LIGO-G040252-00-Z

Status of LIGO Searches for Binary Inspiral Gravitational Waves

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For the LIGO Scientific Collaboration
Inspiral Analysis Group

LIGO PAC Meeting

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Caltech

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(Formerly known as the Inspiral Upper Limit Group)

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Inspiral searches in progress

- **BNS inspiral search: LIGO S2 *coincidence* analysis**
  - – Neutron star binaries with component masses between 1 and 3 $M_?$
  - – Coincident analysis: “L1 and (H1 or H2)”
  - – Focus on detection rather than upper limit.
  - – Still not in astrophysically interesting regime
  - – Analysis and paper nearing completion
  - – Reporting on this today
- **BNS inspiral search: Joint analysis of LIGO S2 + TAMA DT8**
  - – analysis under intense development
- **BNS inspiral search: Search using LIGO+GEO S3 data**
  - – analysis under intense development
- **Binary Black Hole MACHO Search using LIGO S2 & S3 data**
  - – Binaries with component masses between 0.1 and 1 $M_?$
  - – analysis rather advanced, plan to finalize by August LSC meeting
- **Search for Non-Spinning Binary Black Hole Systems**
  - – analysis under intense development
- **Search for *Spinning* Binary Black Hole Systems**
  - – analysis in relatively early stages of development

Outline

- Inspiral group and analyses
- Gravitational waves from binary inspirals
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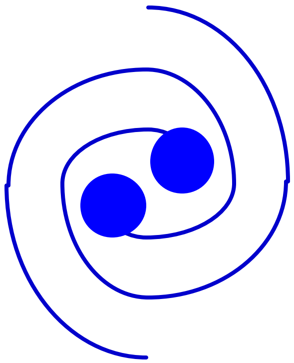
Binary Orbit Evolution



A binary system in a close orbit has a time-varying quadrupole moment
➔ emits gravitational waves

$$f_{\mathrm{GW}} = 2\, f_{\mathrm{orbit}}$$

Gravitational waves carry away energy and angular momentum

$$dE/dt \;\propto\; -f^{10/3}$$

➔ Frequency increases, orbit shrinks

$$df/dt \;\propto\; f^{11/3} \qquad dr/dt \;\propto\; -f^{2}$$

Objects spiral in until they finally coalesce

Additional relativistic effects kick in as (Gm/rc^2) grows away from zero

Notable Binary Neutron Star Systems

PSR B1913+16

Hulse and Taylor, 1974 *ApJ* ***195***, *L51*

Masses: 1.44 $M_?$, 1.39 $M_?$

Orbital decay exactly matches prediction from gravitational wave emission

Total lifetime ~365 Myr

PSR B1534+12

Wolszczan, 1991 *Nature 350, 688*

Masses: 1.339 $M_?$, 1.339 $M_?$

Total lifetime ~ 2.9 Gyr

PSR J0737-3039 **NEW!**

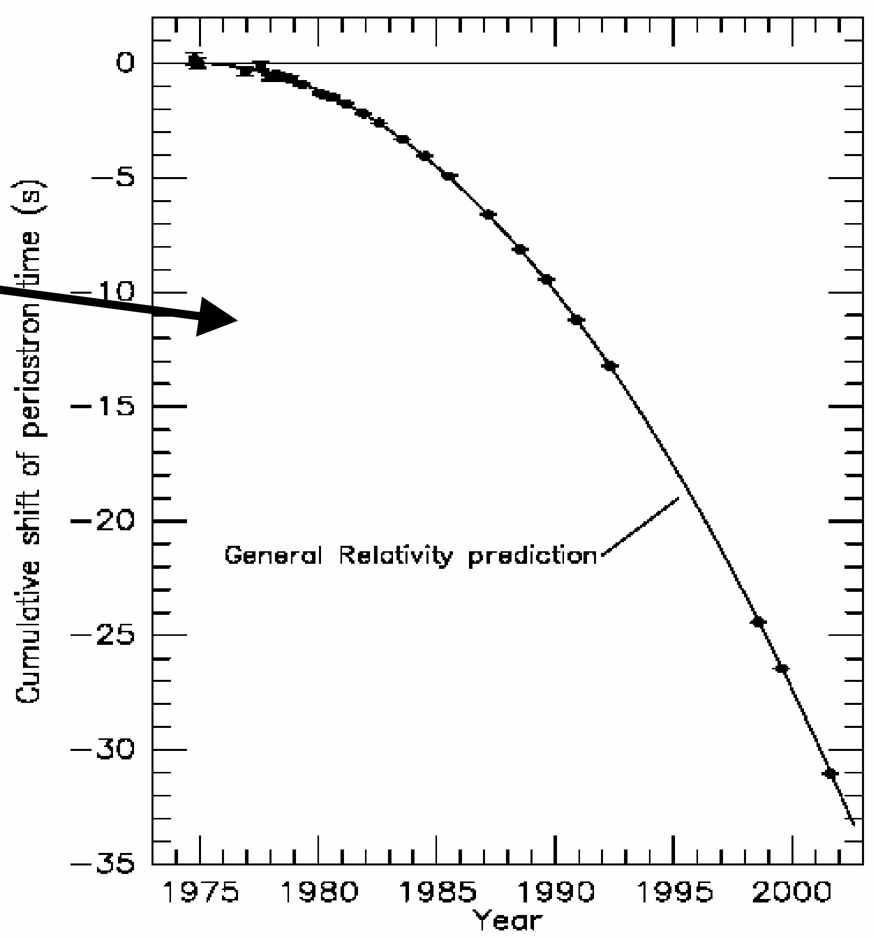
Burgay *et al.*, 2003 *Nature* ***426***, *531*

Orbital period = 2.4 hours

Will coalesce in ~85 Myr

(total lifetime ~185 Myr)

Will yield improved tests of G.R.



Weisberg & Taylor, astro-ph/0211217

Binary Neutron Star Inspiral Rate Estimates

Base on observed systems, or on population synthesis Monte Carlo

Kalogera *et al.*, 2004 *ApJ **601**, L179*

- Statistical analysis of the 3 known systems with “short” merger times
- Simulate population of these 3 types
- Account for survey selection effects

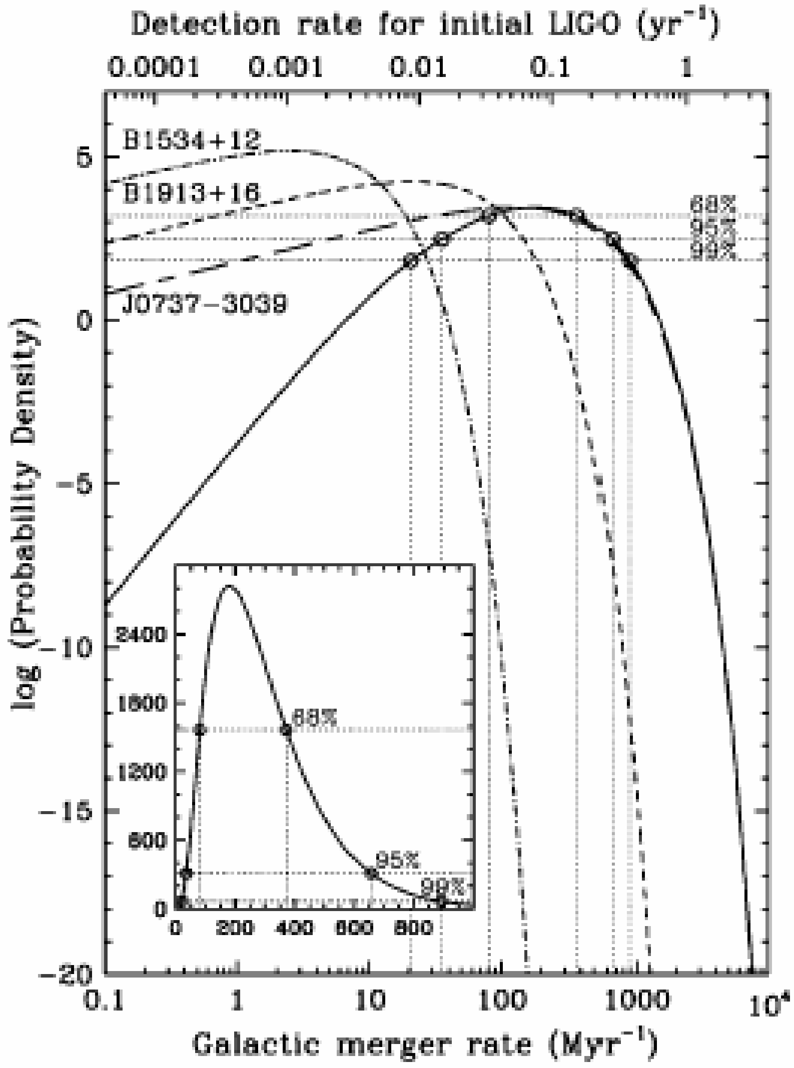
For reference population model:

(Bayesian 95% confidence)

- Milky Way rate: 180^{+477}_{-144} per Myr
- LIGO design: 0.015–0.275 per year
- Advanced LIGO: 80–1500 per year

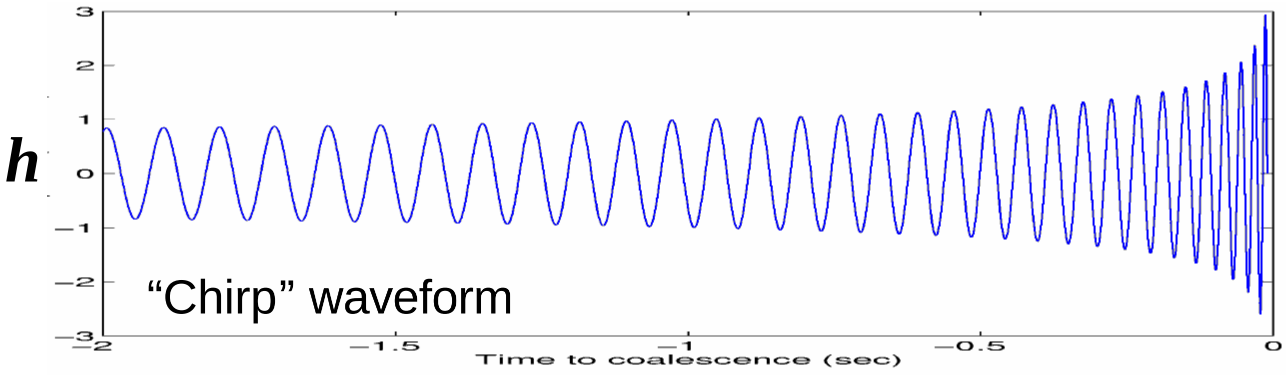
Binary black holes, BH-NS:

- No known systems; must Monte Carlo



Inspiral Gravitational Waves

For compact objects (neutron stars & black holes), inspiral accelerates up to the point of merger



"Chirp" waveform

In LIGO frequency band (40–2000 Hz) for a short time just before merging: anywhere from a few minutes to <<1 second, depending on mass

Waveform is known accurately for objects up to ~3 $M_?$

"Post-Newtonian expansion" in powers of (Gm/rc^2) is adequate

➔ Use matched filtering

Higher-mass systems are more complicated

Non-linear G.R. effects and spin can have a significant effect on waveform

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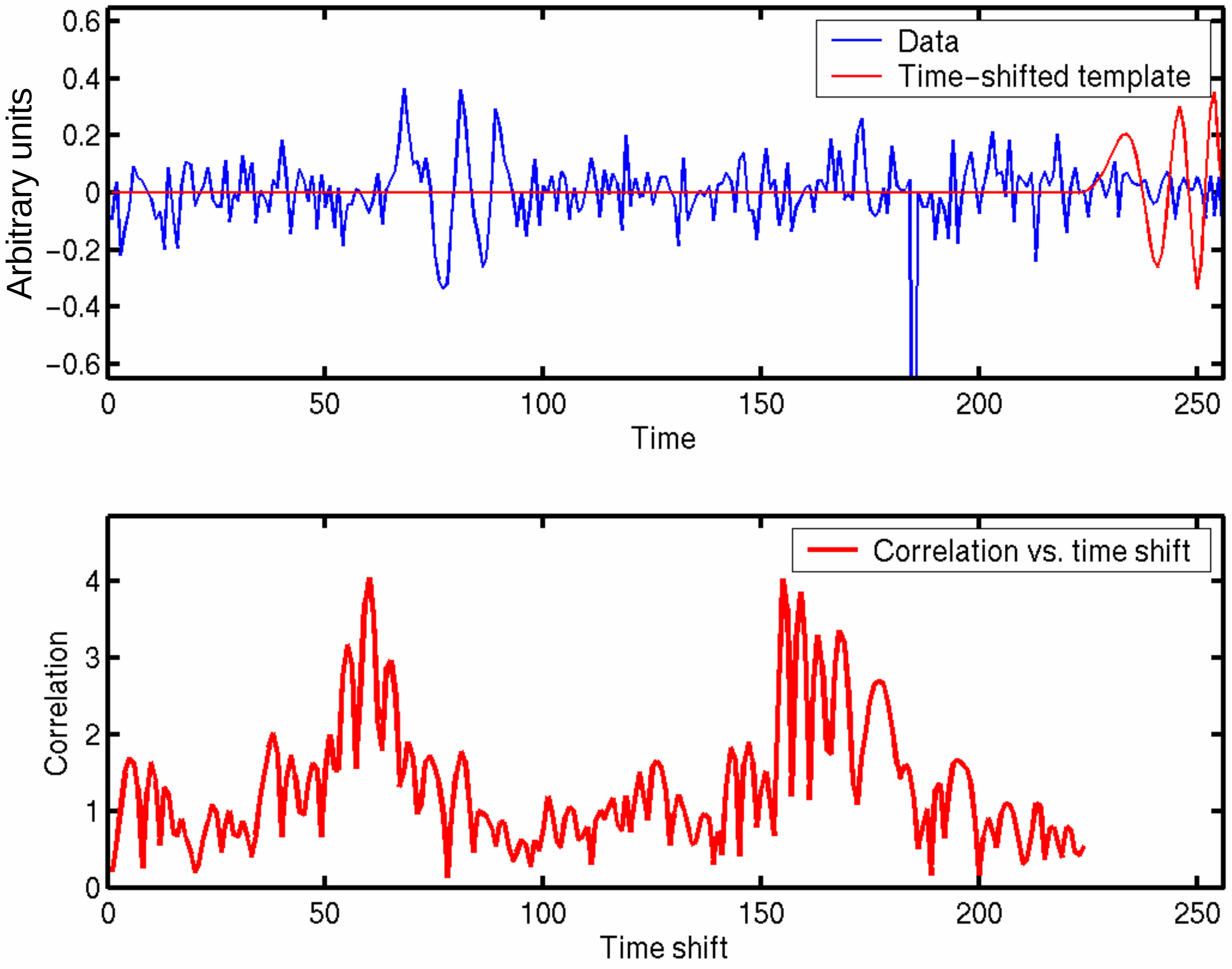
Illustration of Matched Filtering



Overview of Inspiral Search Technique (1)

Use Wiener optimal matched filtering in frequency domain

Template Data

$$z(t) = 4 \int_0^\infty \frac{\tilde{h}^*(f)\ \tilde{s}(f)}{S_n(f)}\ e^{2pift}\ df$$

Noise power spectral density

Look for maximum of $|z(t)|$ above some threshold ➔ “trigger”

Describe with time t, template params m_1, m_2 , SNR r, effective distance D

Check consistency of signal with expected waveform

Divide template into p frequency bands which contribute equally, on average

Calculate $c^2(t) = p \sum_{l=1}^{p} \| z_l(t) - z(t)/p \|^2$

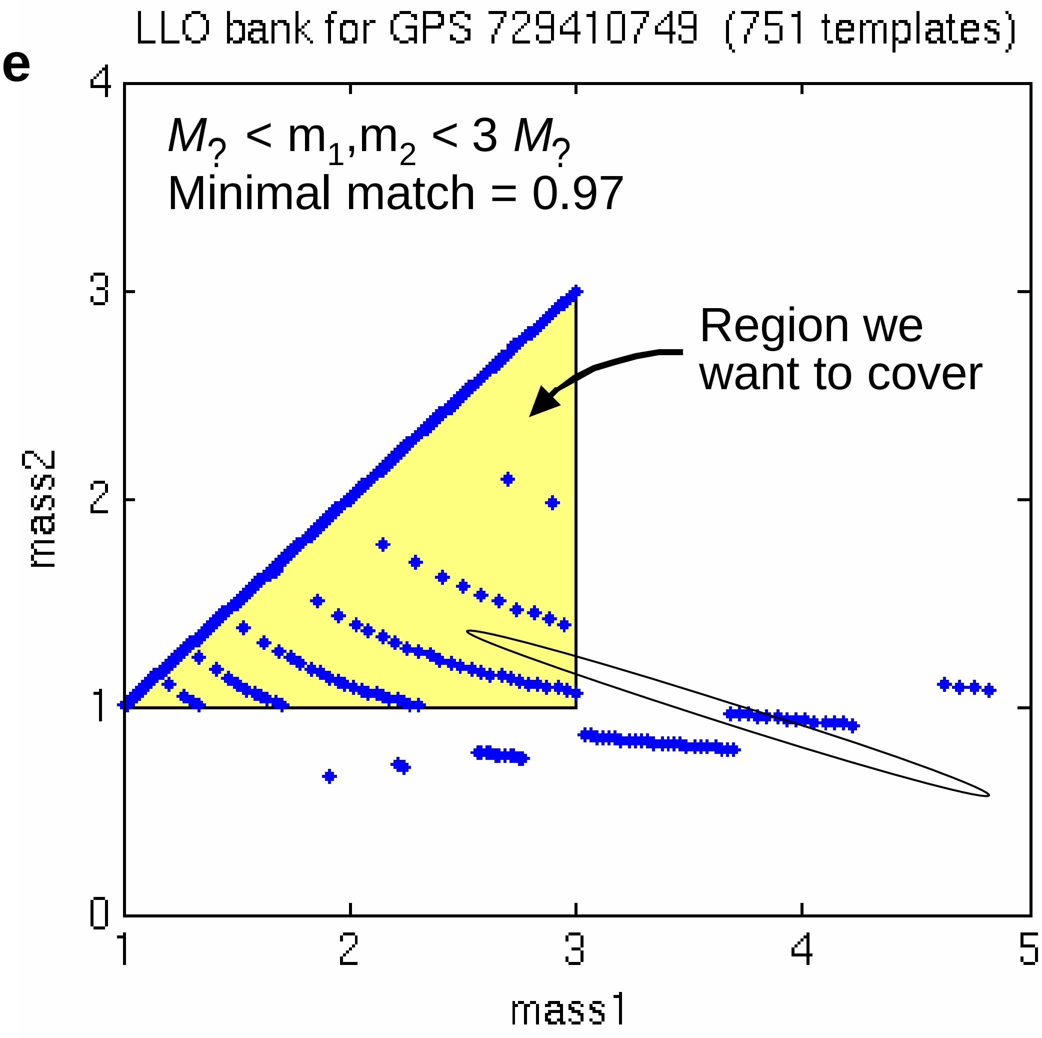
Other waveform consistency tests are being considered

Overview of Inspiral Search Technique (2)

Use a bank of templates to cover parameter space

Require a certain “minimal match” with all possible signals

Process data in parallel on many CPUs

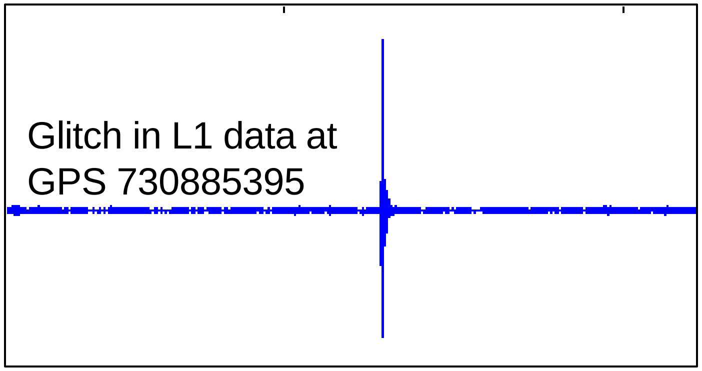


Overview of Inspiral Search Technique (3)

Process only good data, based on data quality checks

Validate search algorithm with simulated signals

Use auxiliary channels to veto environmental / instrumental glitches



Glitch in L1 data at GPS 730885395

Tune algorithm parameters and vetoes using "playground" data

- ~10% of data, excluded from final result

Require coincidence to make a detection

- Consistent time, signal parameters in multiple interferometers
- Follow up event candidates with coherent analysis

… or set an *upper limit* on event rate, using a population Monte Carlo to determine the efficiency of the analysis pipeline

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Previous Binary Neutron Star Inspiral Search Using S1 Data

Binaries with component masses between 1 and 3 $M_?$

2nd-order post-Newtonian waveforms are reliable; spin effects negligible

S1 visible range for 1.4+1.4 $M_?$ (optimally oriented, with SNR=8)**:**

L1 ~175 kpc ← Milky Way and Magellanic Clouds
H1 ~38 kpc ← Most of Milky Way
H2 ~35 kpc

Analyzed 236 hours of data when L1 and/or H1 was running

Used "maximum-SNR" statistical method to set an upper limit

Efficiency of search calculated by Monte Carlo

Simple spatial model; mass distribution from population synthesis model

Result (90% C.L.): Rate < 170 per year per MWEG

To appear in Phys. Rev. D; gr-qc/0308069

[Milky Way Equivalent Galaxy]

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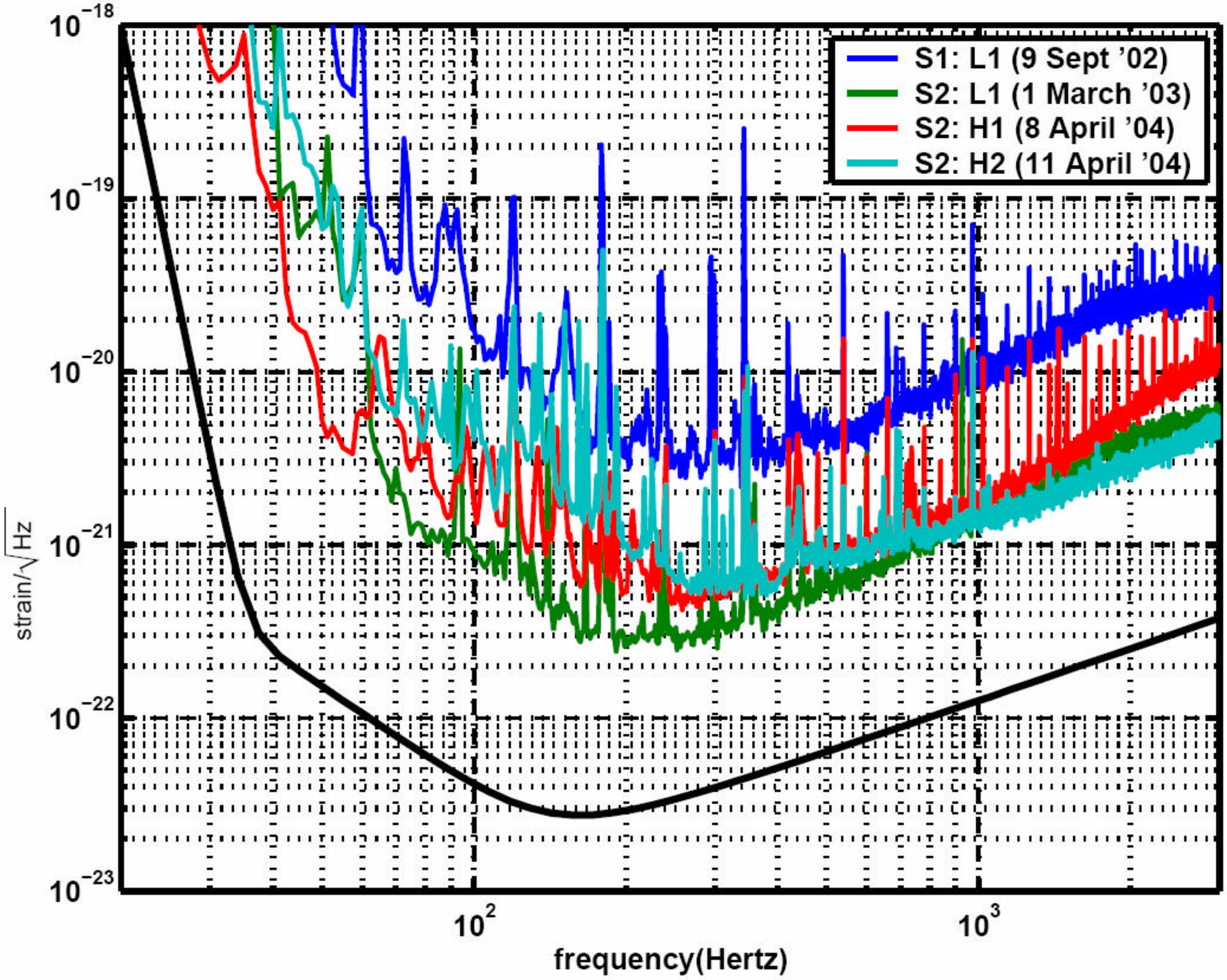
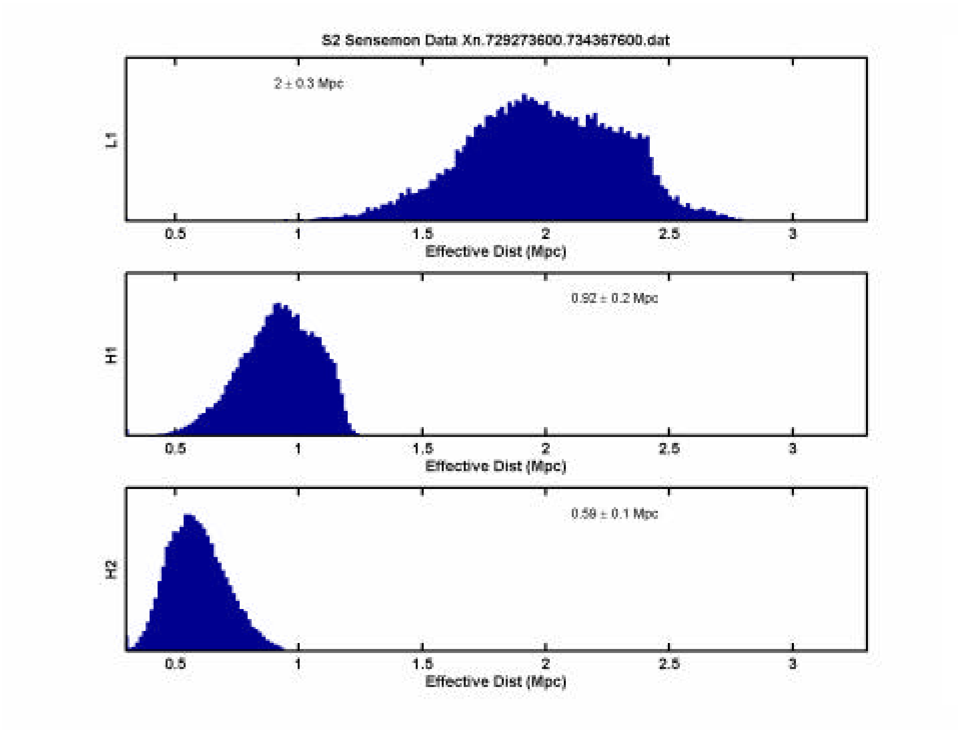
LIGO Strain sensitivity, S1 → S2



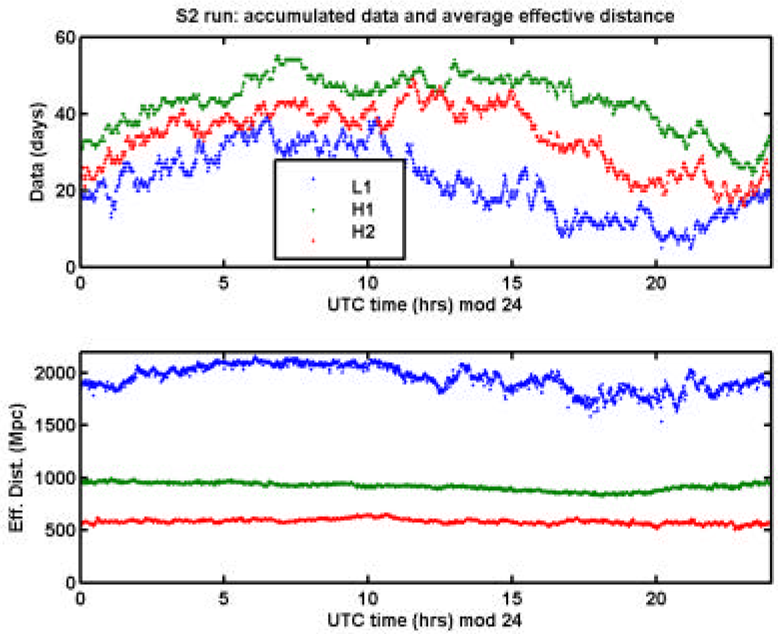
Detector “reach”: effective distance

SenseMon **online monitoring of noise spectrum and calibration lines produces an estimate of detector sensitivity to 1.4+1.4 $M_?$ binary inspirals (effective distance) every minute.**

Distribution of eff. distance



Eff. distance vs hour



S2 Reach for Inspiral Searches

S1 visible range for 1.4+1.4 $M_?$
(optimally oriented, with SNR=8) **:**

L1 ~175 kpc ← Milky Way and Magellanic Clouds
H1 ~38 kpc ← Most of Milky Way
H2 ~35 kpc

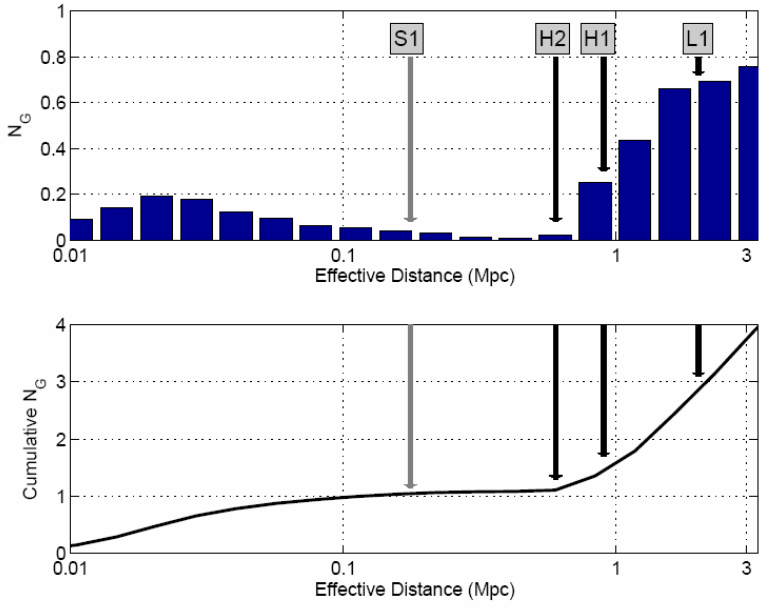
S2 visible range for 1.4+1.4 $M_?$:

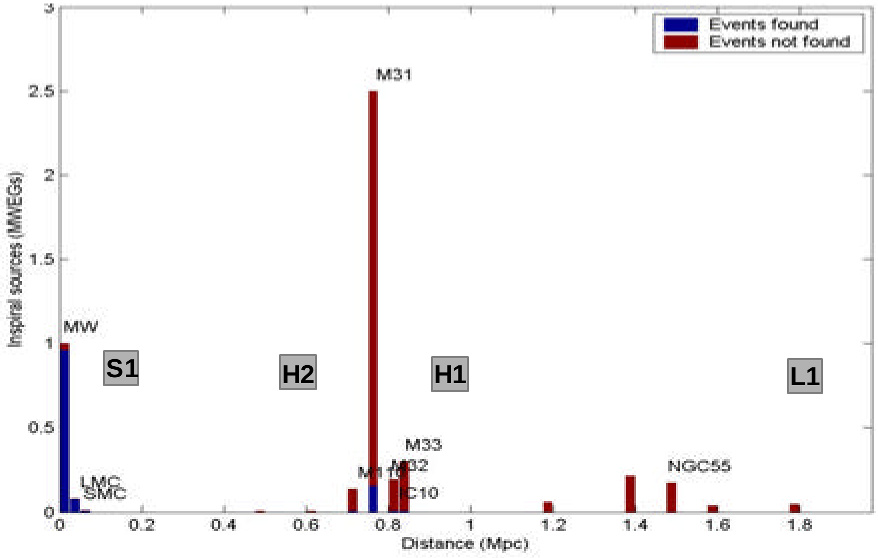
L1 ~1.8 Mpc ← Reaches M31, M32, M33, M110
H1 ~0.9 Mpc ← Barely reaches M31, etc.
H2 ~0.6 Mpc

- Significantly larger reach from S1 → S2

- essentially 100% sensitive to sources in MW, LMC, SMC, and now sensitive to Andromeda (M31/M33);

- BUT, there's a lot of empty space between MW and M31!





S2 coincident observation time for Inspiral Searches

S1: Analyzed 236 hours of data when L1 and/or H1 was running

S2: Over 1200 hours of "science mode" data

Various combinations of interferometers

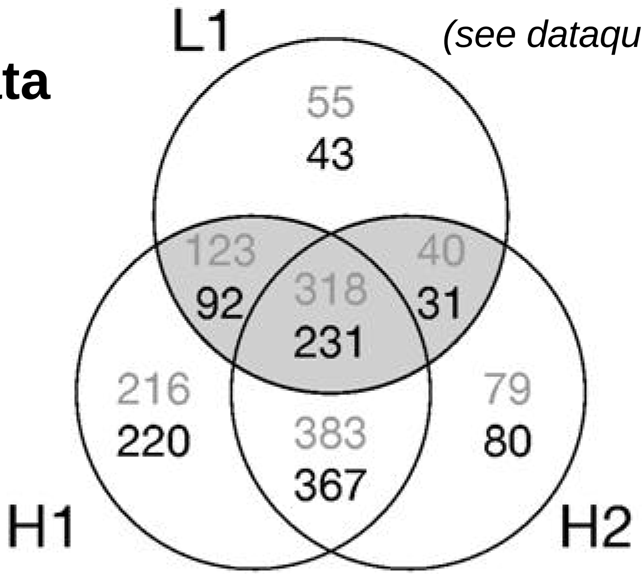
For this analysis, use only *coincident* data from both sites

"L1 and (H1 or H2)"

Avoid "H1 and H2 and not(L1)"
due to concerns about correlated
glitches from environmental disturbances

➔ Use data from which a believable detection could be made

➔ 481 hours total, 355 hours searchable; POB_I veto yields 345 hrs



Total data
Searchable
(see dataqual slide)

For the remainder, look for coincidences with TAMA (and GEO for S3) ➔ analysis in progress

Coincidence requirement: pros/cons

Require coincidence between LLO and LHO (H1 or H2 or both):

- suppress noise trigger rate
- permit lower threshold
- estimate remaining background from data, via time-lags
- greatly increase detection confidence

Down-sides:

- times when only a single detector/site is in science mode are excluded, reducing live time to 1/3 of total
- only as sensitive as the less-sensitive detector/site

Optimized for detection confidence, NOT optimized for best upper limit

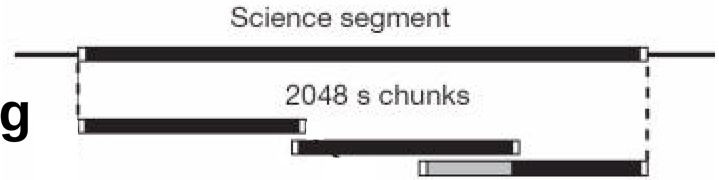
- Use the single-IFO data, in coincidences with TAMA (and GEO for S3)
  ➔ analysis in progress

Data Selection and Processing

These things reduce amount of data searched for inspirals

“Data quality” cuts – omit times with:

- Data files missing, or outside official S2 run epoch
- Calibration information missing or unreliable
- Servo control settings not at nominal values
- Timing problems in hardware
- High broadband noise in H1 interferometer for at least 3 minutes
- Photodiode saturation



Data processed in “chunks” 2048 sec long

- Ignore good-data segments shorter than 2048 sec
- Filter code does not search for triggers in first or last 64 sec of each chunk
  ➔ overlap chunks to analyze entire good-data segment except ends
- Noise power spectrum estimated from data in each chunk;
  interferometer response calibration averaged over chunk

“Playground” data processed together with other data

- Triggers separated afterward; only non-playground data used for final result

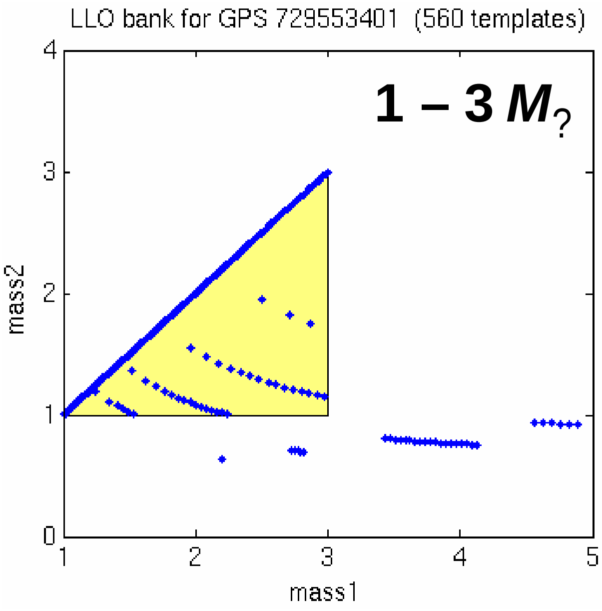
Template Bank Generation

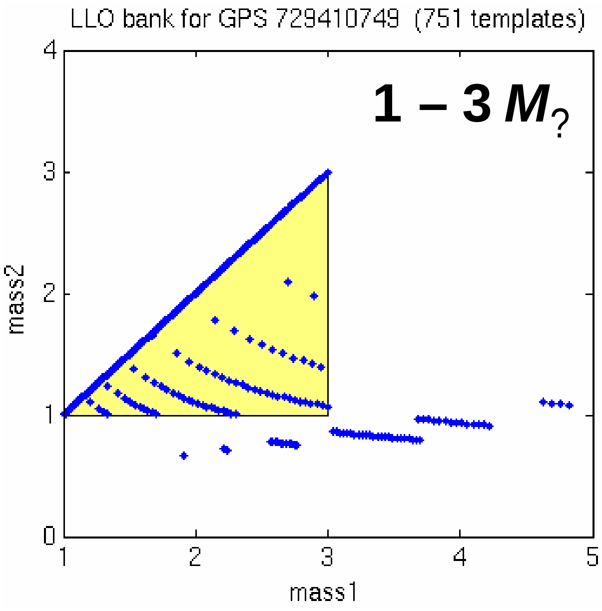
Template bank generated for each chunk of L1 data

Use noise power spectrum estimated from that chunk

Low-frequency cutoff for search: 100 Hz

Banks with fewest and most templates:





Same template bank used for all three interferometers

L1 bank used because it is most sensitive interferometer.
Others: SNR loss < 3%

Chi-Squared Test

Tuned using playground data with and without simulated signals

Chose p=15 frequency bands

$$c^{2}(t) \;=\; p\sum_{l=1}^{p}\left\| z_l(t) - z(t)/p \right\|^{2}$$

Allow large signals to have higher c^2 values, due to mismatch with discrete template bank

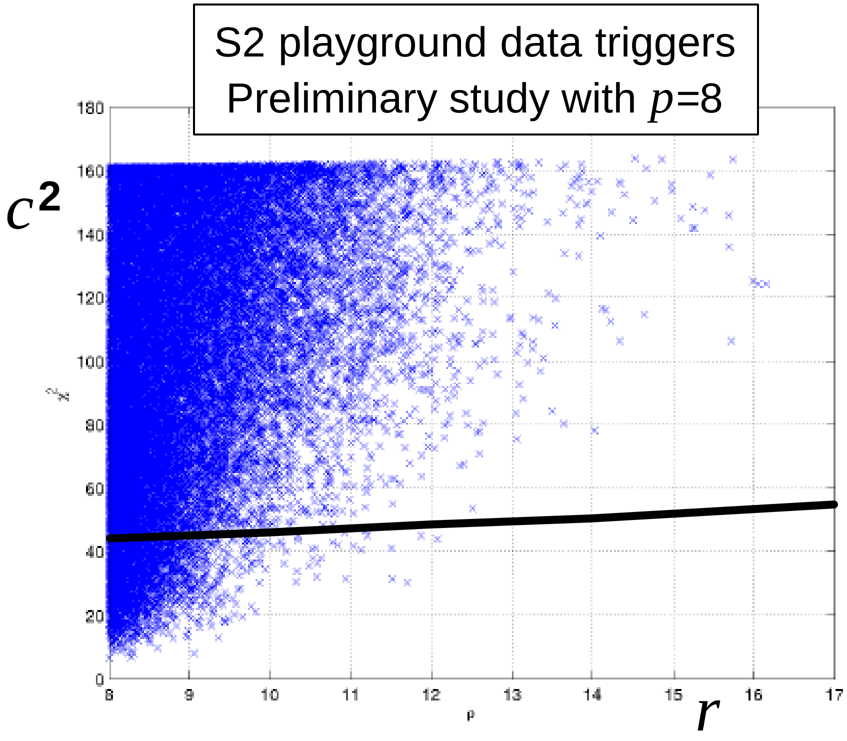
Keep cut rather loose,
to avoid losing real signals

L1:

$$c^{2} \;\le\; 5\;\left(p + 0.01\, r^{2}\right)$$

H1, H2:

$$c^{2} \le 12.5\left(p + 0.01\, r^{2}\right)$$



S2 playground data triggers
Preliminary study with p=8

Auxiliary-Channel Vetoes

There are occasional “glitches” in the gravitational-wave channel

- Transients larger than would be expected from Gaussian stationary noise
- Chi-squared test eliminates many, but not all

Checked for corresponding glitches in other channels

- Environmental channels (accelerometers, etc.)
- Auxiliary interferometer channels

Found a fairly effective veto for L1

- “L1:LSC-POB_I” with a 70 Hz high-pass filter
- Eliminates 13% of inspiral triggers with SNR>8 (and more at higher SNR)
- Deadtime = 3.0%
- Used hardware injections to verify that a gravitational wave would not appear in this channel

No effective veto found for H1 or H2

Coincidence Requirements

An “event candidate” is required to be detected by same template in L1 and in either H1 or H2

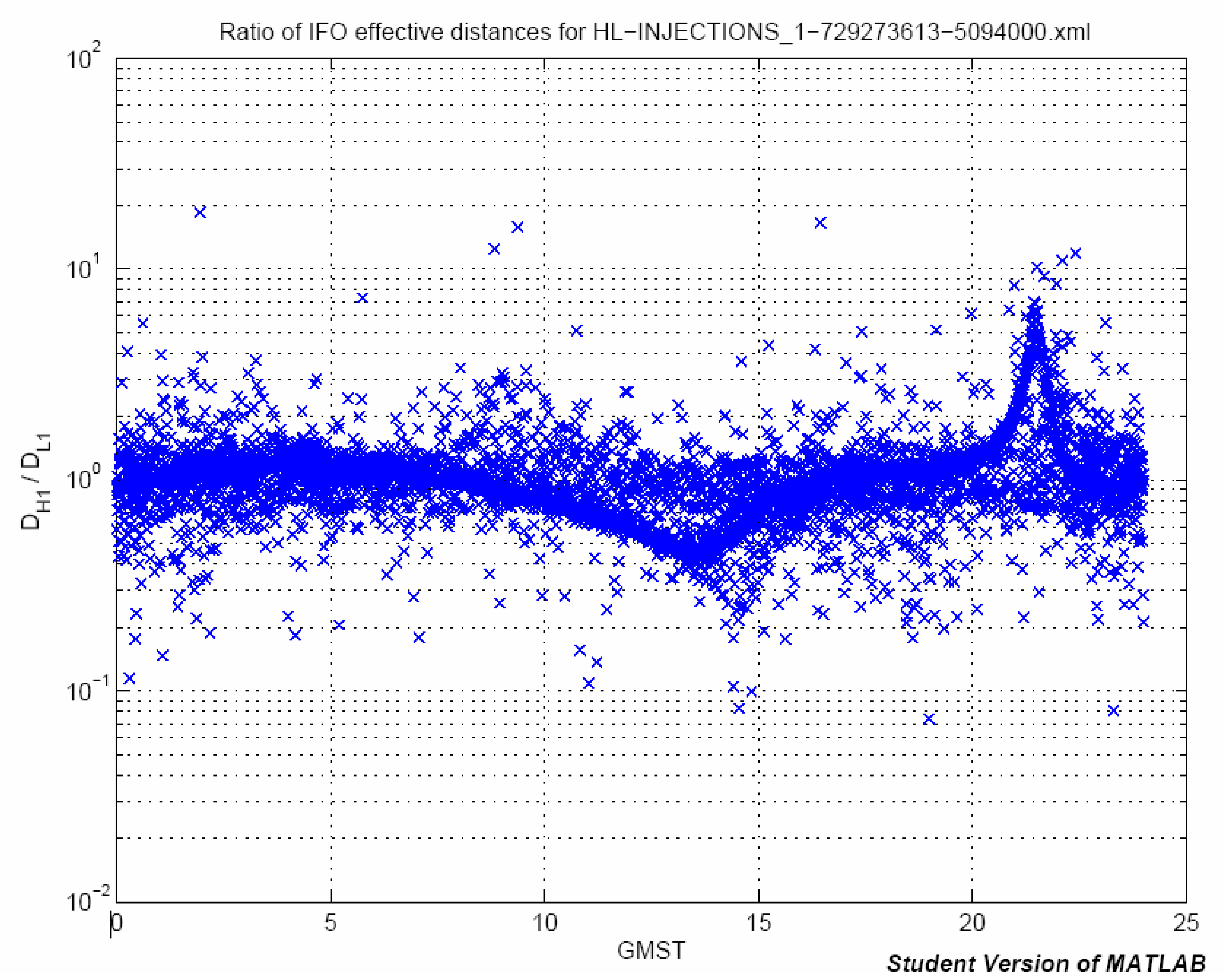
- If all three operating, then must be detected in all three *unless* too weak to be detected in H2
  - If on the edge of detectability in H2, it is searched for but not required

Consistency criteria depend on the detector pair

	H1-H2	**L1-H1 / L1-H2**
Time:	$\Delta t < 1$ ms	$\Delta t < 11$ ms
Template:	$\Delta m_1, \Delta m_2 = 0$	$\Delta m_1, \Delta m_2 = 0$
Effective distance:	$\frac{\lvert D_{H1} - D_{H2} \rvert}{D_{H1}} < 0.5 + \frac{2}{r_{H1}}$	No requirement, since LHO and LLO are not exactly co-aligned

Ratio of effective distances (H1/L1) vs sidereal time

At certain sidereal times, Galactic sources fall into null response of one detector site but not the other, yielding very different effective distances.



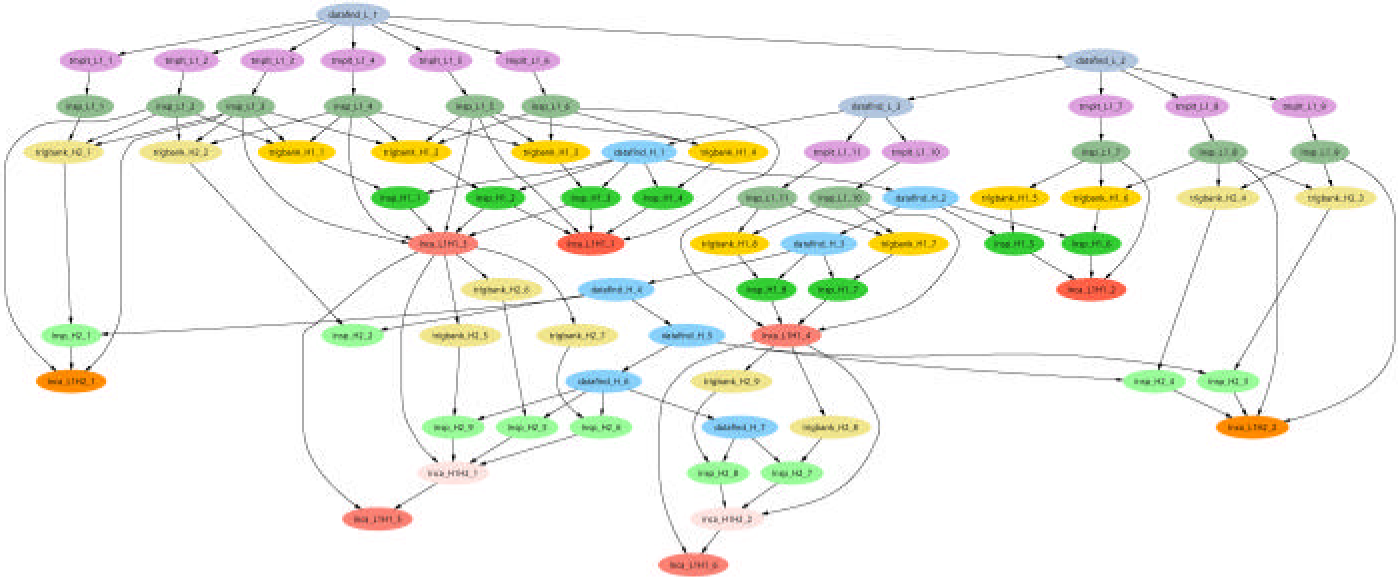
Fully automated analysis pipeline

Analysis pipeline as automated as possible, to avoid bias

- **template matched filtering of single-detector data**
- **multi-detector coincidence, including time lags (signal and bckgnd)**
- **efficiency determination using software injections**

Dependencies of processing steps expressed as a Directed Acyclic Graph (DAG) generated from a parameter file

Analysis runs on a Condor cluster using DAGMan meta-scheduler

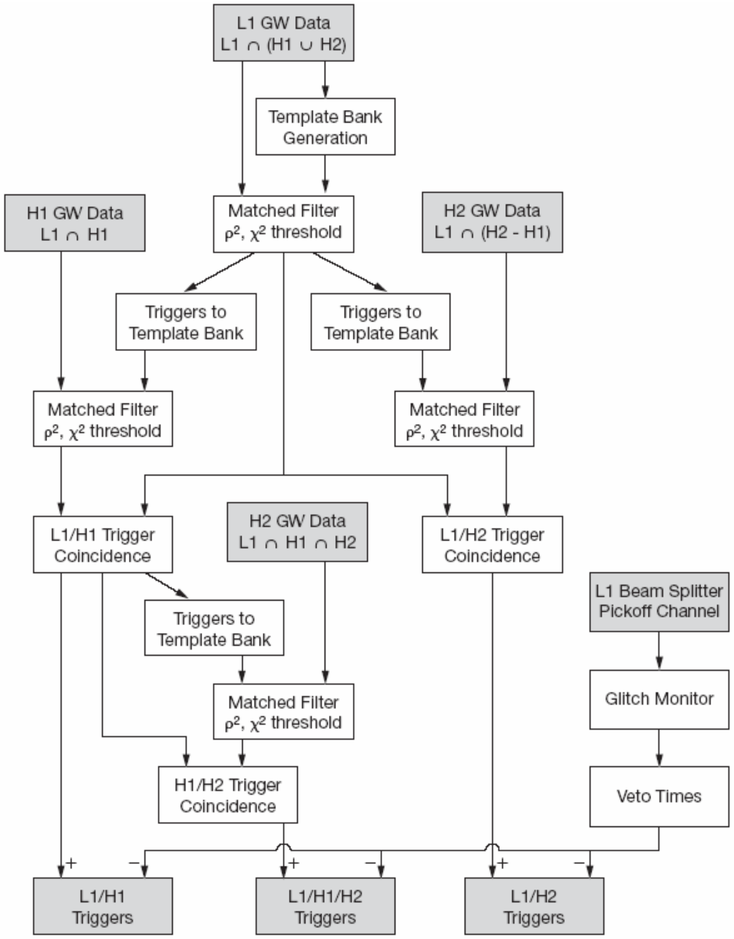


Analysis Pipeline

Pipeline is designed to avoid unnecessary processing

- Only process chunks which belong to "L1 and (H1 or H2)" data set
- For each L1 chunk, generate template bank
- Filter L1 data to produce triggers
- Filter H1 / H2 chunks using **only** those templates which yielded at least one L1 trigger in the corresponding L1 chunk (saves heaps of cpu time!)
- Check for coincident triggers
- In 3-interferometer data, filter H2 using templates which yielded L1-H1 coinc

Final output from pipeline is a list of event candidates



Background Estimation

Data filtered with a low SNR threshold = 6

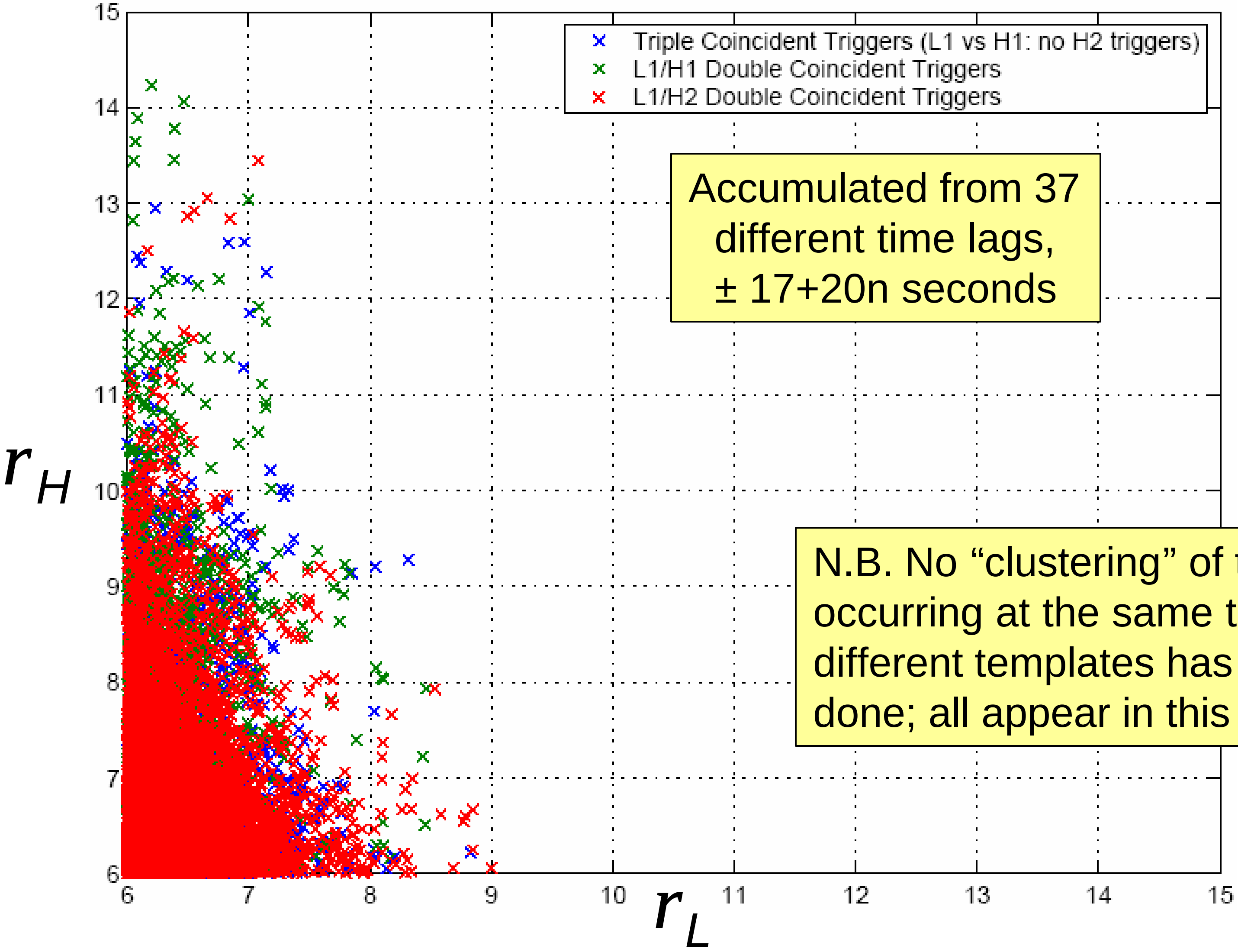
- Many triggers are found in each interferometer with SNR ˜ 6 – 8
- ➔ Expect some accidental coincidences

Estimate background by time-sliding triggers

- Introduce artificial lag in H1/H2 trigger times relative to L1
  - Keep H1 and H2 together, in case of any local correlations
- Use many different lags (+ or –) between 17 sec and a few minutes
- Collect event candidates passing analysis pipeline
  - Only have to re-do coincidence tests, not matched filtering (DAG was generated to support time lags of up to several minutes)

Did this before looking at true (un-slid) coincidences

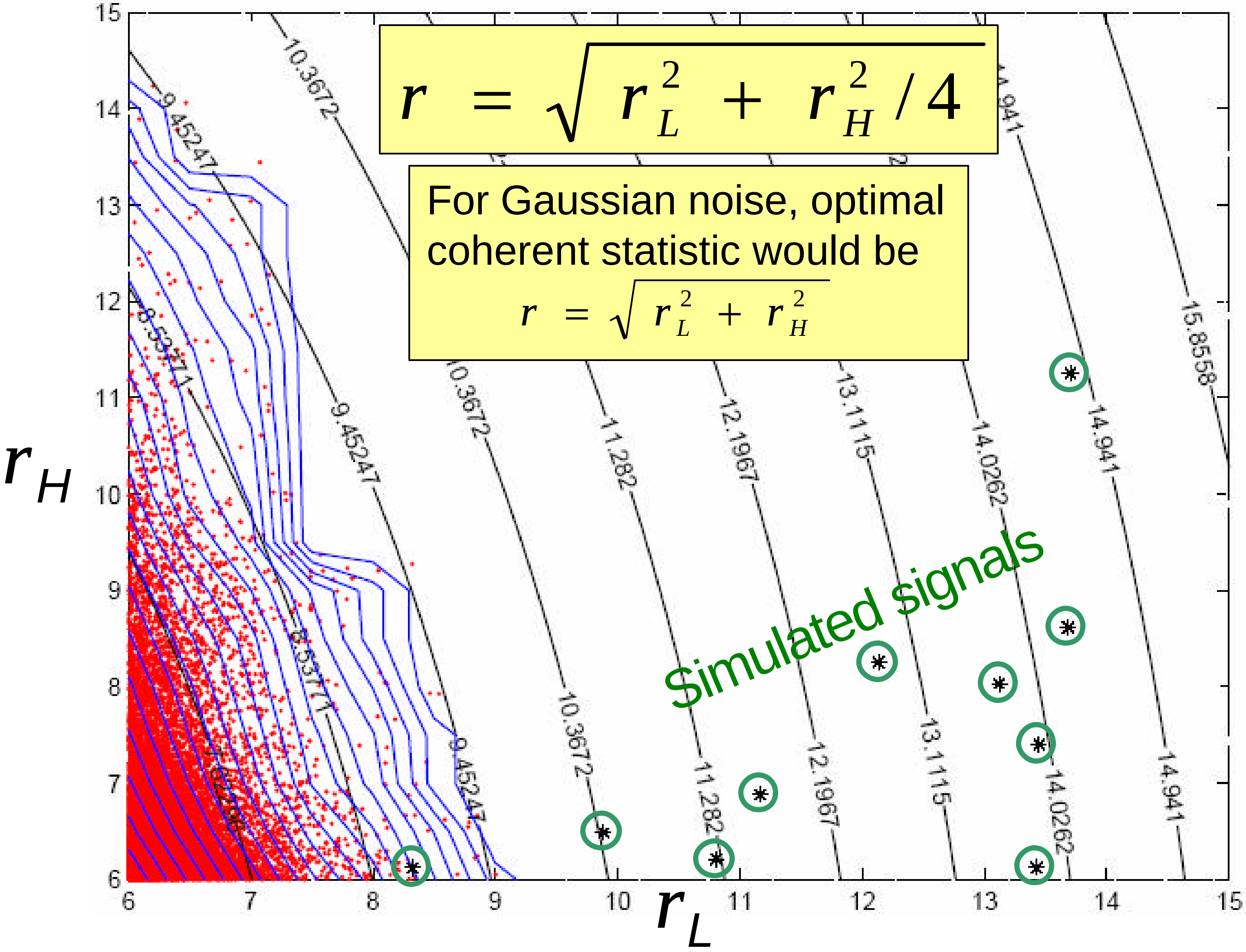
Background Event Candidates



Accumulated from 37 different time lags, ± 17+20n seconds

N.B. No “clustering” of triggers occurring at the same time in different templates has been done; all appear in this plot

Empirical Figure-of-Merit Statistic

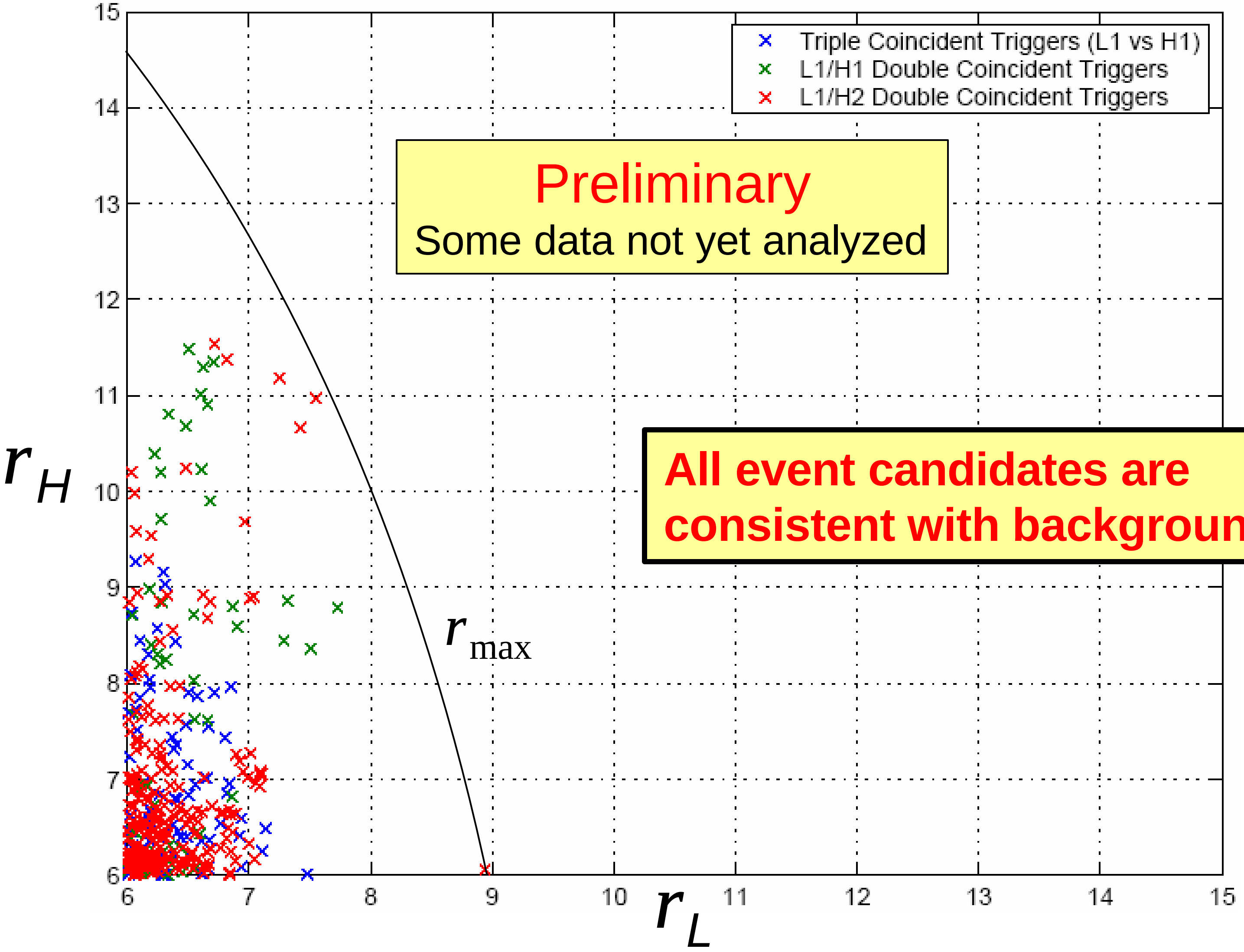


$$r = \sqrt{r_L^2 + r_H^2/4}$$

For Gaussian noise, optimal coherent statistic would be

$$r = \sqrt{r_L^2 + r_H^2}$$

Event Candidates Observed



Preliminary

Some data not yet analyzed

All event candidates are consistent with background

Background due to accidental coincidences

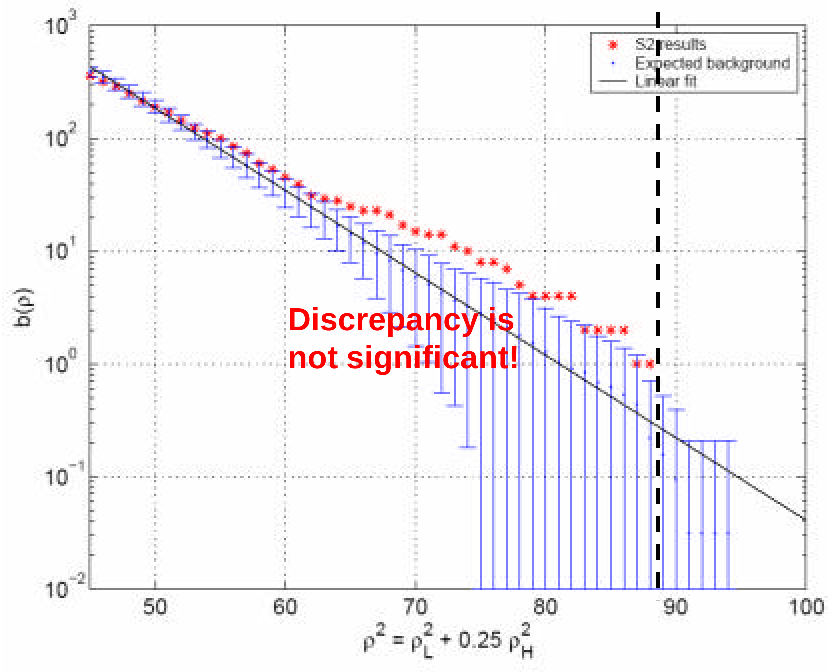
Estimate background due to accidental coincidences,
using 37 time lags,
each longer than the longest template (~ 4 seconds):
± (17 + 10n), n = 0…18.

I : Number of accidental triggers vs r^2
*** : Number of in-time triggers**

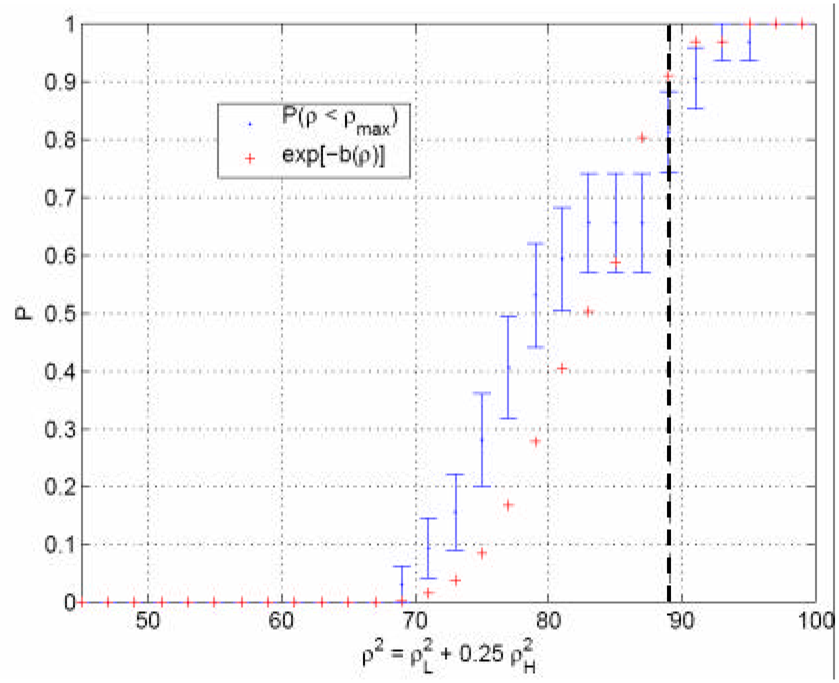
Probability that there are no background events above some maximum r^2

Loudest in-time coincident trigger in S2 has $r^2 = 89$;

20% chance that it is a background event.



Discrepancy is not significant!



Upper Limit Calculation

Base calculation on the observed $r_{\mathbf{max}}$: "loudest event statistic"

No event candidates (real or background) were observed with $r > r_{\text{max}}$ in total observation time T_{obs}

Need to know *efficiency* of analysis pipeline for target population, given this $r_{\mathbf{max}}$

Use Monte Carlo with set of galaxies, equivalent to N_{MWEG} Milky Ways (going out to ~ 3 Mpc, surveys give ~ 6.3 MWEG's)

e = Fraction of sources which would be found with $r > r_{\text{max}}$

Can take expected background into account

P_b = Chance of all background events having $r < r_{\text{max}}$

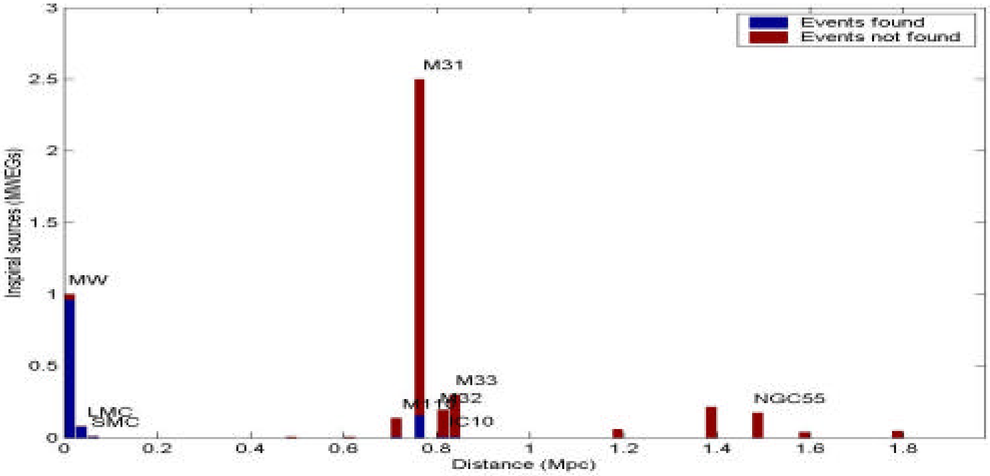
Rigorous frequentist confidence interval (one-sided) :
(Brady Creighton, Wiseman, 2004)

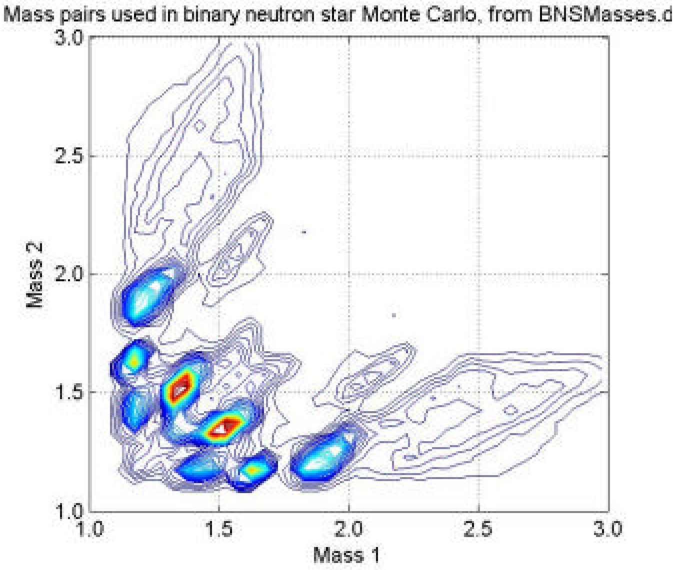
$$R_{90\%} = \frac{2.303 + \ln P_b}{T_{\text{obs}}\, e\, N_{\text{MWEG}}}$$

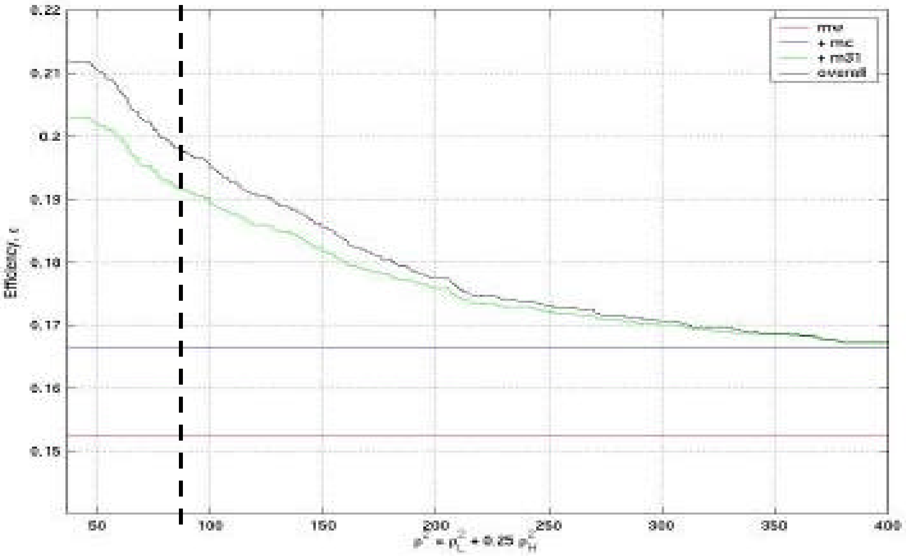
LIGO S2 BNS inspiral search efficiency

From detailed simulations:

- waveform injection into S2 data
- Galactic and extra-galactic source distribution
- m_1/m_2 distribution (pop synth)
- antenna pattern response
- full search pipeline







Sources of Systematic Uncertainty

On e :

- Distances to galaxies
- Accuracy of template waveforms
- distribution of m_1 , m_2
- Calibration
- Effect of cuts on real vs. simulated signals
- Finite statistics of simulation

These uncertainties are correlated

On N_{MWEG} :

- Number of sources in galaxies other than the Milky Way
  - Use blue light luminosity
  - Metallicity corrections
- Blue light luminosity of the Milky Way

Since the efficiency is evaluated with SAME pipeline as data,

with injections throughout S2 data sample,

there's no syst error associated with pipeline;

bugs or non-optimal pipeline algorithms can only lead to worse UL.

Simple sanity checks give ~ expected efficiency

Preliminary Upper Limit Result

$$R_{90\%} = \frac{2.303 + \ln P_b}{T_{\mathrm{obs}}\ e\ N_{\mathrm{MWEG}}}$$

Observation time (T_{obs}) : 345 hours

Conservative lower bound on the product ($e\ N_{\mathrm{MWEG}}$) : 1.2

Omit background correction term ($\ln P_b$)

➔ Conservative upper limit:

Rate < 50 per year per MWEG **(90% frequentist C.L.)**

c.f. **S1 result: < 170 per year per MWEG**

Detection confidence

- Pipeline is automated, but …
- The behavior of the detector is not ideal (non-Gaussian, non-stationary) and not yet fully understood
- Establishing data quality cuts and aux-channel vetoes NOT yet automated
- Detection confidence tests NOT yet automated, not yet fully designed
- Does that mean that we can't claim detection?

  No, only that detection confidence WILL be subject to bias...
- As we build confidence in our detector characterization,

  we will build confidence in our ability to claim detection with minimal bias. S3? S4?

Detection confidence tests for loudest triggers:

- Identify candidates with low background probability
- Check GW channel time series near candidate
- Is there a coincident candidate in burst search? Ringdown?
- What data quality flags were on>
- Was there anything strange in sci-mon or ops e-logs?
- Any data corruption evident between the data used in the analysis and the raw data archived at Caltech?
- Are injection channels clear?
- Are the candidates stable against changes in segmentation?
- Are the candidates stable against small changes in calibration consistent with systematic uncertainties?
- What are the parameters of the event? Are the masses reasonable? Is the distance reasonable? What position information is available via the time-delays? Are distances as measured in both instruments consistent with position information? Can the harmonics give useful information?
- If we cut signals by regions of parameter space, does this change the false alarm probability per week?
- What does the reconstructed waveform look like?
- Where does the candidate lie in parameter space of snr, chisq, masses, etc.
- Did the template bank ring-off all over? Is this consistent with a signal?
- How does the snr v time and chisq v time plot look?
- Make a follow up with coherent multi-detector code. How does it look?
- Are there are any auxiliary or PEM channels which indicate that the instrument was not behaving correctly?
- Lightning storms, high wind, other noisy weather?
- Are there any EM triggers in coincidence?
- Were any other detectors operational during the period when the candidate was identified?

Outline

- Inspiral group and analyses
- Gravitational waves from binary inspirals
- Overview of inspiral search technique
- Recap S1 search result
- S2 search for binary neutron star inspirals
- Other searches in progress
- Summary

Other Binary Neutron Star Searches in Progress

Joint analysis of LIGO S2 + TAMA DT8

Will use rest of LIGO S2 data (~700 hours) requiring coincidence with TAMA

Will exchange trigger data, look for coincident triggers

Search using LIGO+GEO S3 data

Max. visible range:	H1: **~4 to 10 Mpc**
(for 1.4+1.4 $M_?$,	L1: ~2.5 Mpc
optimally oriented,	H2: ~2 Mpc
SNR=8)	GEO: ~45 kpc (operated for part of S3 run)

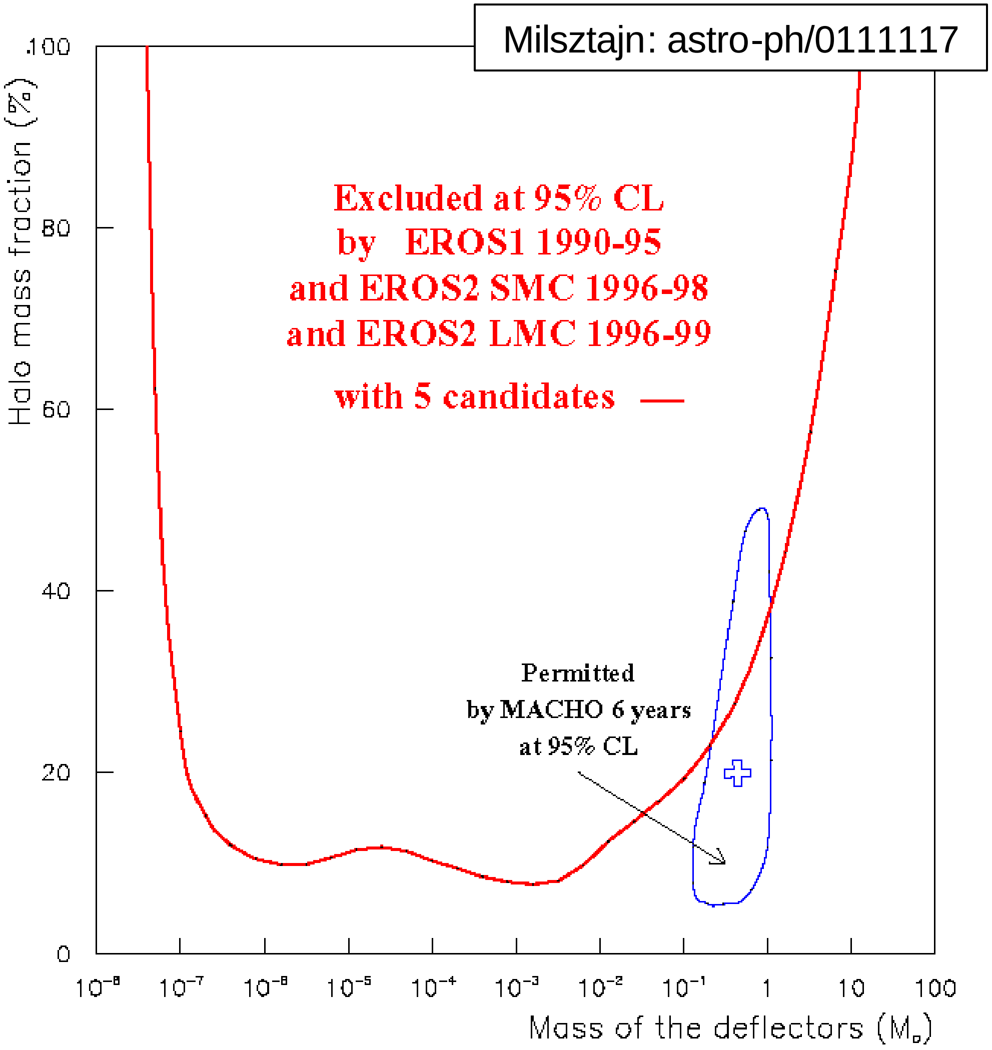
All 3 LIGO detectors more sensitive than most sensitive detector during S2

All 3 LIGO detectors sensitive to the Local Group

Three-site coherent analysis is interesting but challenging

Binary Black Hole MACHO Search

- **Galactic halo mass could consist of primordial black holes with masses ?1 $M_?$**
  - Some would be binaries inspiraling within the age of the universe
- **Simple extension of binary neutron star search**
  - S2 data being analyzed now
- **Mass range limited by available CPU**
  - Probably can go down to m = (0.25~0.3) $M_?$ HDLO

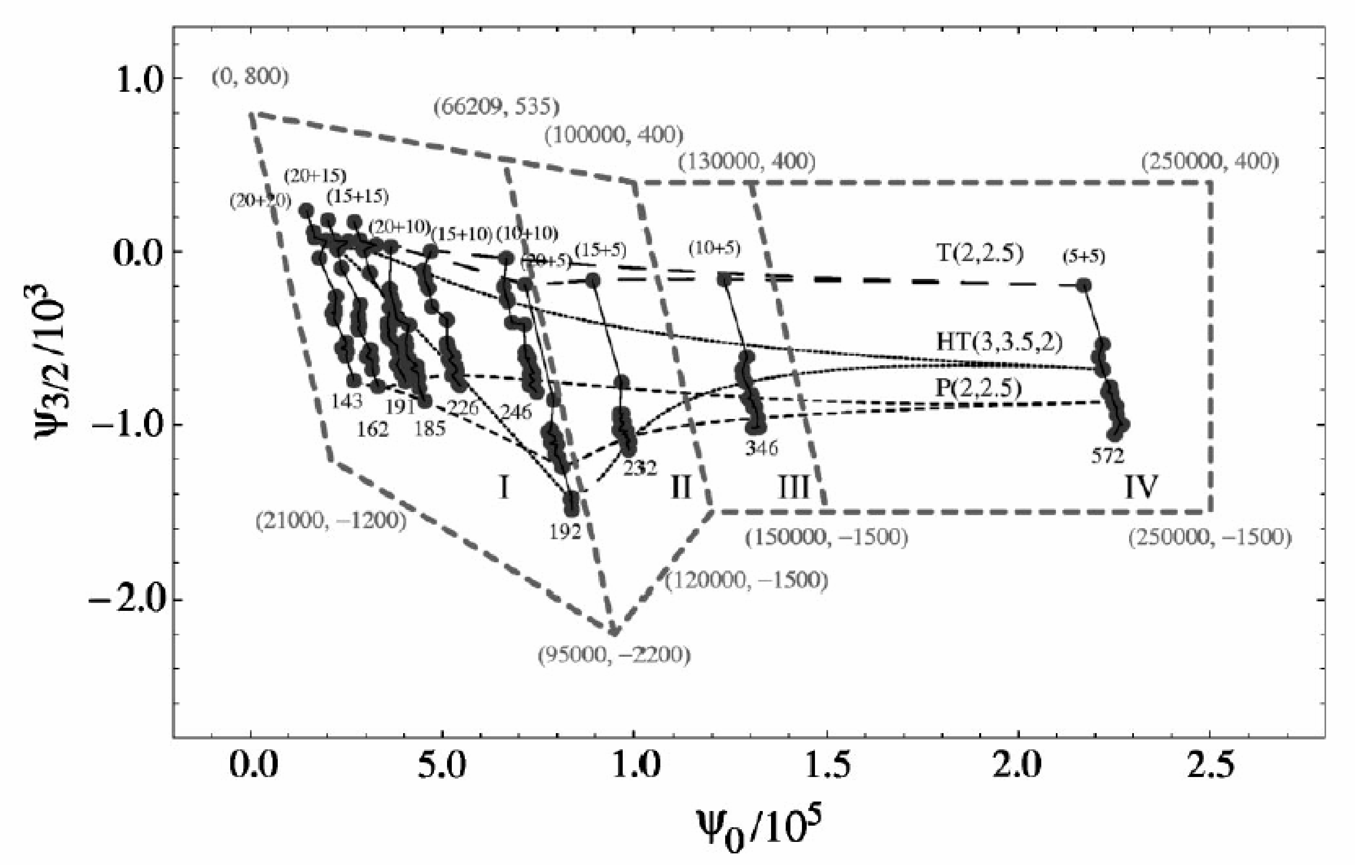


Milsztajn: astro-ph/0111117

Search in Progress for Non-Spinning Binary Black Hole Systems

- **Waveforms not known reliably**
  - Target masses: 3+3 to 20+20 $M_?$
  - Post-Newtonian expansion is inaccurate for mergers within LIGO band
- **Use matched filtering with “BCV detection template family”**
  - Buonanno, Chen, and Vallisneri, Phys. Rev. D **67**, 024016 (2003)
  - Semi-empirical template waveforms, like post-Newtonian but with additional parameters
  - Can achieve good matching to various post-Newtonian model waveforms
- **Algorithm implemented; studies in progress**
  - Template bank generation
  - Parameter ranges corresponding to physical signals
  - Issue: how to perform a χ^2 test for very short signals

BCV Parameter Space (Projected)



Plan to Search for *Spinning* Binary Black Hole Systems

Spin complicates waveforms considerably

- Precession ➔ phase and amplitude modulation
- Introduces several additional signal parameters

BCV have treated this in the post-Newtonian adiabatic-inspiral limit

- Phys. Rev. D **67**, 104025 (2003)
- Continue “detection template family” approach
- Introduce sinusoidal phase modulation
- Leads to a manageable parameter space

Also shown to be good for black hole–neutron star systems

Summary

Binary neutron star inspiral rate limit ~published using S1 data

Searched for binary neutron star inspirals in LIGO S2 data

- Analysis pipeline designed for coincident detection
- No coincident event candidates observed above background
- *Preliminary* upper limit: Rate < 50 per year per MWEG

Currently doing several analyses using S2 and S3 data

- Combined analysis with other interferometer projects
- Lower- and higher-mass systems

Interferometers are getting sensitive enough to see binary systems out into the universe !