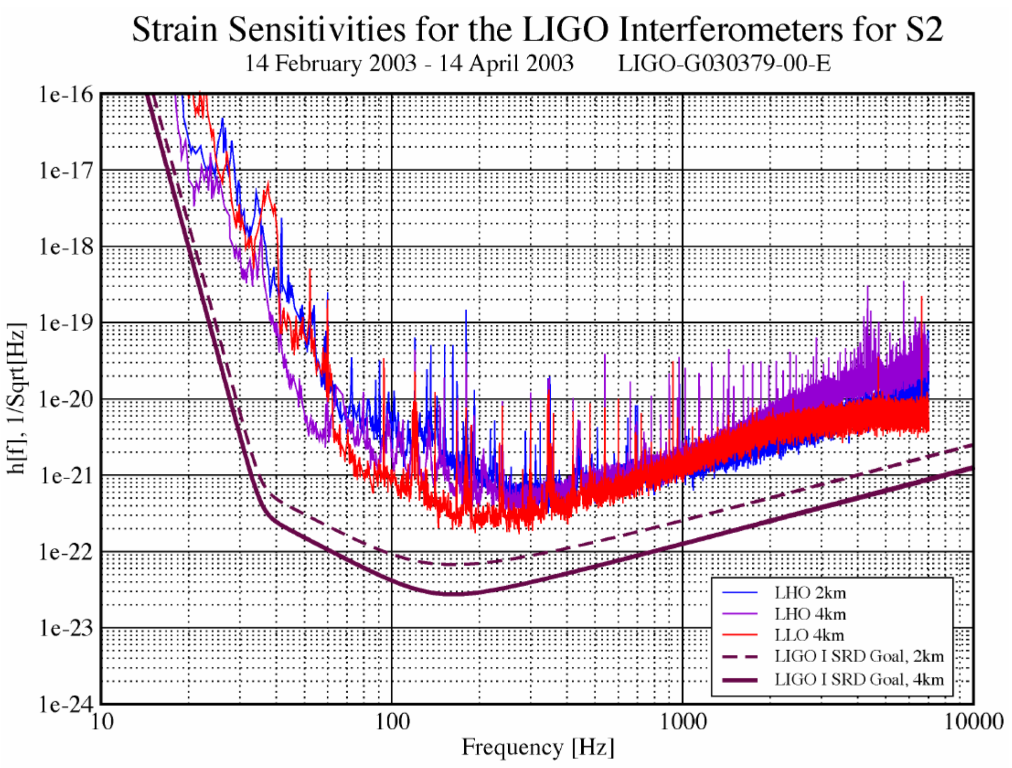
Astrophysical Rates:
$R < 1 \times 10^{-5}$
per year per MWEG

Upper Limit:
$R_{90\%} < 1.7 \times 10^{2}$
per year per MWEG

1999 40m Result:
$R_{90\%} < 4.4 \times 10^{3}$
per year per MWEG

S2 Inspiral Sensitivity

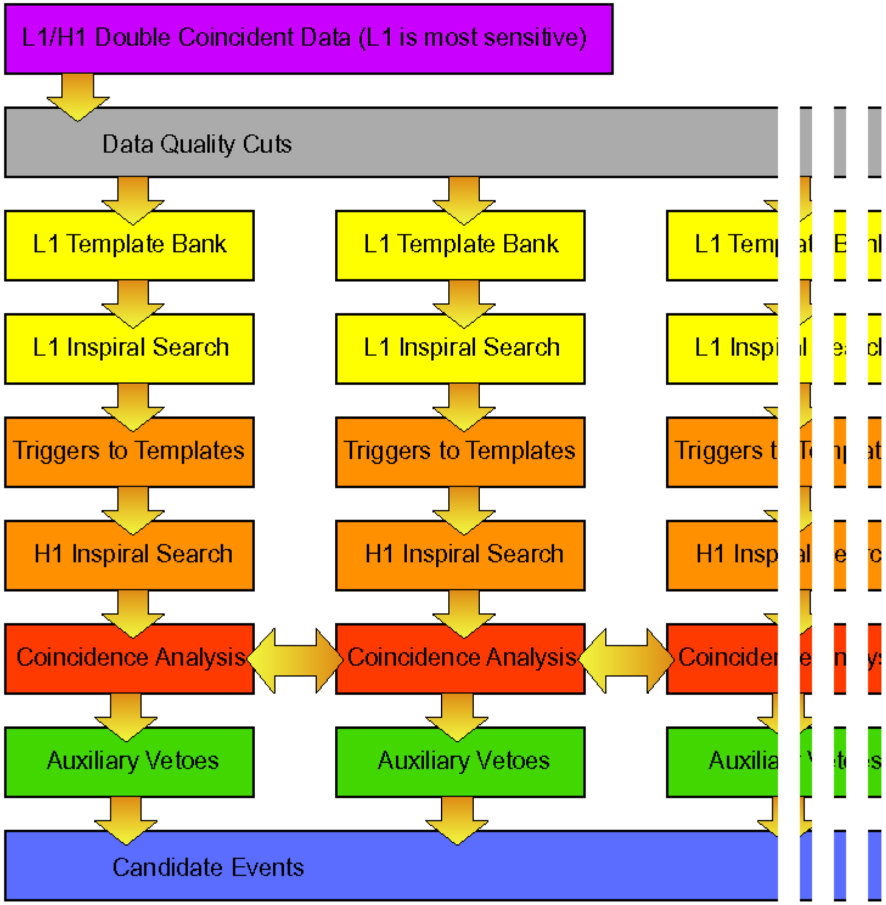
- Average sensitivity to optimally oriented 2 x 1.4 M_{sun} neutron star binary at r = 8 in playground data:
  - LLO 4k: 1.81 Mpc
  - LHO 4k: 0.90 Mpc
  - LHO 2k: 0.60 Mpc


Strain Sensitivities for the LIGO Interferometers for S2

14 February 2003 - 14 April 2003 LIGO-G030379-00-E

- Sensitive to inspirals in
  - Milky Way
  - Magellanic Clouds
  - Andromeda
  - M33, M32, M110

S2 Inspiral Search Pipeline



L1/H1 Double Coincident Data (L1 is most sensitive)

Data Quality Cuts

L1 Template Bank

L1 Inspiral Search

Triggers to Templates

H1 Inspiral Search

Coincidence Analysis

Auxiliary Vetoes

L1 Template Bank

L1 Inspiral Search

Triggers to Templates

H1 Inspiral Search

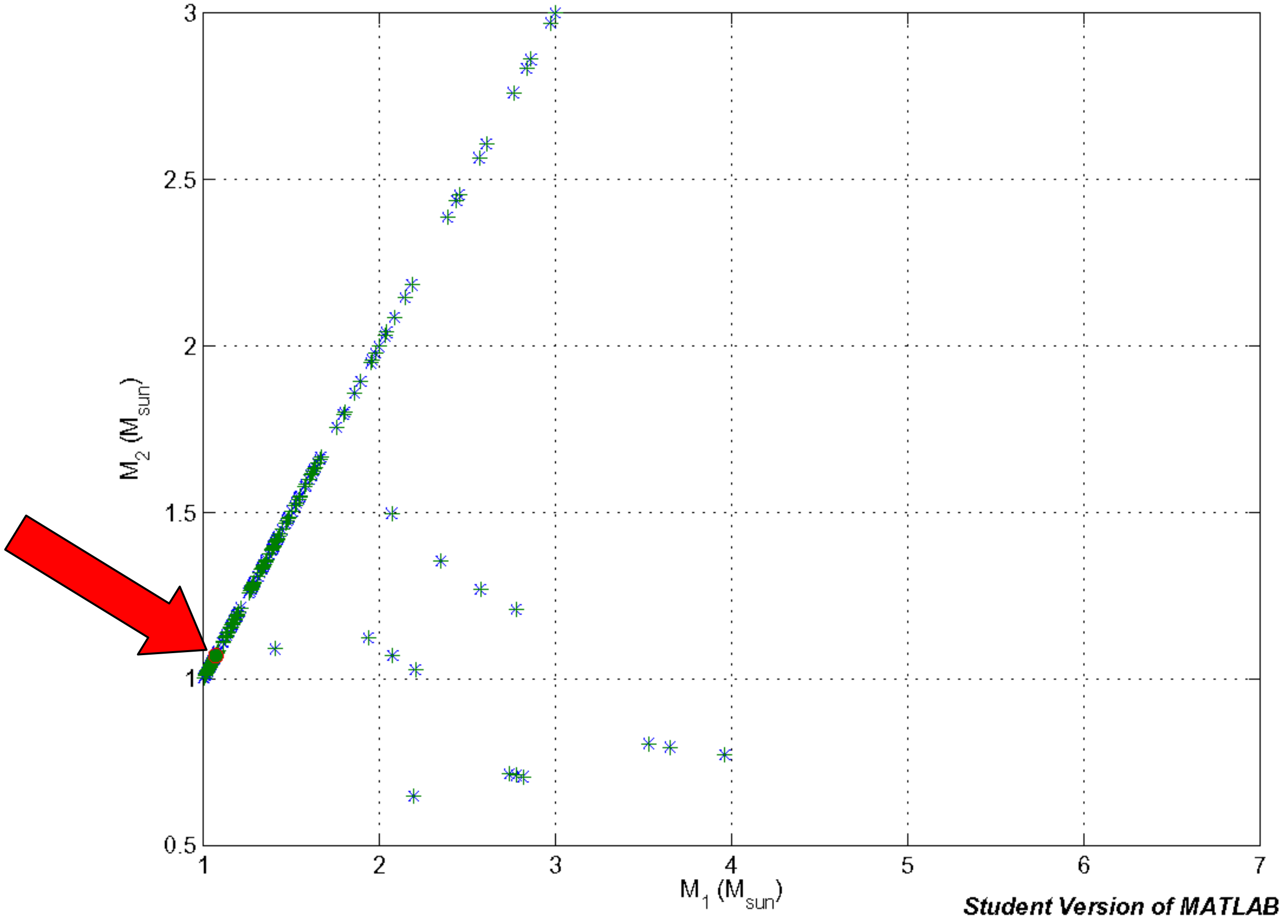
Coincidence Analysis

Auxiliary Vetoes

Candidate Events

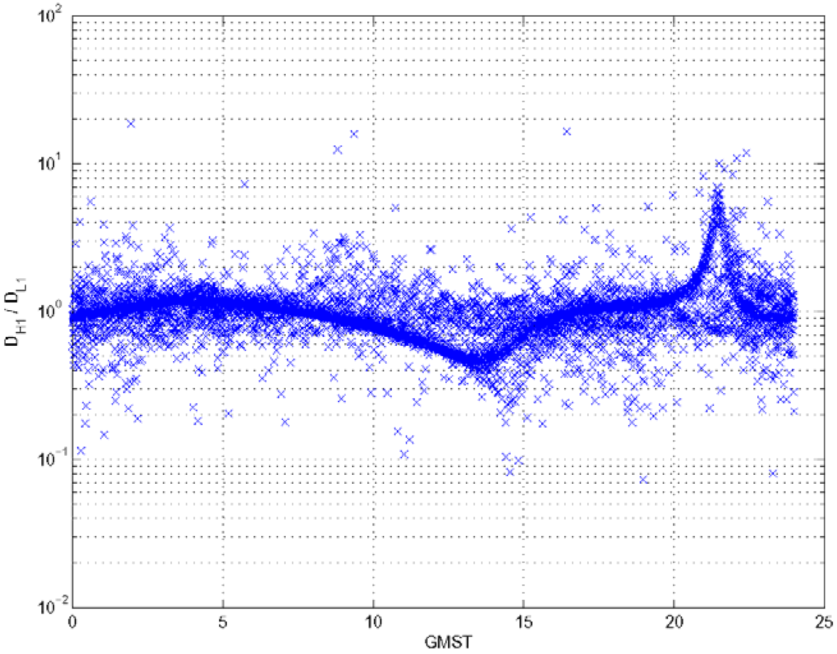
- Better data quality cuts
- Only use coincident interferometer data
  - » Double or triple
- Use a triggered search
- Coincidence is always demanded
- Better pipeline infrastructure
  - » GRID based codes

Triggered Inspiral Search



Trigger Coincidence Test

- Look for coincident triggers
  - Present in all interferometers
  - Coincident to within 11 ms between sites, 1 ms at the same site
  - Coincident in both mass parameters



- L and H detectors are not co-aligned, so ratio of effective distance varies
- Cannot use an amplitude cut on coincident signals
- Could use arrival time of signals
  - Obtain information about sky position from time delay between sites
  - Will not be used in S2

Detection of an Event

- Best result of search would be a detection!

- Time slide the data from one interferometer and look for coincidences between shifted and un-shifted interferometer
  - Slide by longer than a chirp length
  - Any coincidences must be due to background, not events

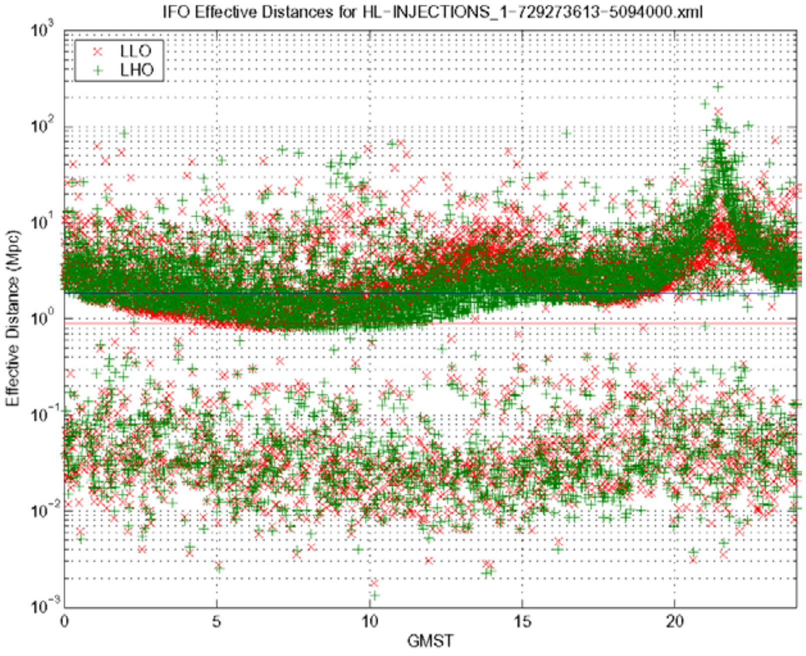
- Pick signal-to-noise threshold ,ρ_* , so only get a coincident trigger 1 in 100 times

- Look for coincidence in un-shifted data
  - Any coincident event would have 1% chance of being background

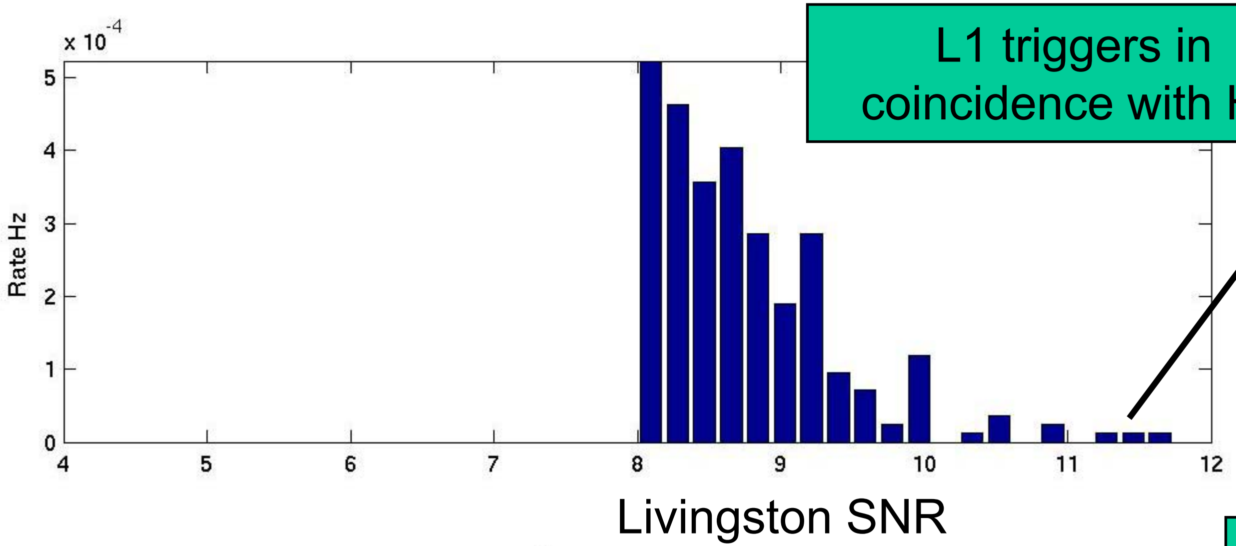
- Follow up candidate events in other interferometer channels (auxiliary interferometer, PEM, etc.)

Upper Limit on the Rate

- In absence of detection, construct an upper limit on event rate
- Simulate a population of binaries
- Inject signals from population into data from all three LIGO interferometers
- Determine efficiency, e, for detection of simulated signals at threshold ρ_*
- Rate is given by $(e(\rho_*) \ T)^{-1}$

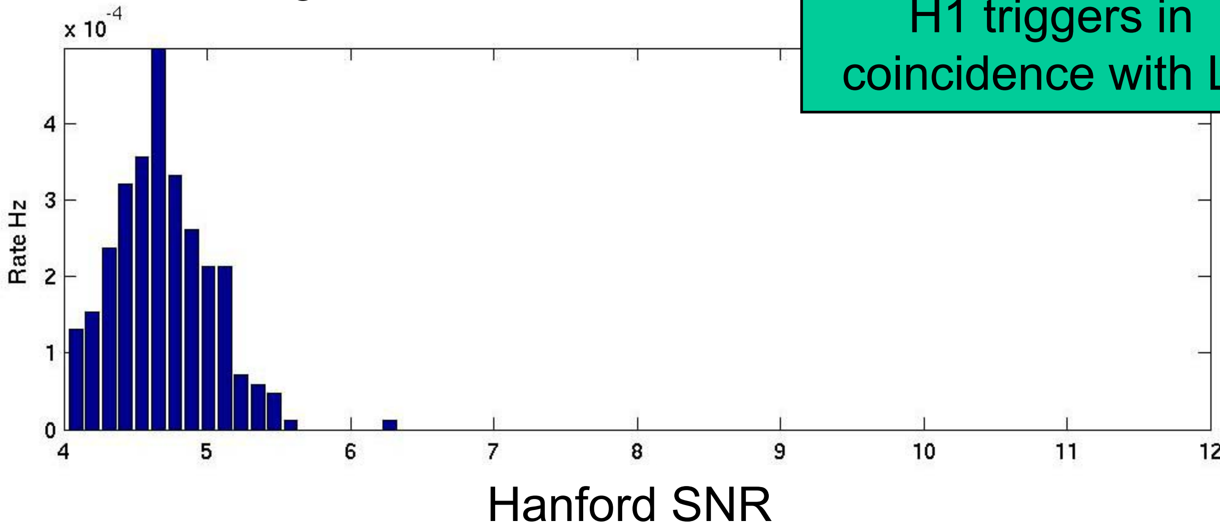


Distribution of Background Triggers



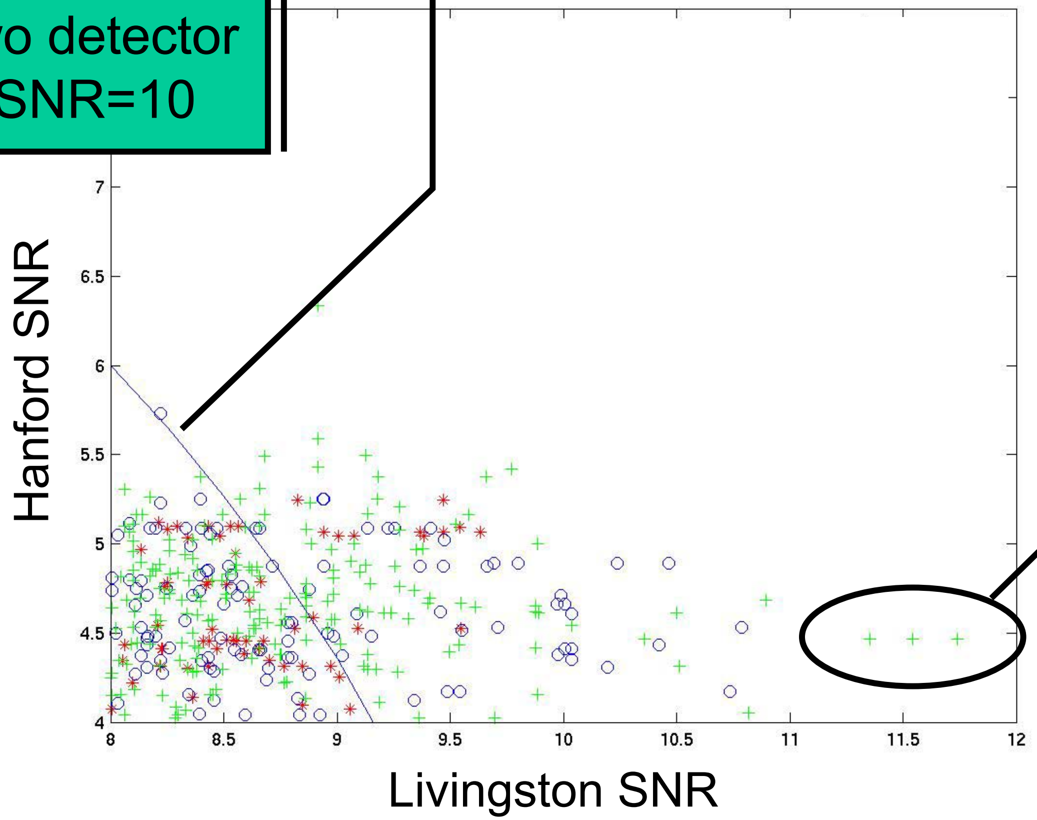
L1 triggers in coincidence with H1

Take a closer look at these candidates



H1 triggers in coincidence with L1

Time Lag analysis: SNR in each detector

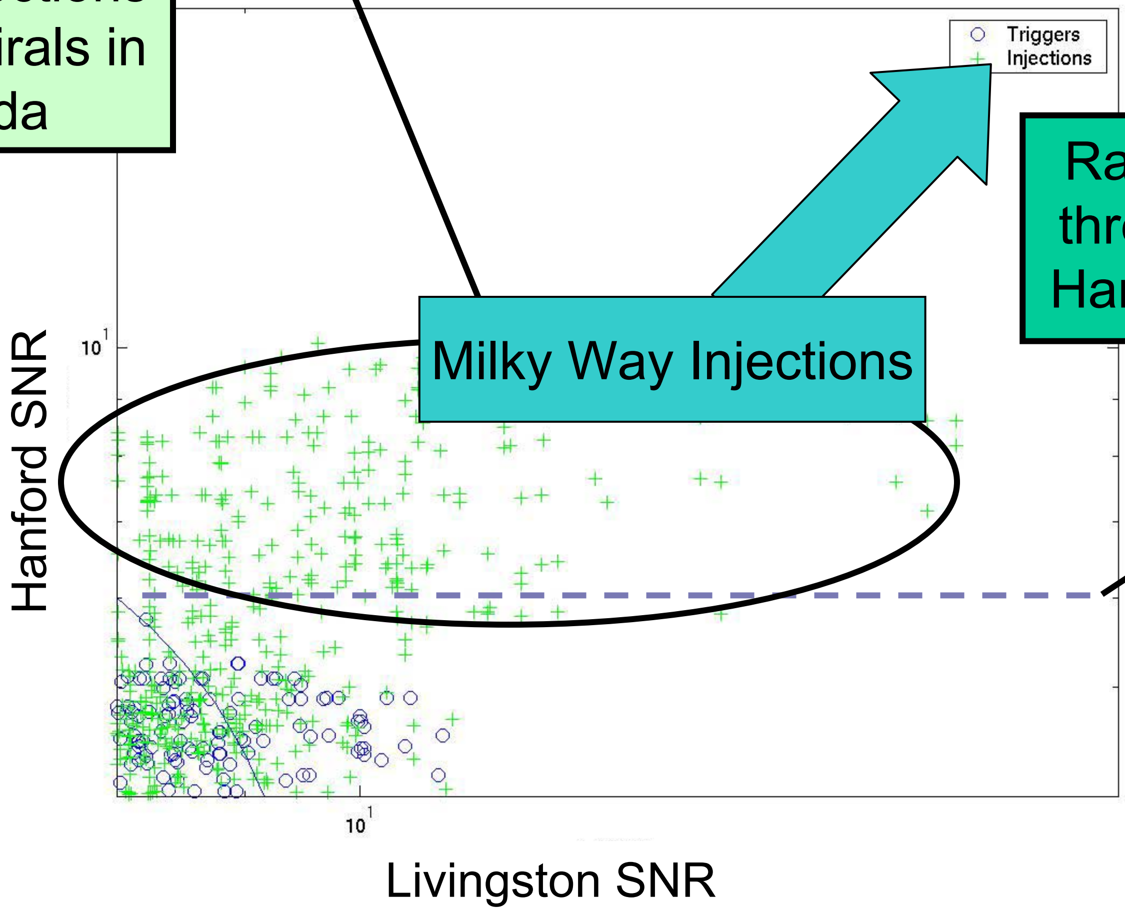


Coherent two detector SNR=10

Large SNR in Livingston coincident with low SNR at Hanford

Time-lag analysis: triggers versus injections

Simulated injections of binary inspirals in Andromeda

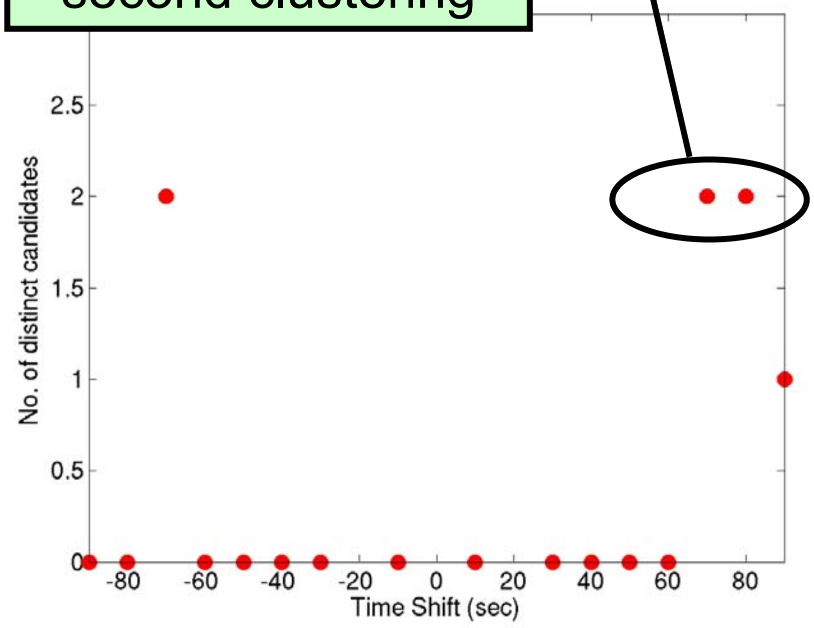


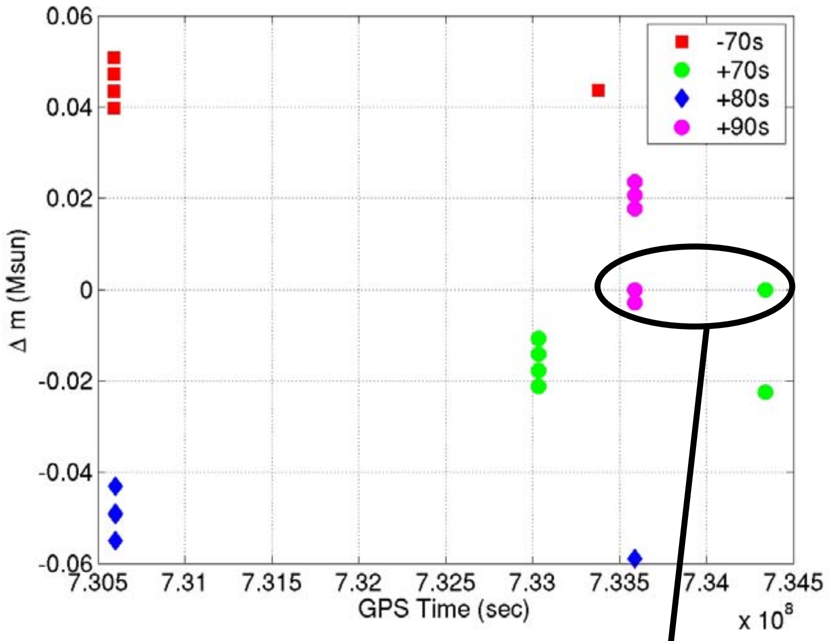
Milky Way Injections

Raise SNR threshold in Hanford to 6

Time-lag analysis: full bank & adjusted thresholds

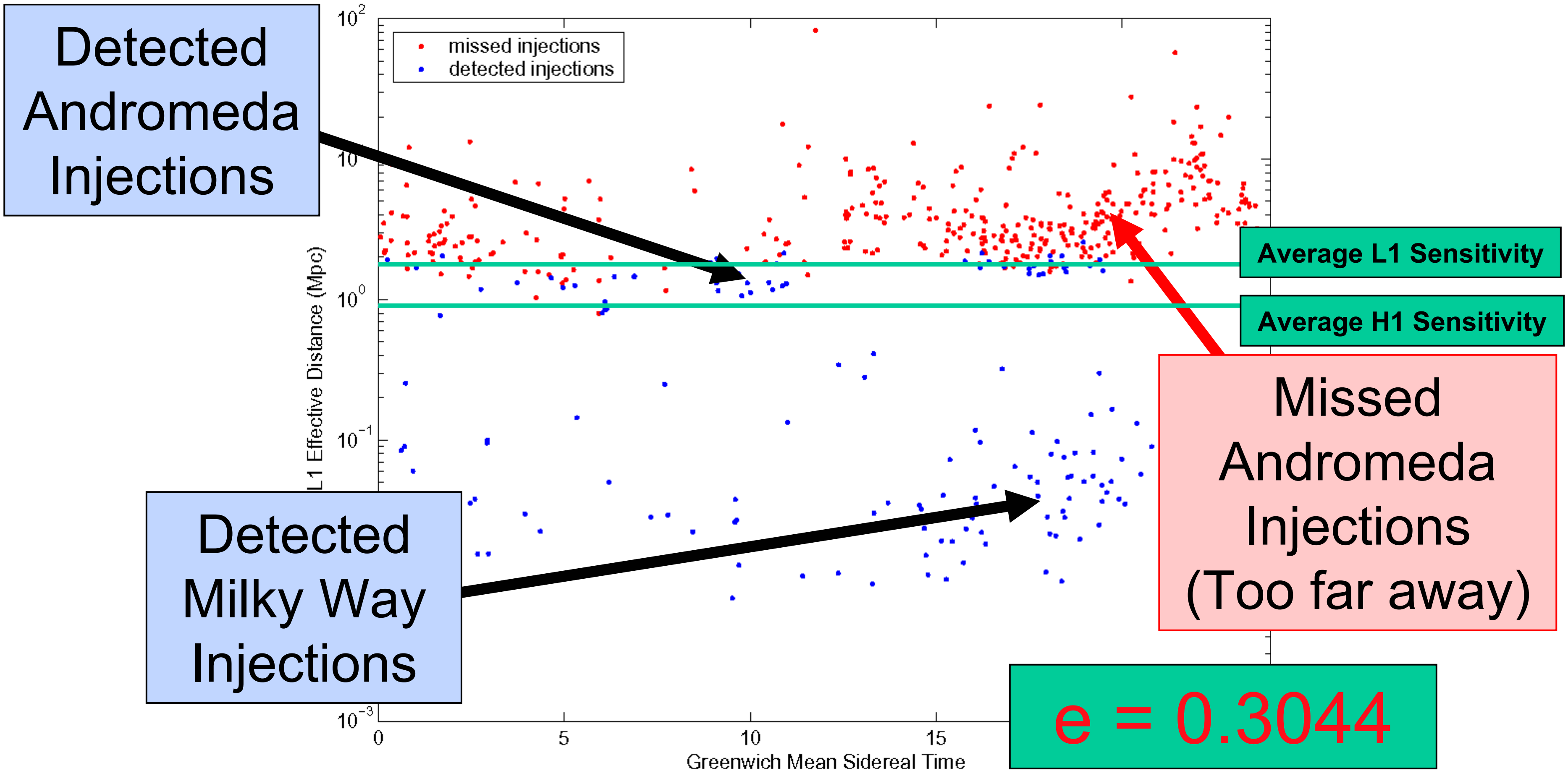
No. of distinct candidates after 1 second clustering





Two out of 18 time-lags have coincidence in templates of same mass

Playground Results: Pipeline Efficiency



Detected Andromeda Injections

Detected Milky Way Injections

Average L1 Sensitivity

Average H1 Sensitivity

Missed Andromeda Injections (Too far away)

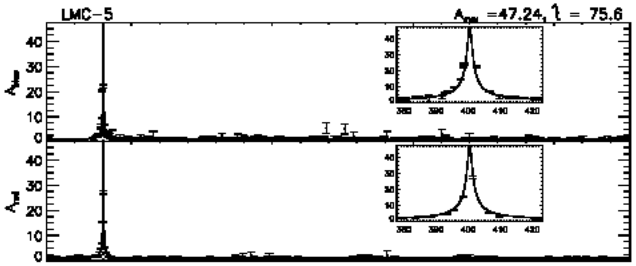
e = 0.3044

The MACHO Project and Microlensing

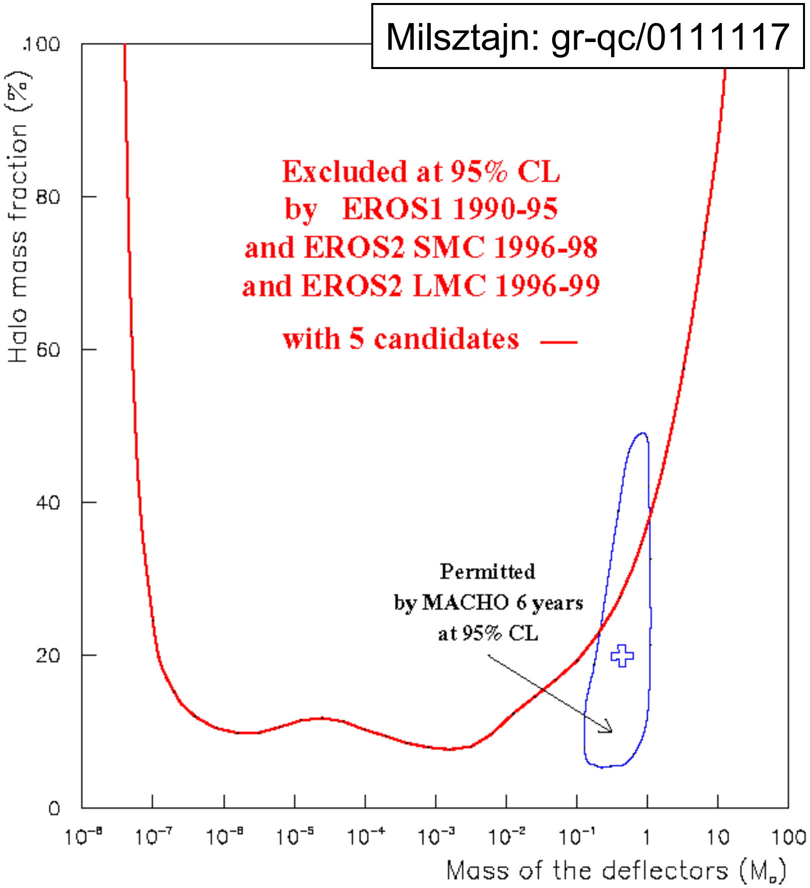
- Standard galactic halo has mass 4×10^{11} M_{sun} out to 50kpc

- MACHOs have been proposed as a candidate for the missing halo mass

- Microlensing experiments observe large star fields towards the LMC and SMC and look for gravitational microlensing events



- Latest results (2000):
  - 20% of halo, mass range 0.15 – 0.9 M_{sun}
  - Found one binary event in 13-17 events



Milsztajn: gr-qc/0111117

MACHO candidates

- Brown Dwarfs
  - Observation of halo population suggests contribution is small
- White Dwarfs
  - Possible candidate for halo matter
  - Observations have not ruled this out
- Primordial Black Holes (BHMACHOs)
  - ~ 1 M_{sun} formed during QCD epoch (Jedamzik 1997 PRD **55** 5871)
  - 0.1 – 1 M_{sun} formed due to multiple scalar fields during inflation (Yokoyama astro-ph/9509027)

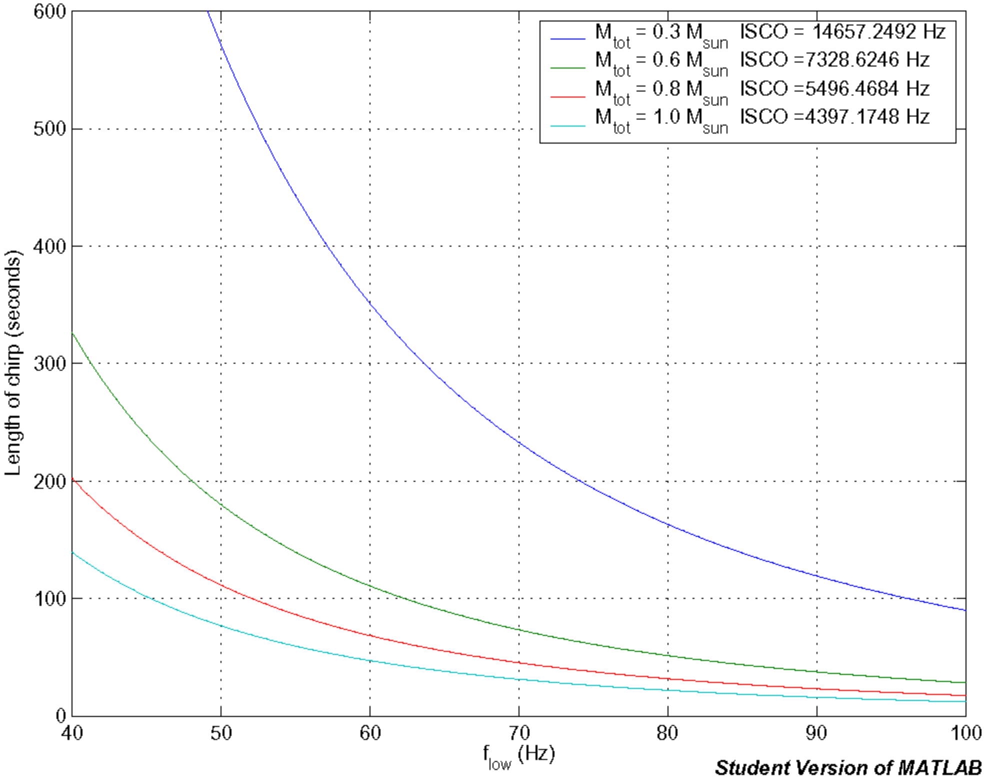
BHMACHOs and LIGO

- If a pair of PBHs are close enough, their energy density will be larger than the radiation energy density
  - Pair decouples from cosmic expansion to form a bound system
  - Expect some fraction of binaries to have coalescence time of the order of the age of the universe
  - Binary Black Hole MACHOs with $t_c \sim t_0 = 10^{10}$ yr
  - (Nakamura et. al. (1997) ApJ **487** L139)

- Expected values for BBHMACHOs
  - Fraction in 10 AU binaries 0.8 – 7% (consistent with 1 observed 10 AU binary in 13-17 events)
  - 5×10^{-2} per year per MWEG
  - c.f. 1×10^{-5} per year per MWEG for NS/NS (Phinney)
  - (Ioka et. al. astro-ph/9807018)

Detecting BBHMACHOs with LIGO

- Excellent candidate for Initial LIGO
  - » Waveforms well known using 2nd order post-Newtonian approximation
  - » Spend a long time in the LIGO sensitive band
  - » Signal well above noise level in instruments
- Long templates
  - » Need a lot of templates!



Conclusions

- Have a result for BNS rate from S1
  - $R_{90\%} < 1.7 \times 10^2$ per year per MWEG
  - Have gained valuable experience from S1 which is now being applied to S2

- S2 binary neutron star search is almost complete
  - Final results will be under internal LSC review in January

- Two other searches underway that are not yet mature:
  - Non-spinning binary black hole search
  - Search for binary black holes MACHOs in the galactic halo

- Search for spinning black hole binaries are currently being planned for S3 and beyond