# Results from LIGO Searches for Binary Inspiral Gravitational Waves

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**For the LIGO Scientific Collaboration**

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# Binary Orbit Evolution

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

$$f_{GW} = 2f_{orbit}$$

Gravitational waves carry away energy
and angular momentum

➔ **Orbit shrinks over time**

**Objects spiral in until they finally coalesce**

Additional relativistic effects kick in as velocities approach the speed of light

# Famous Binary Neutron Star Systems

**LIGO**

## PSR 1913+16

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

Masses: 1.44 $M_\odot$ , 1.39 $M_\odot$

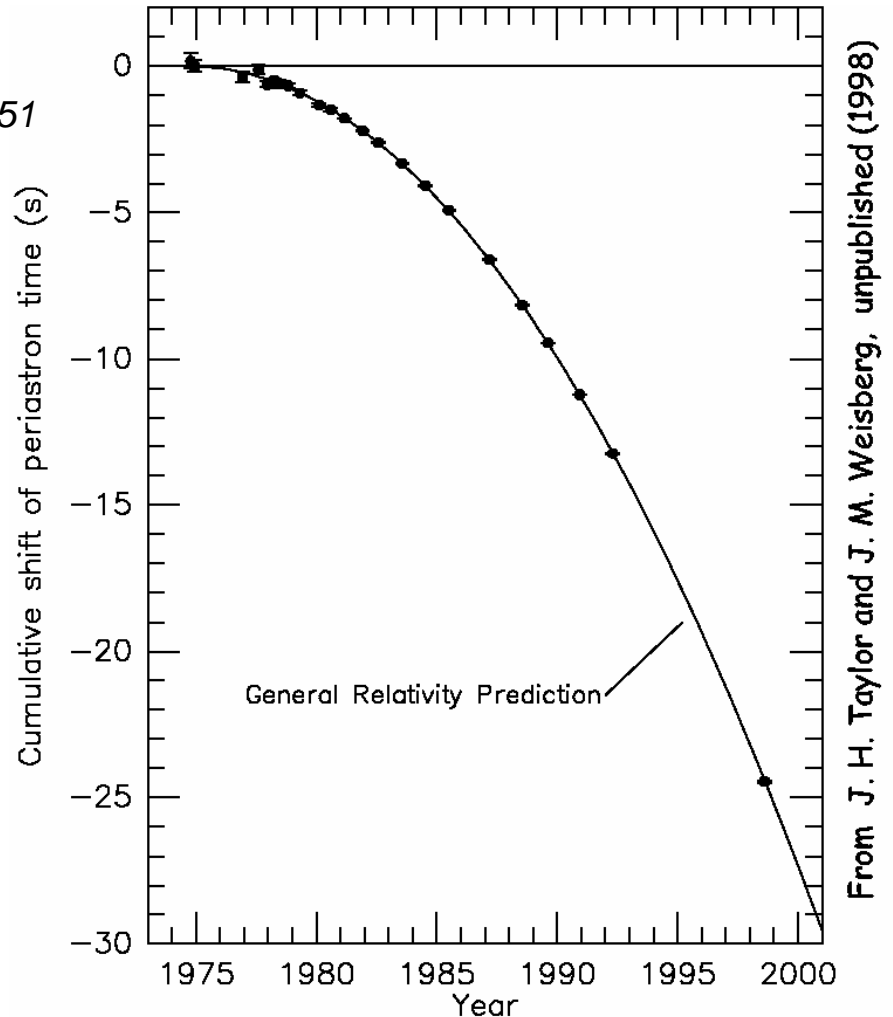Orbital decay exactly matches prediction from gravitational wave emission

## PSR J0737-3039

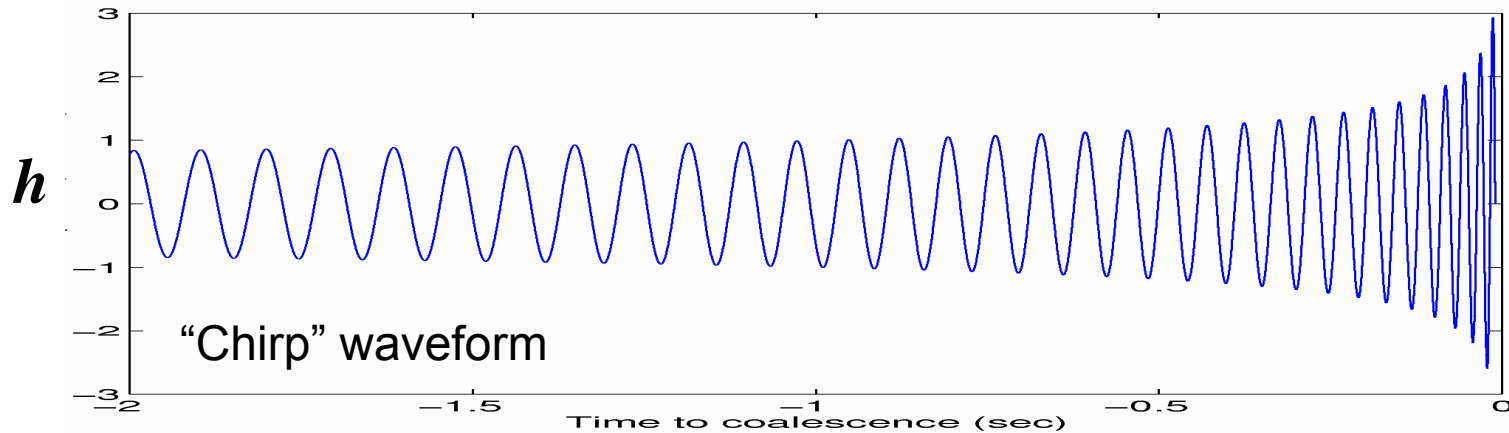Burgay *et al.*, 2003    *Nature **426**, 531*

Orbital period = 2.4 hours

Will coalesce in ~85 Myr

Will yield improved tests of G.R.



From J. H. Taylor and J. M. Weisberg, unpublished (1998)

General Relativity Prediction

# 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$_\odot$**

"Post-Newtonian expansion" 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

# Binary Neutron Star Inspiral Rate Estimates

**Can base estimates on the 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
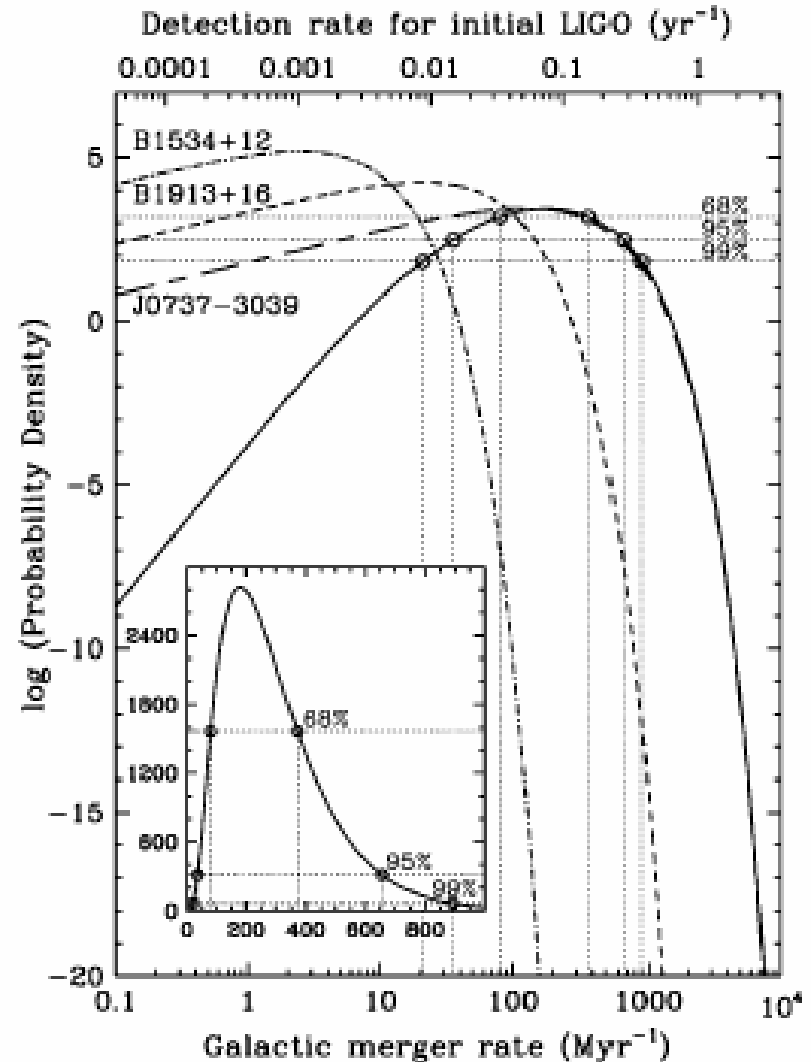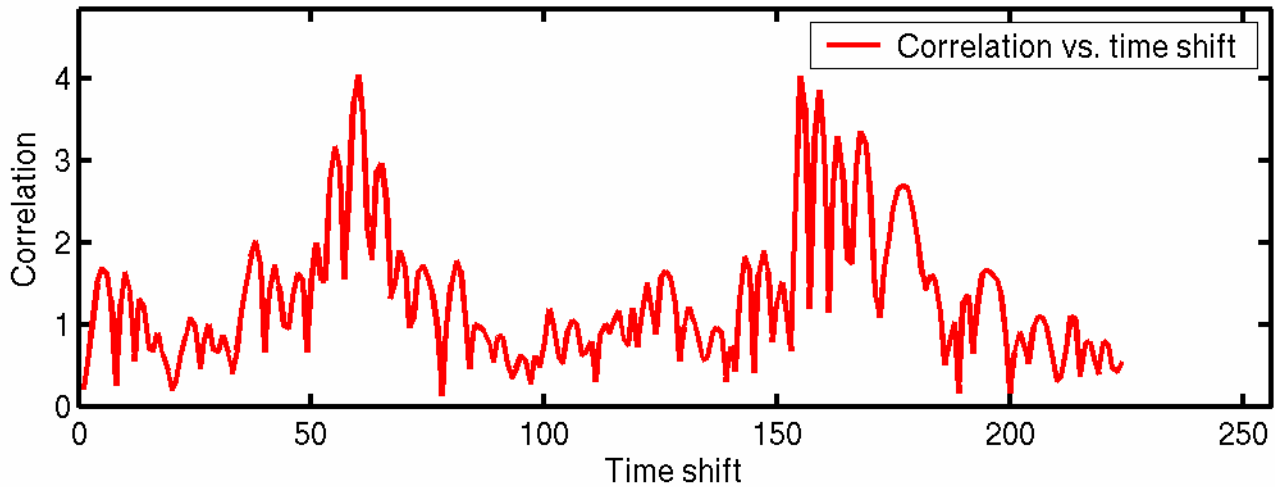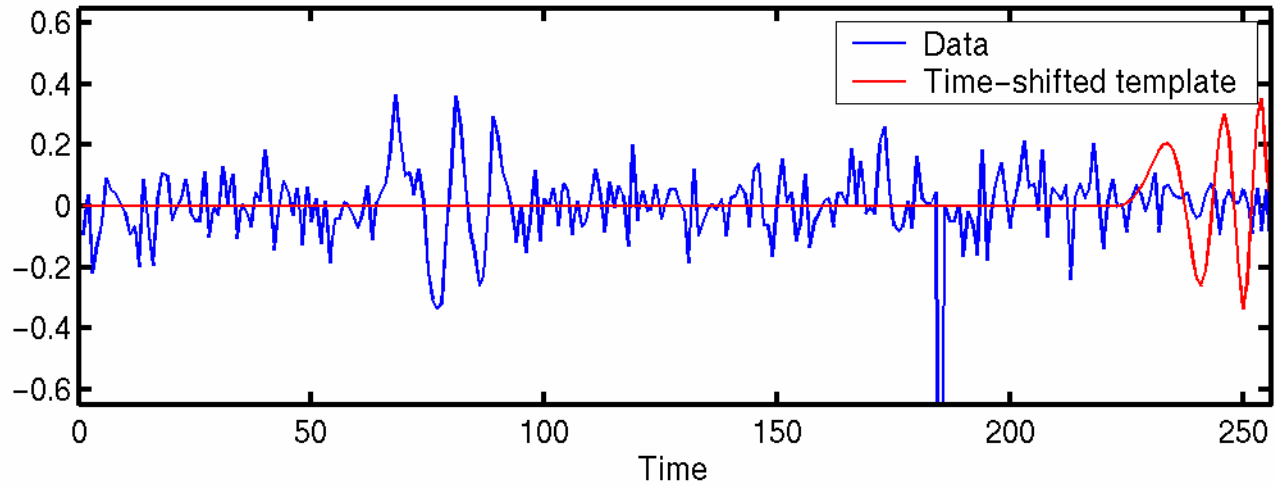
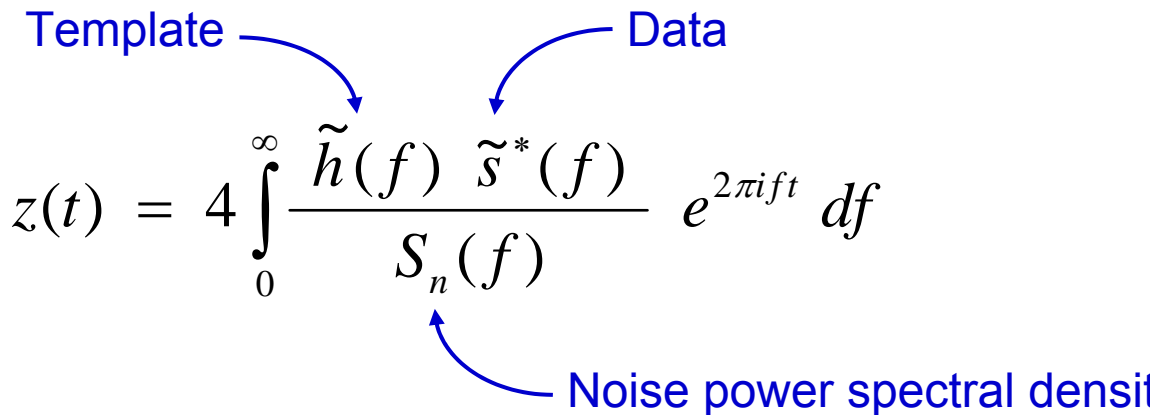**Binary black holes, BH-NS:  ???**

# Illustration of Matched Filtering

**Use optimal matched filtering in frequency domain**

Template ⟶          ⟵ Data

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

Noise power spectral density

Look for maximum of $|z(t)|$ above some threshold ➜ "trigger"
Describe with template params, SNR $\rho$, effective distance $D$

**Check consistency of signal with expected waveform**

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

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

Other waveform consistency tests are being considered
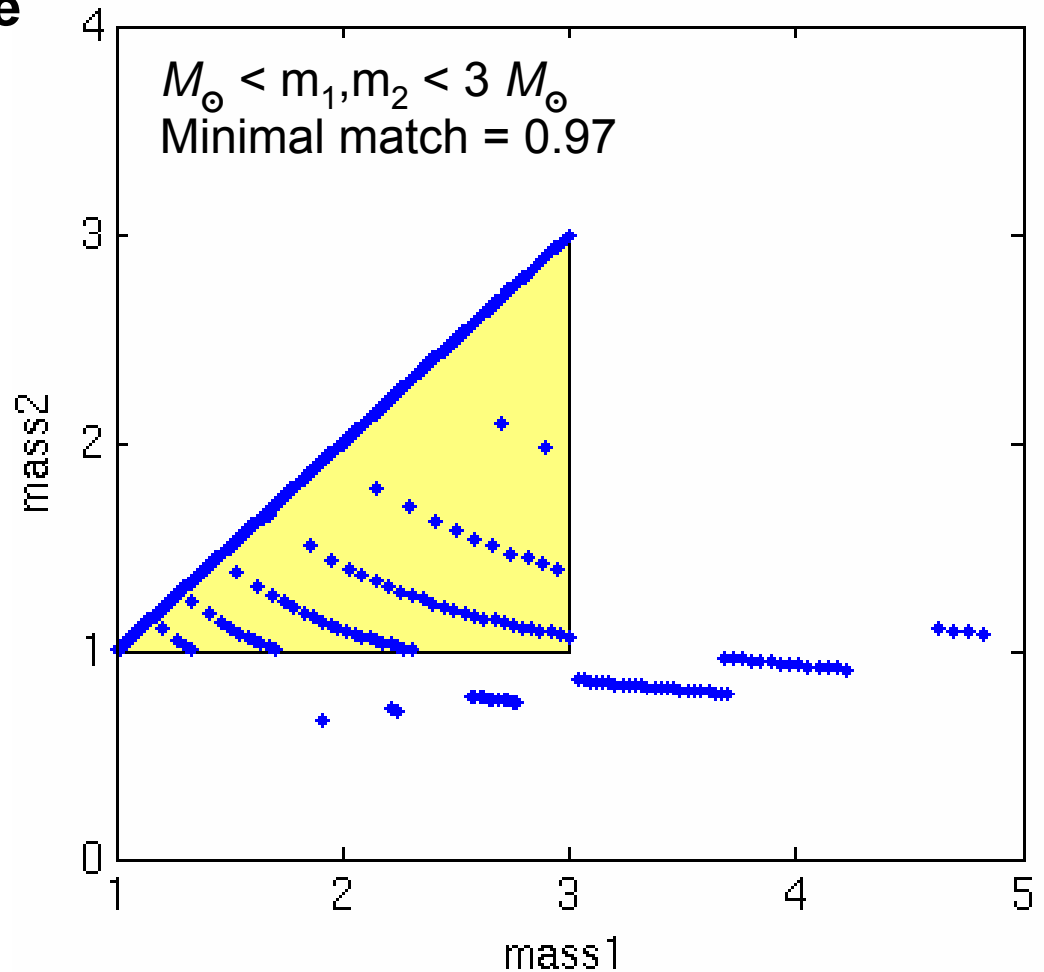
# Overview of Inspiral Search Technique (2)

**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**



LLO bank for GPS 729410749  (751 templates)

$M_\odot < m_1, m_2 < 3\ M_\odot$
Minimal match = 0.97

# Overview of Inspiral Search Technique (3)

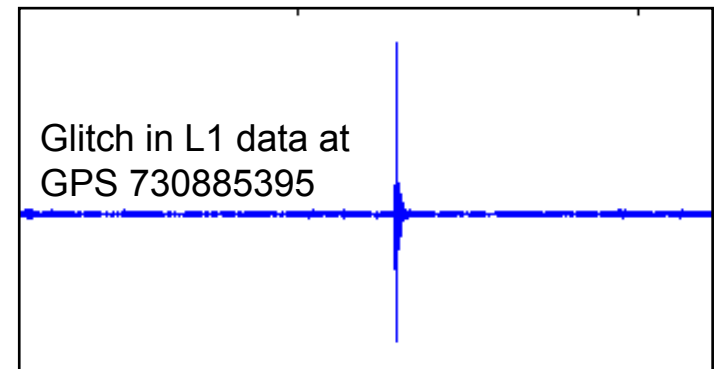**Process only good data, based on <span style="color:red">data quality</span> checks**

**<span style="color:red">Validate</span> search algorithm with simulated signals**

**Use auxiliary channels to <span style="color:red">veto</span> environmental / instrumental glitches**



Glitch in L1 data at
GPS 730885395

**<span style="color:red">Tune</span> algorithm parameters and vetoes using "playground" data**

~10% of data, excluded from final result

**Require <span style="color:red">coincidence</span> to make a detection**

Consistent time, signal parameters in multiple interferometers

Eventually, will do coherent analysis

**… or set an *upper limit* on event rate, using a <span style="color:red">population Monte Carlo</span> to determine the efficiency of the analysis pipeline**

# Previous Binary Neutron Star Inspiral Search Using S1 Data

**Binaries with component masses between 1 and 3 $M_\odot$**

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

**Visible range for 1.4+1.4 $M_\odot$ (optimally oriented, with SNR=8):**

L1   ~175 kpc   ← Milky Way and Magellanic Clouds
H1   ~38  kpc
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]*

# S2 Data for Inspiral Searches

**Visible range for 1.4+1.4 $M_\odot$** (optimally oriented, with SNR=8)**:**

L1 ~1.8 Mpc
H1 ~0.9 Mpc
H2 ~0.6 Mpc

**Over 1200 hours of "science mode" data**

Various combinations of interferometers

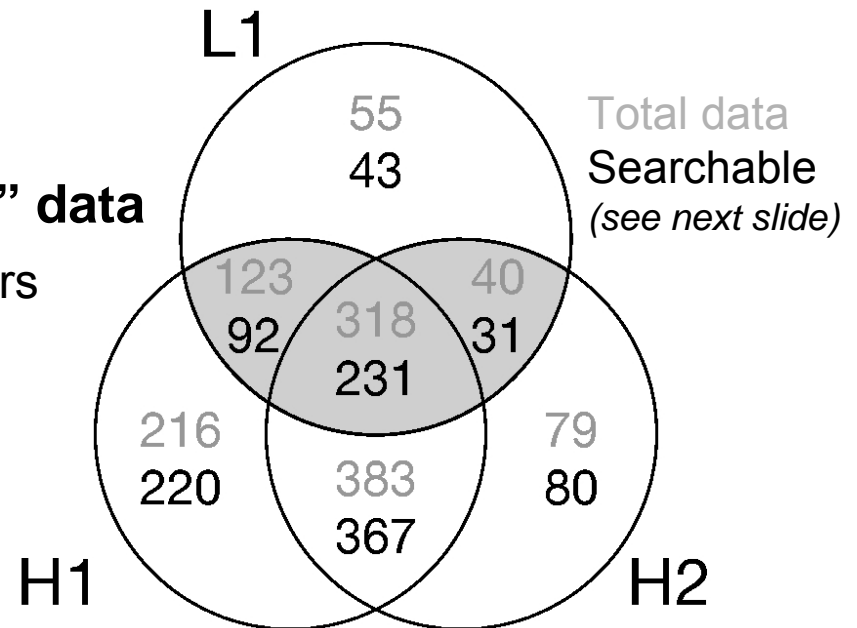**For this analysis, use only *coincident* data from both sites**

"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

L1

55
43

Total data
Searchable
*(see next slide)*

123
92

40
31

318
231

216
220

383
367

79
80

H1

H2

# Data Selection and Processing

**"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

> These things reduce amount of data searched for inspirals

**Data processed in "chunks" 2048 seconds long**

Ignore good-data segments shorter than 2048 seconds

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**

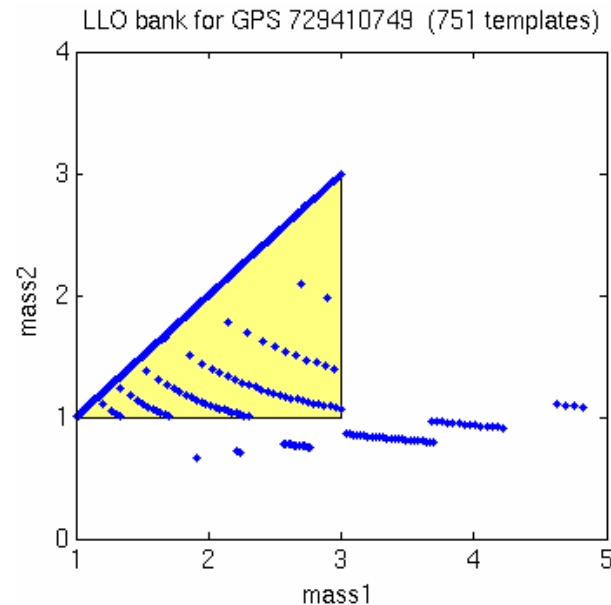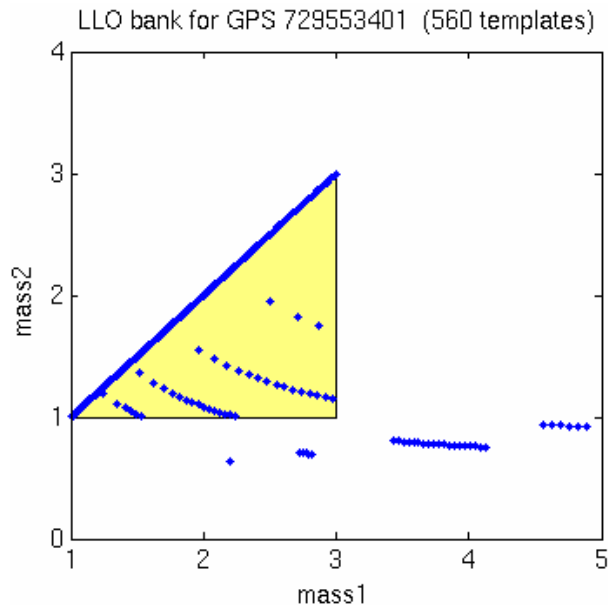Triggers separated afterward; only non-playground data used for final result

# 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

# Chi-Squared Test

**Tuned using playground data with and without simulated signals**

Chose $p$=15 frequency bands

**Allow large signals to have higher $\chi^2$ values, due to mismatch with discrete template bank**

Keep cut rather loose, to avoid losing real signals

L1: $$\chi^2 \leq 5\left(p + 0.01\,\rho^2\right)$$

H1, H2: $$\chi^2 \leq 12.5\left(p + 0.01\,\rho^2\right)$$

**(Plots of $\rho$ vs. $\chi^2$, for data and simulated signals, should go here)**

# 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**

|  | **L1-H1 / L1-H2** | **H1-H2** |
|---|---|---|
| **Time:** | $\Delta t$ < 11 ms | $\Delta t$ < 1 ms |
| **Effective distance:** | No requirement, since LHO and LLO are not exactly co-aligned | $\dfrac{\left\lvert D_{H1} - D_{H2} \right\rvert}{D_{H1}} < 0.5 + \dfrac{2}{\rho_{H1}}$ |

# Analysis Pipeline

**Have developed automated "pipeline" to filter appropriate data chunks and check for coincidences**

- 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

**<span style="color:red">Pipeline is designed to avoid unnecessary processing</span>**

- 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

- 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

**Filtering used 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

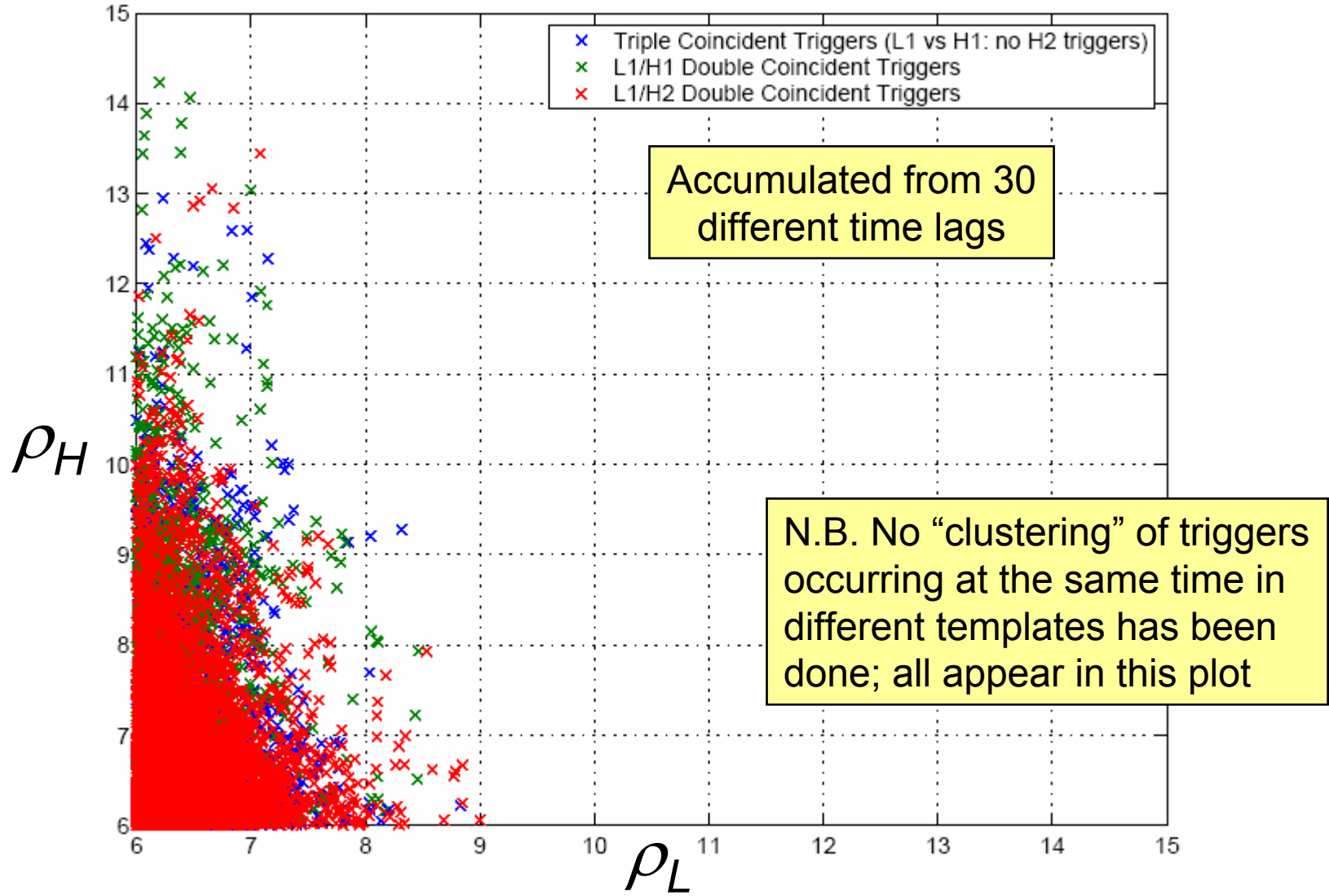Use many different lags ($+$ or $-$) between 17 sec and a few minutes

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

# Empirical Figure-of-Merit Statistic



$$\rho = \sqrt{\rho_L^2 + \rho_H^2 / 4}$$

For Gaussian noise, optimal coherent statistic would be

$$\rho = \sqrt{\rho_L^2 + \rho_H^2}$$

Simulated signals

$\rho_H$

$\rho_L$

# Event Candidates Observed



**Did not find any event candidate inconsistent with background**

$\rho_{max}$ = 9.44

(N.B. no L1-H1 coincidence was strong enough to be seen in H2)
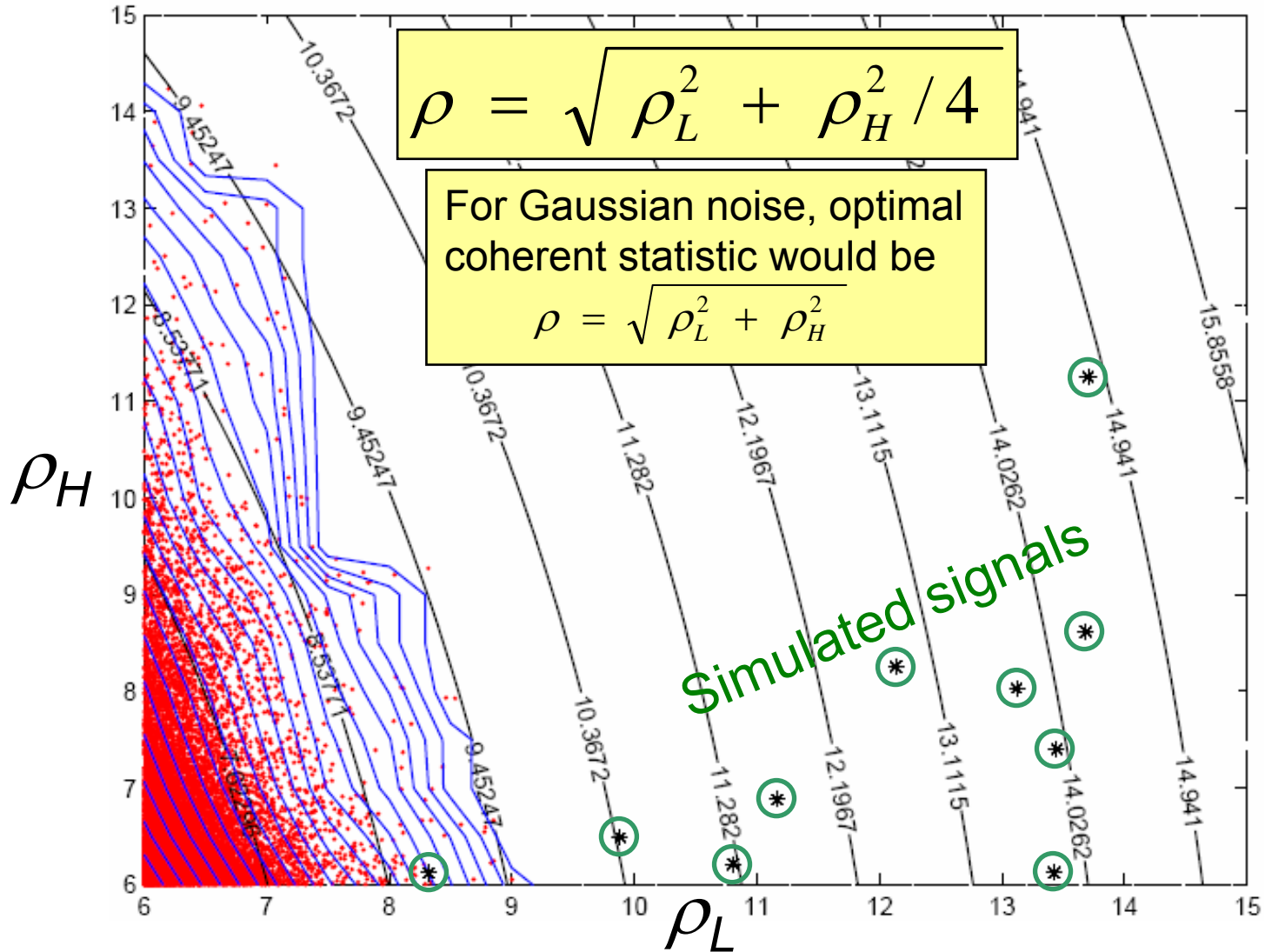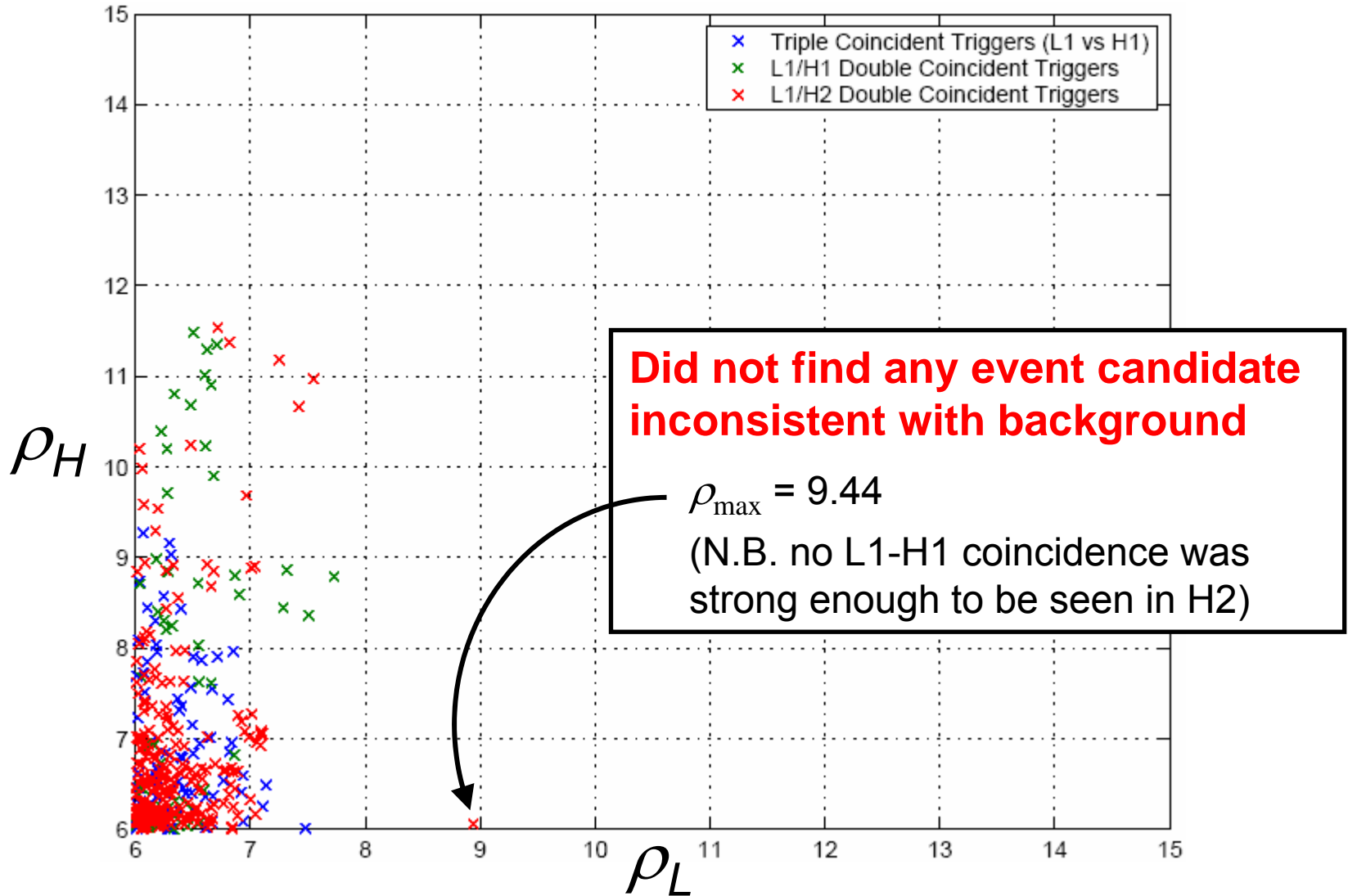
# Upper Limit Calculation

**Base calculation on the observed $\rho_{\text{max}}$**

No event candidates (real or background) were observed with $\rho > 9.44$ in $T_{\text{obs}} = 355$ hours of data

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

Fraction of target population sources which would be found with $\rho > 9.44$

Use Monte Carlo with $N_{\text{MWEG}} = 6.3$ in population (galaxies within 3 Mpc)

**Can take expected background into account**

$P_b$ = Chance of all background events having $\rho < 9.44$

**Rigorous frequentist confidence interval**   (one-sided)

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

# Sources of Systematic Uncertainty

**On $\varepsilon$:**

Distances to galaxies

Accuracy of template waveforms

Calibration

Effect of cuts on real vs. simulated signals

Finite statistics of simulation

**On $N_{\mathrm{MWEG}}$:**

Number of sources in galaxies other than the Milky Way

    Use blue light luminosity

    Metallicity corrections

Blue light luminosity of the Milky Way

These uncertainties are correlated

# *Preliminary* Upper Limit Result

**Conservative lower bound on the product ($\varepsilon N_{\mathrm{MWEG}}$) : 1.14**

**Omit background correction term  ($\ln P_b$)**

**➔ Conservative upper limit:**

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

# 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 $M_\odot$,    L1:  ~2.5 Mpc
optimally oriented,    H2:   ~2  Mpc
SNR=8)    GEO: ~45 kpc  (operated for part of S3 run)

All 3 LIGO interferometers sensitive to the Local Group

Three-site coherent analysis is interesting but challenging

# Binary Black Hole MACHO Search

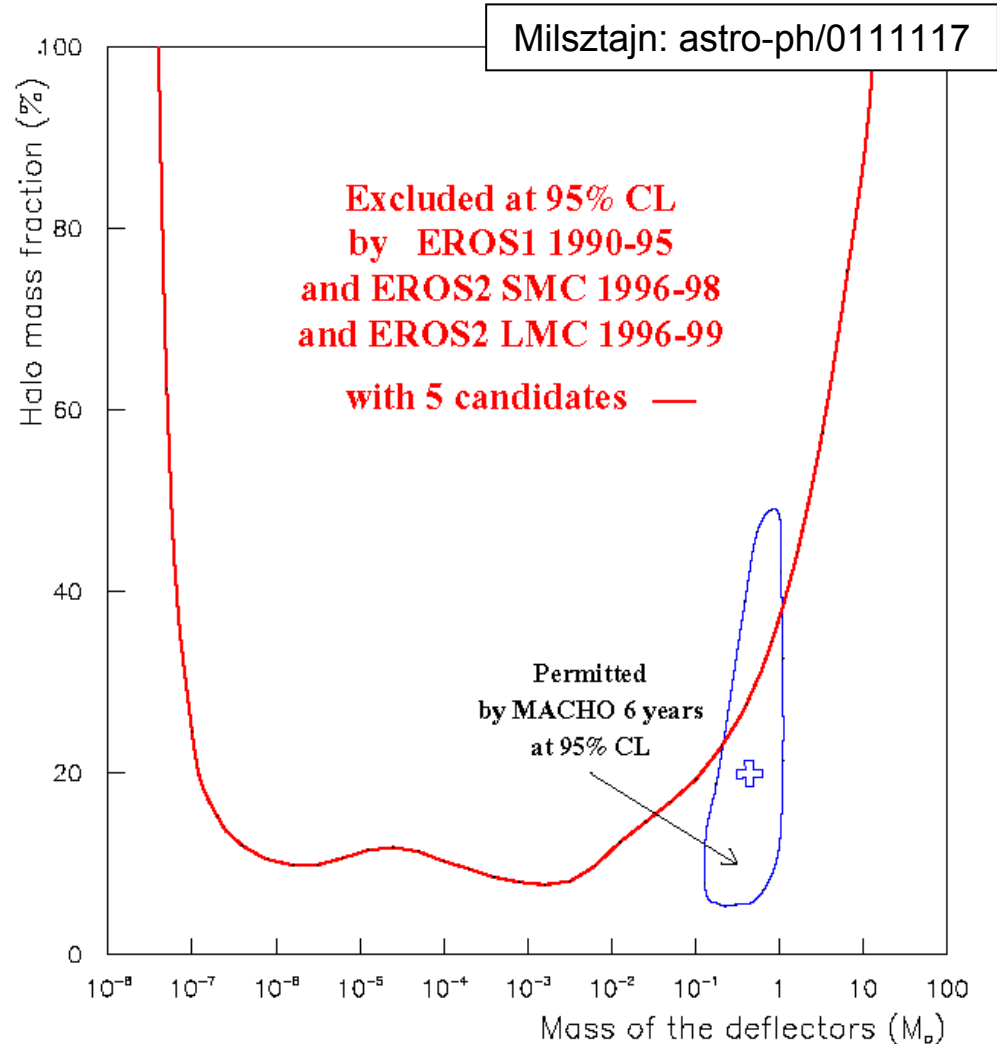**Galactic halo mass could consist of primordial black holes with masses $\lesssim 1$ $M_\odot$**

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 $m = (0.25\sim0.3)$ $M_\odot$ easily

Milsztajn: astro-ph/0111117

Excluded at 95% CL
by EROS1 1990-95
and EROS2 SMC 1996-98
and EROS2 LMC 1996-99

with 5 candidates —

Permitted
by MACHO 6 years
at 95% CL

Halo mass fraction (%)

Mass of the deflectors ($M_\odot$)

# Search in Progress for Non-Spinning Binary Black Hole Systems

**Waveforms not known reliably**

Target masses: 3+3 to 20+20 $M_\odot$

Post-Newtonian expansion breaks down while in LIGO frequency 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 model waveforms

Adiabatic, non-adiabatic, stationary phase, effective-one-body, …

Taylor vs. Padé expansions

**Algorithm implemented; studies in progress**

Template bank generation

Parameter ranges corresponding to physical signals

Issue: how to perform a $\chi^2$ test for very short signals

# 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 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 !**