LIGO-G040233-02-E

Results from LIGO Searches for Binary Inspiral Gravitational Waves

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For the LIGO Scientific Collaboration

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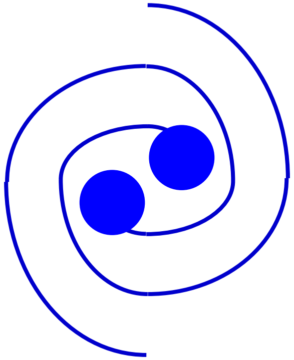
Outline

- **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**

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 $M_\odot$, 1.39 $M_\odot$

Orbital decay exactly matches prediction from gravitational wave emission

Will coalesce in ~300 Myr

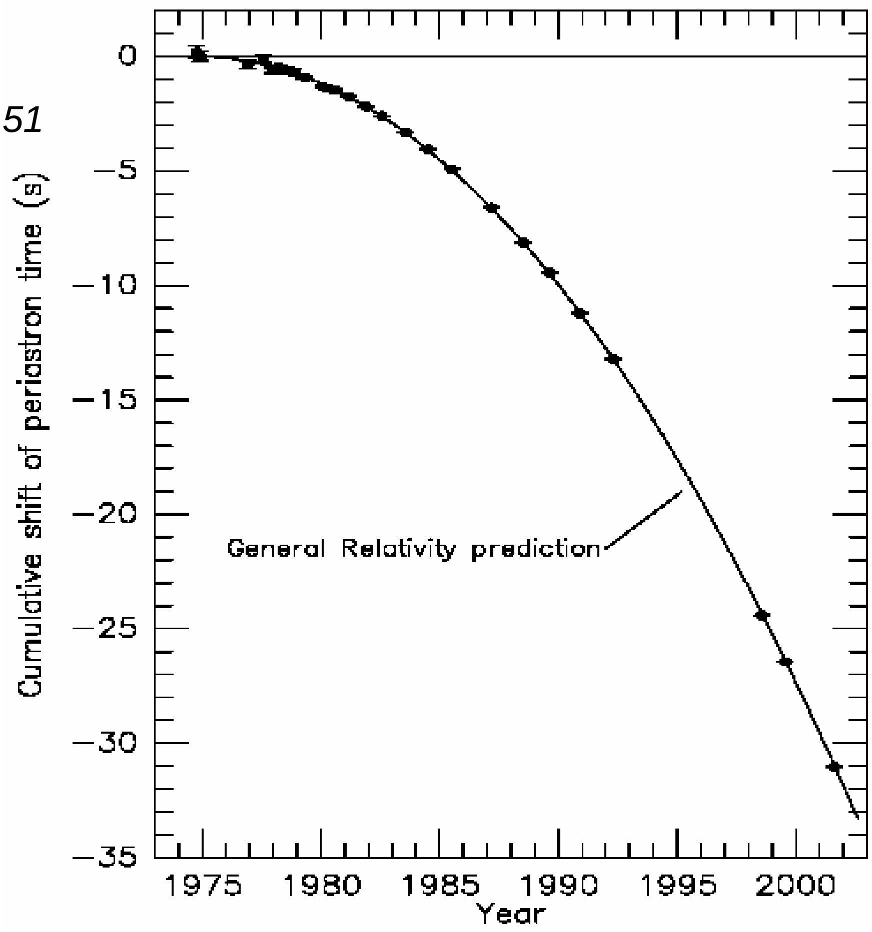
PSR J0737-3039 NEW!

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

Orbital period = 2.4 hours

Will coalesce in ~85 Myr

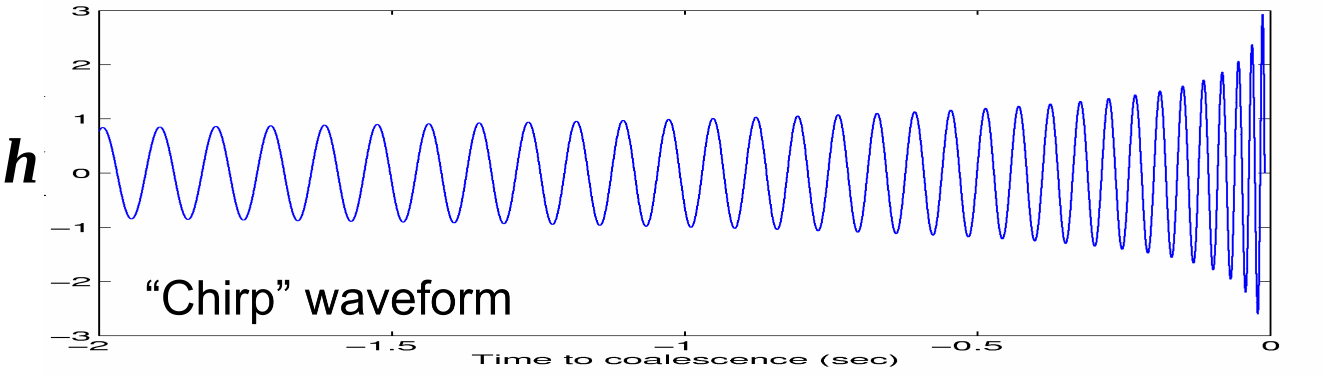
Will yield improved tests of G.R.



Weisberg & Taylor, astro-ph/0211217

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” 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

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

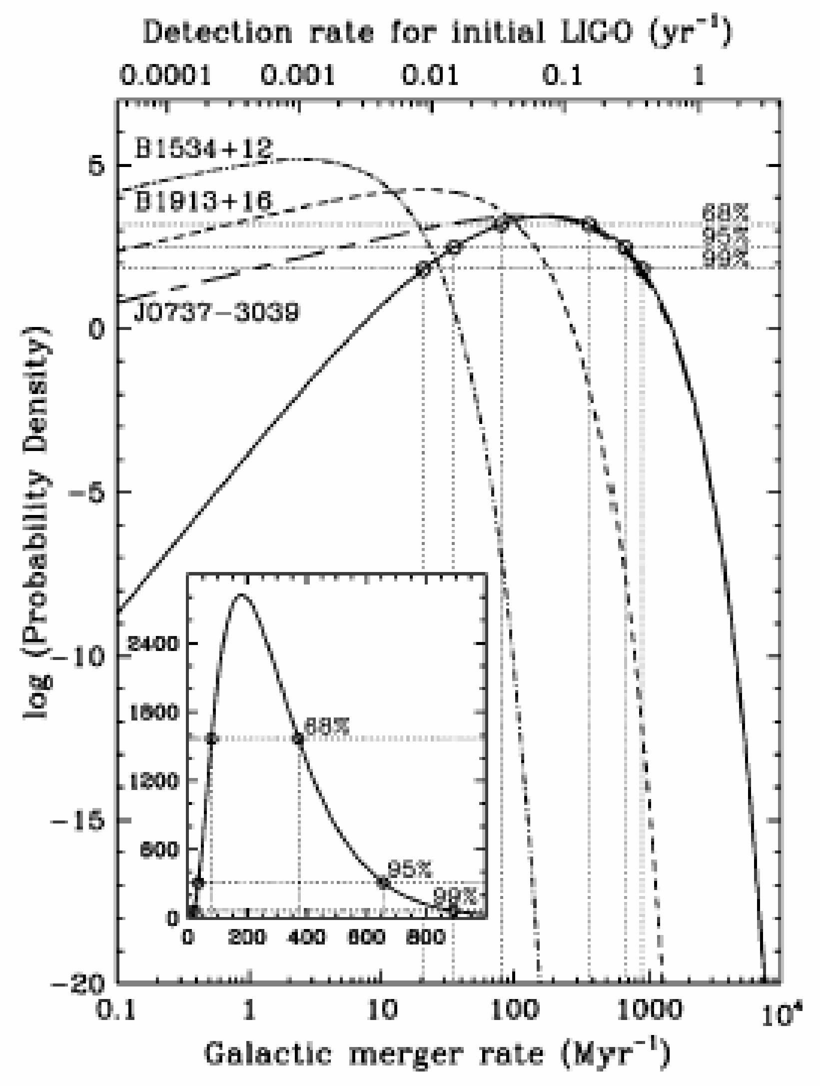


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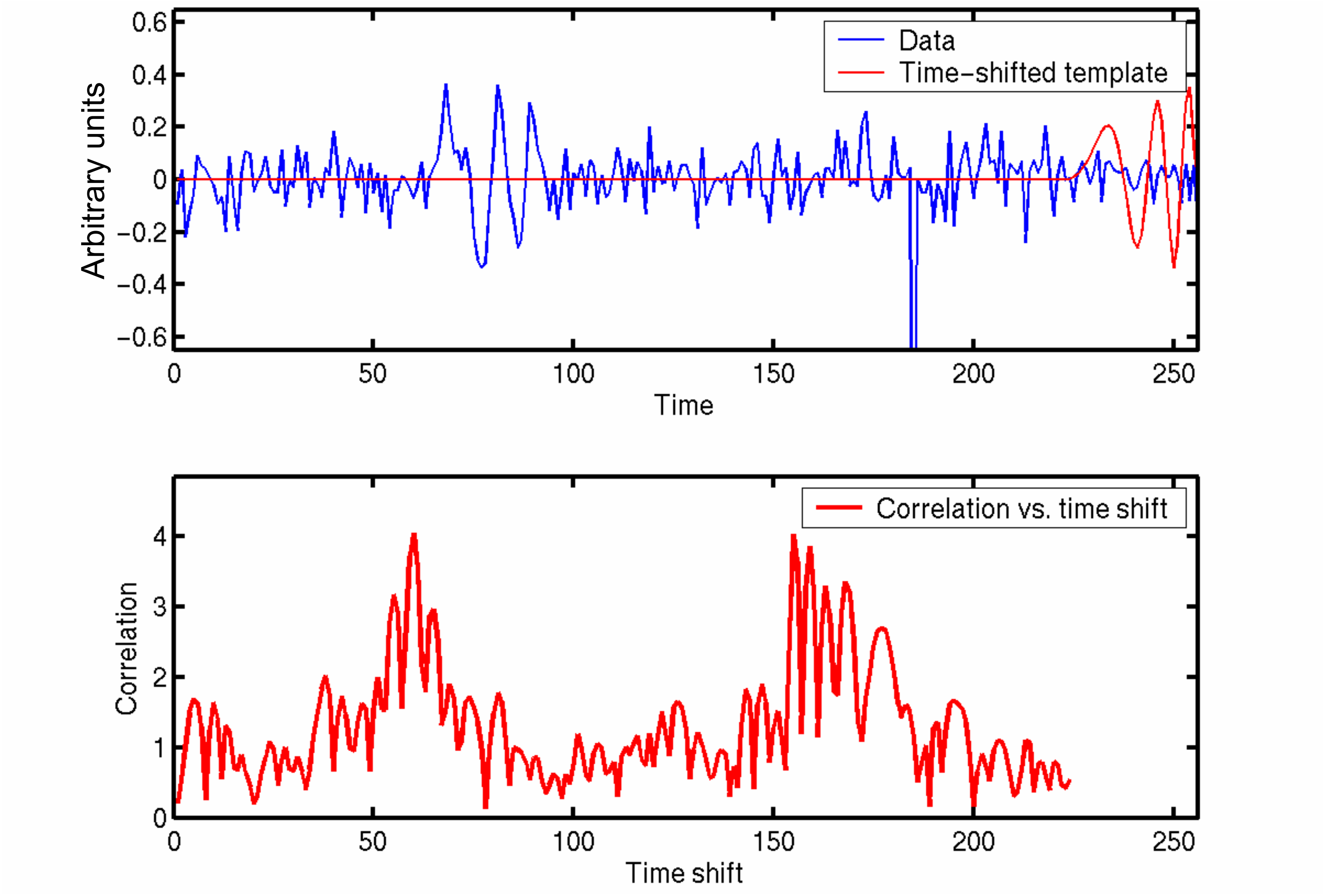
Illustration of Matched Filtering



Overview of Inspiral Search Technique (1)

Use Wiener optimal matched filtering in frequency domain

Template Data

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

Noise power spectral density

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

Describe with template params, SNR ρ, effective distance D

Check consistency of signal with expected waveform

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

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

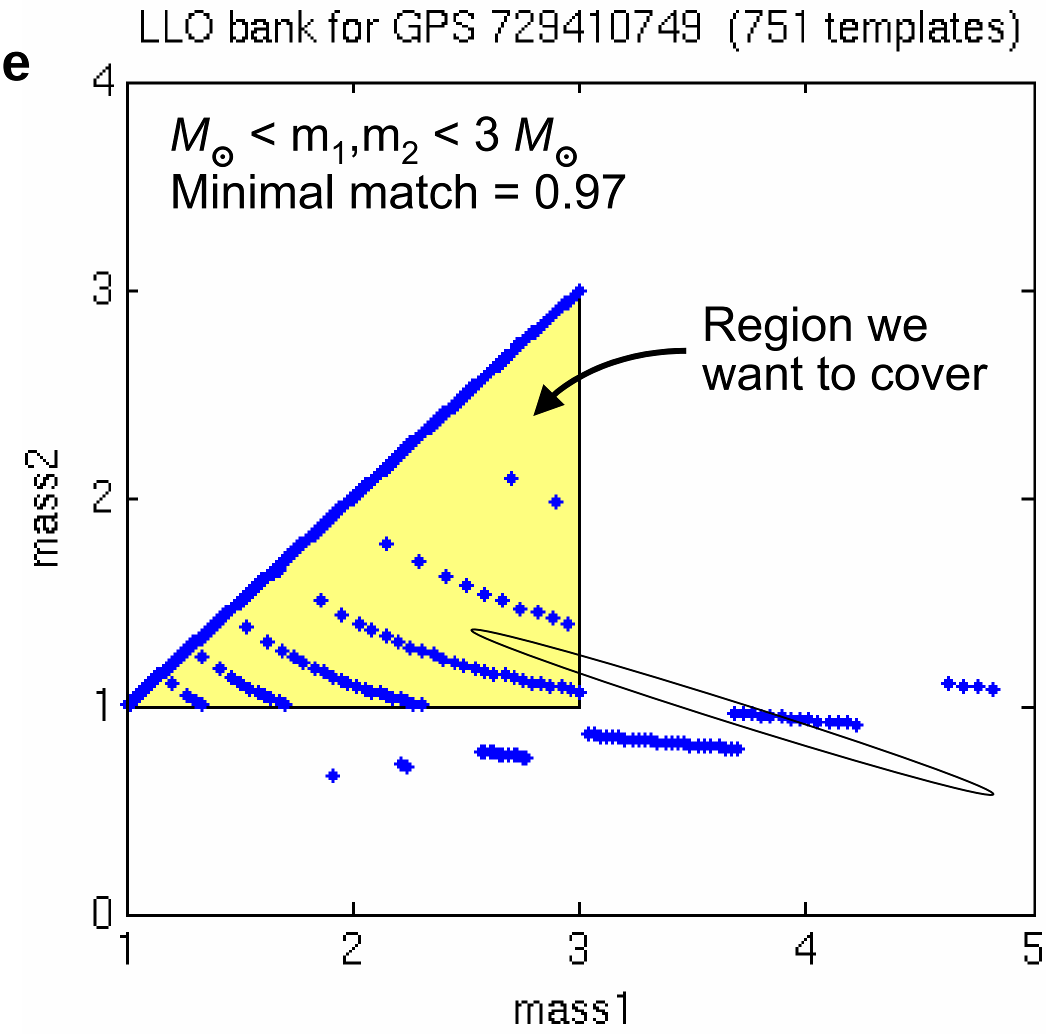
Other waveform consistency tests are being considered

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

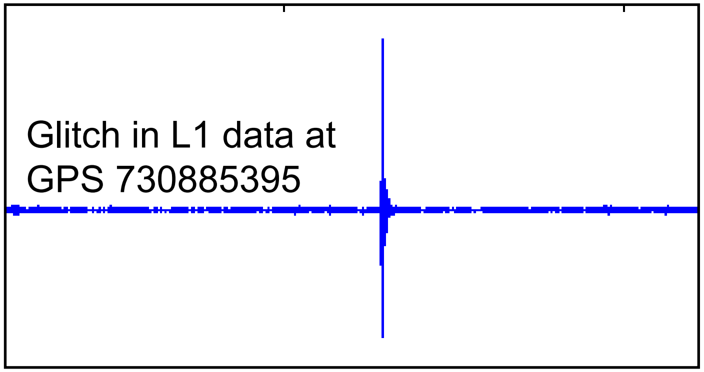


Overview of Inspiral Search Technique (3)

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 $M_\odot$

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

S1 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 ← 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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S2 Data for Inspiral Searches

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

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

Over 1200 hours of “science mode” data

Various combinations of interferometers

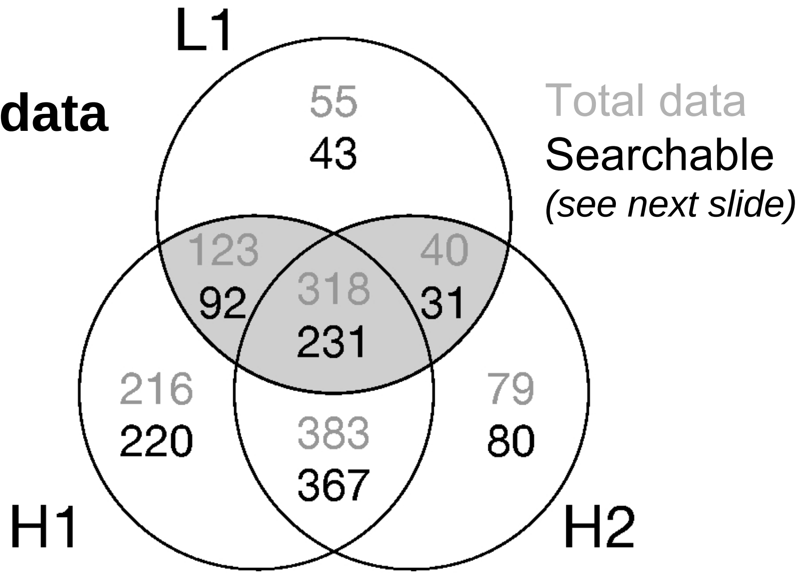
For this analysis, use only *coincident* data from both sites

“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



Data Selection and Processing

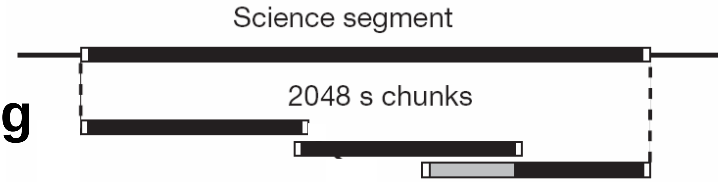
"Data quality" cuts – omit times with:

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 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

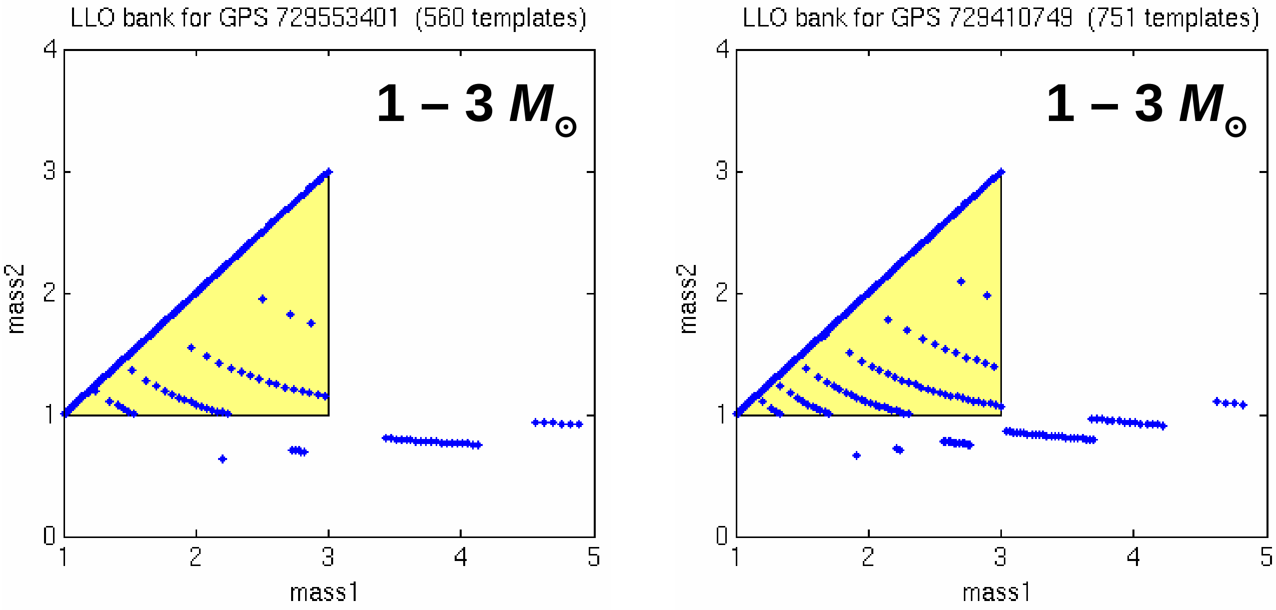
"Playground" data processed together with other data

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

Chi-Squared Test

Tuned using playground data with and without simulated signals

Chose p=15 frequency bands

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

Keep cut rather loose,
to avoid losing real signals

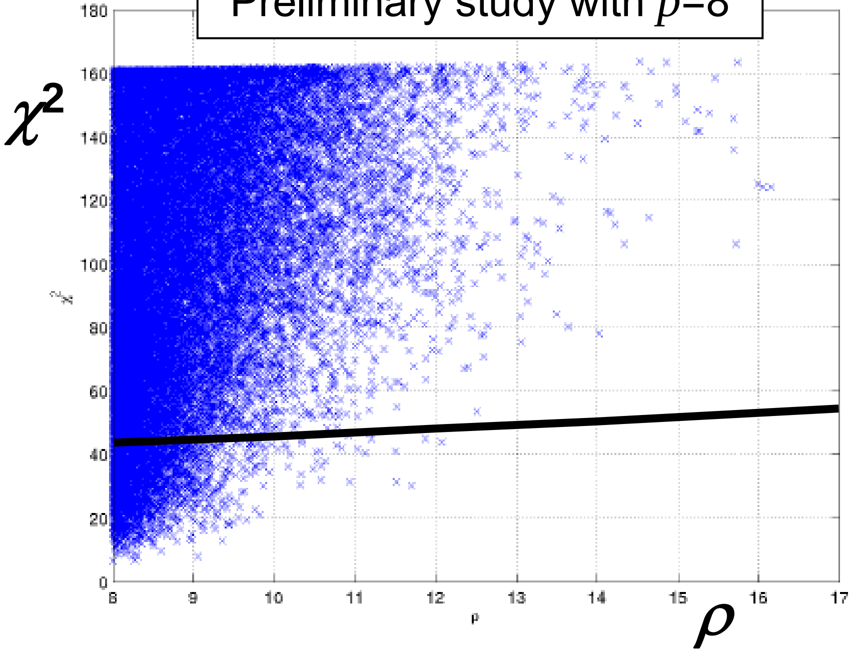
L1:

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

H1, H2:

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

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
Effective distance:	$\frac{\lvert D_{\mathrm{H1}} - D_{\mathrm{H2}} \rvert}{D_{\mathrm{H1}}} < 0.5 + \frac{2}{\rho_{\mathrm{H1}}}$	No requirement, since LHO and LLO are not exactly co-aligned

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

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
- 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

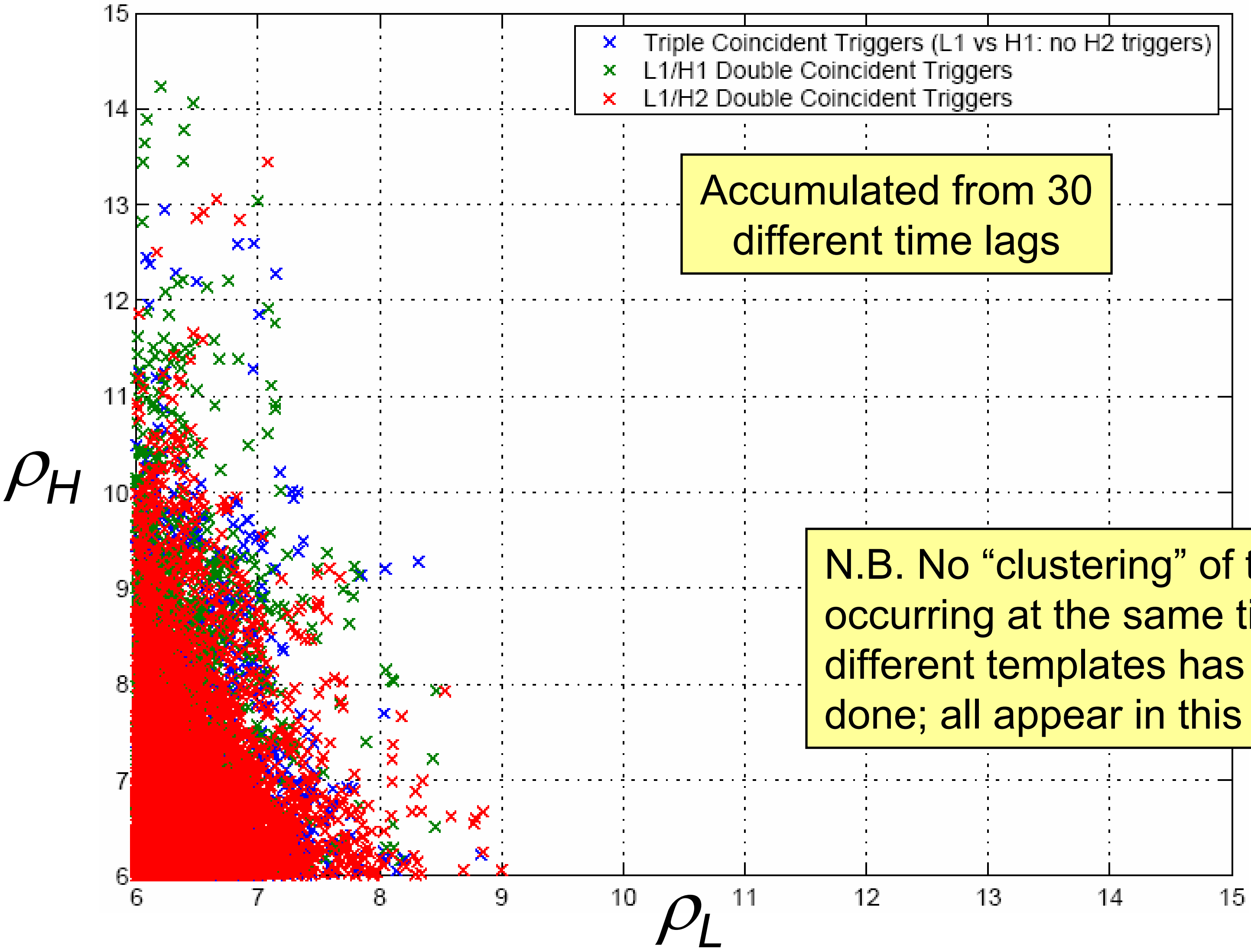
- Many triggers are found in each interferometer with SNR ≈ 6 – 8
- ➔ Expect some accidental coincidences

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

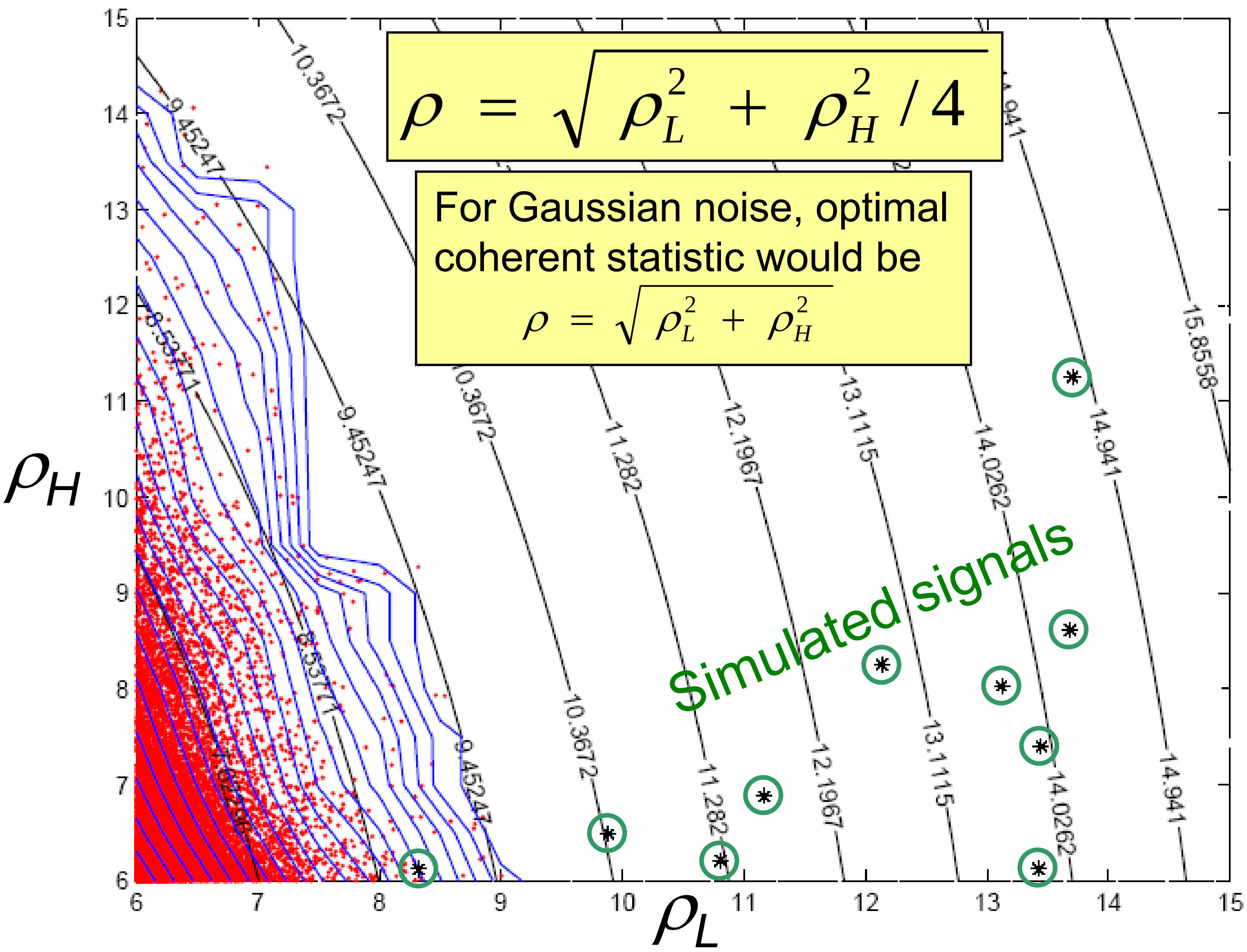
Background Event Candidates



Accumulated from 30 different time lags

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

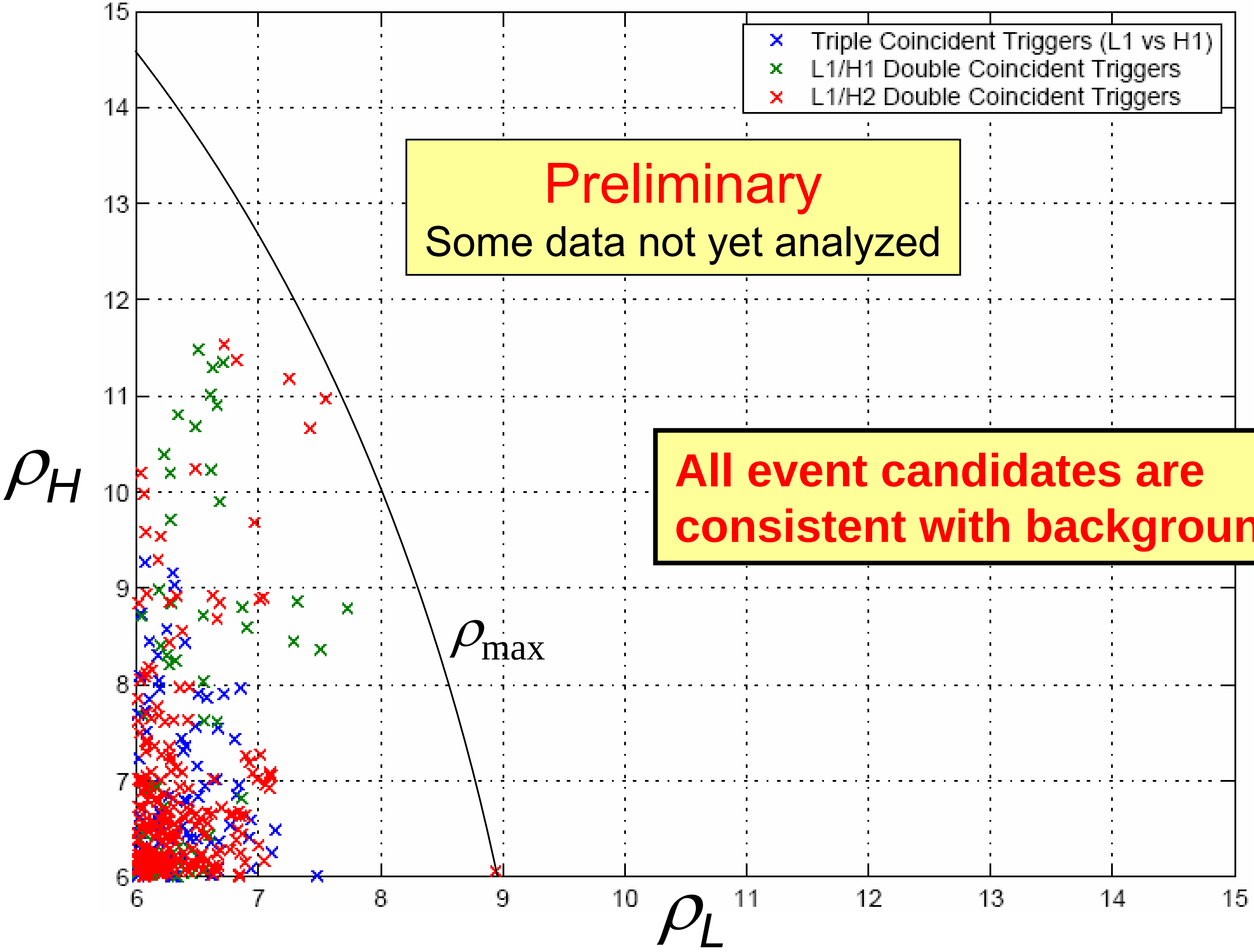


$$\rho = \sqrt{\rho_L^2 + \rho_H^2 / 4}$$

For Gaussian noise, optimal coherent statistic would be

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

Event Candidates Observed



Preliminary

Some data not yet analyzed

All event candidates are consistent with background

Upper Limit Calculation

Base calculation on the observed $\rho_{\mathbf{max}}$

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

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

Use Monte Carlo with set of galaxies, equivalent to N_{MWEG} Milky Ways

ε = Fraction of sources which would be found with $\rho > \rho_{\text{max}}$

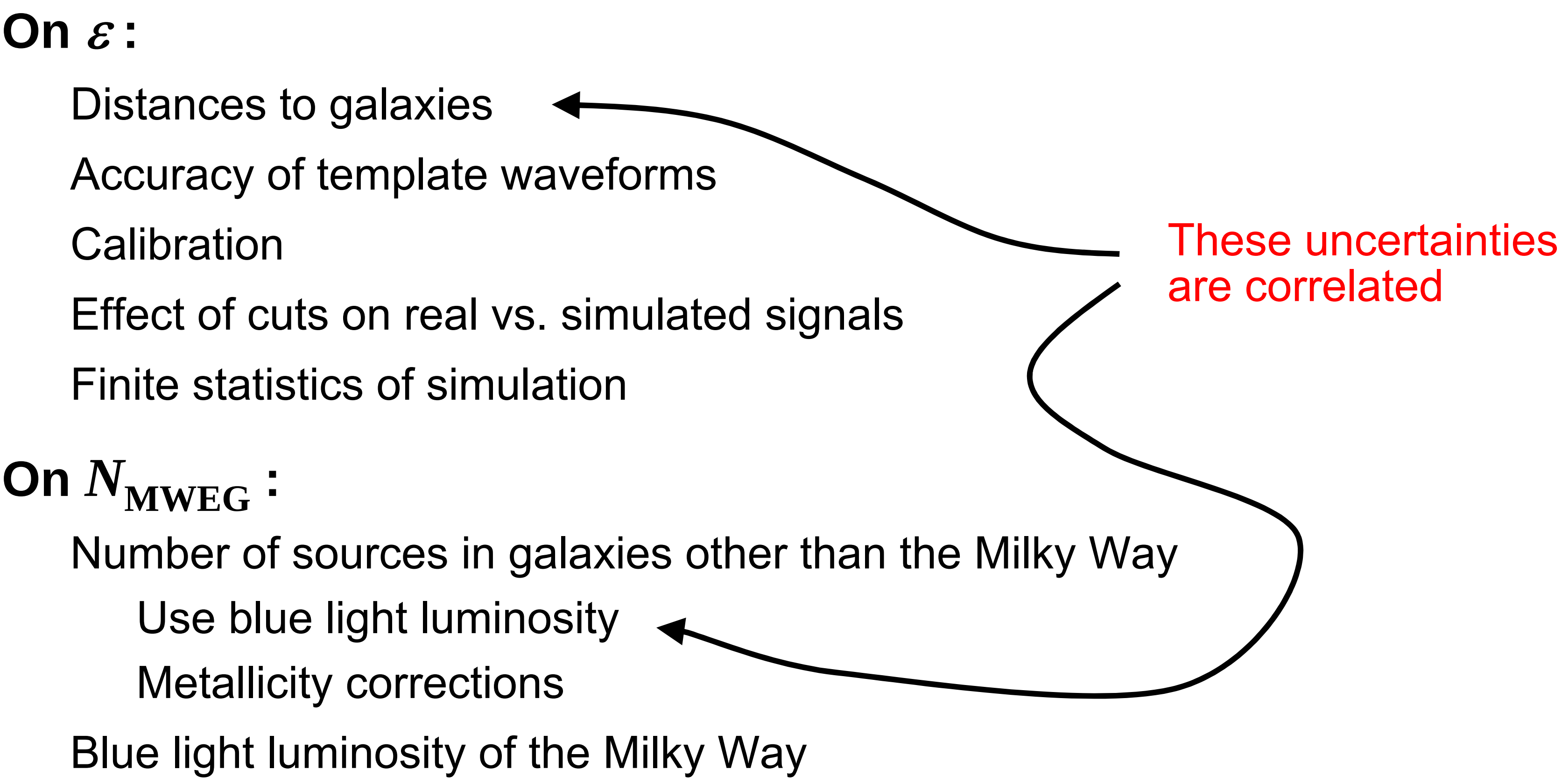
Can take expected background into account

P_b = Chance of all background events having $\rho < \rho_{\text{max}}$

Rigorous frequentist confidence interval (one-sided)

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

Sources of Systematic Uncertainty



On ε :

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

On $N_{\mathbf{MWEG}}$:

- 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

Observation time (T_{obs}) : 355 hours

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.)**

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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

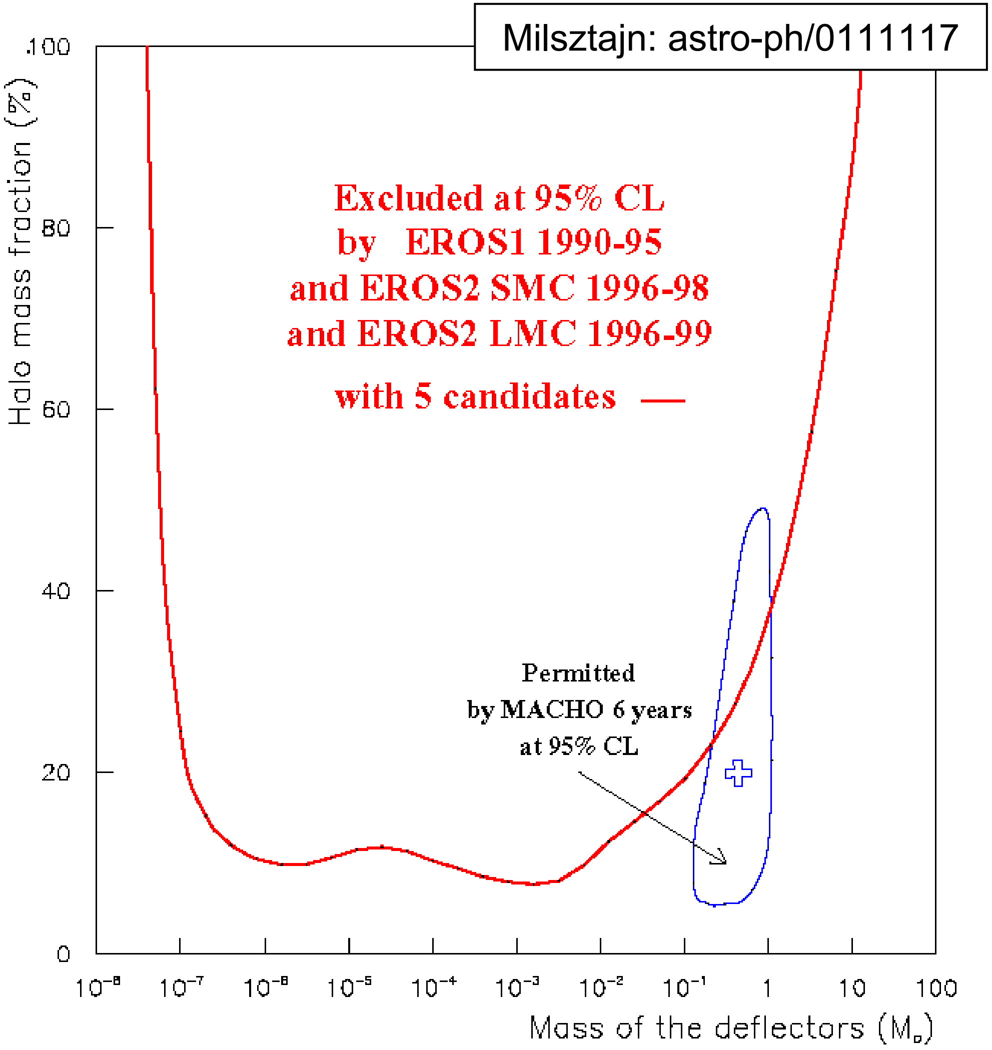
Max. visible range: (for 1.4+1.4 $M_\odot$, optimally oriented, SNR=8)	H1: **~4 to 10 Mpc** L1: ~2.5 Mpc H2: ~2 Mpc GEO: ~45 kpc (operated for part of S3 run)

- 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 $m = (0.25{\sim}0.3)\, M_\odot$ easily

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 $M_\odot$
- Post-Newtonian expansion is inaccurate for mergers within LIGO band

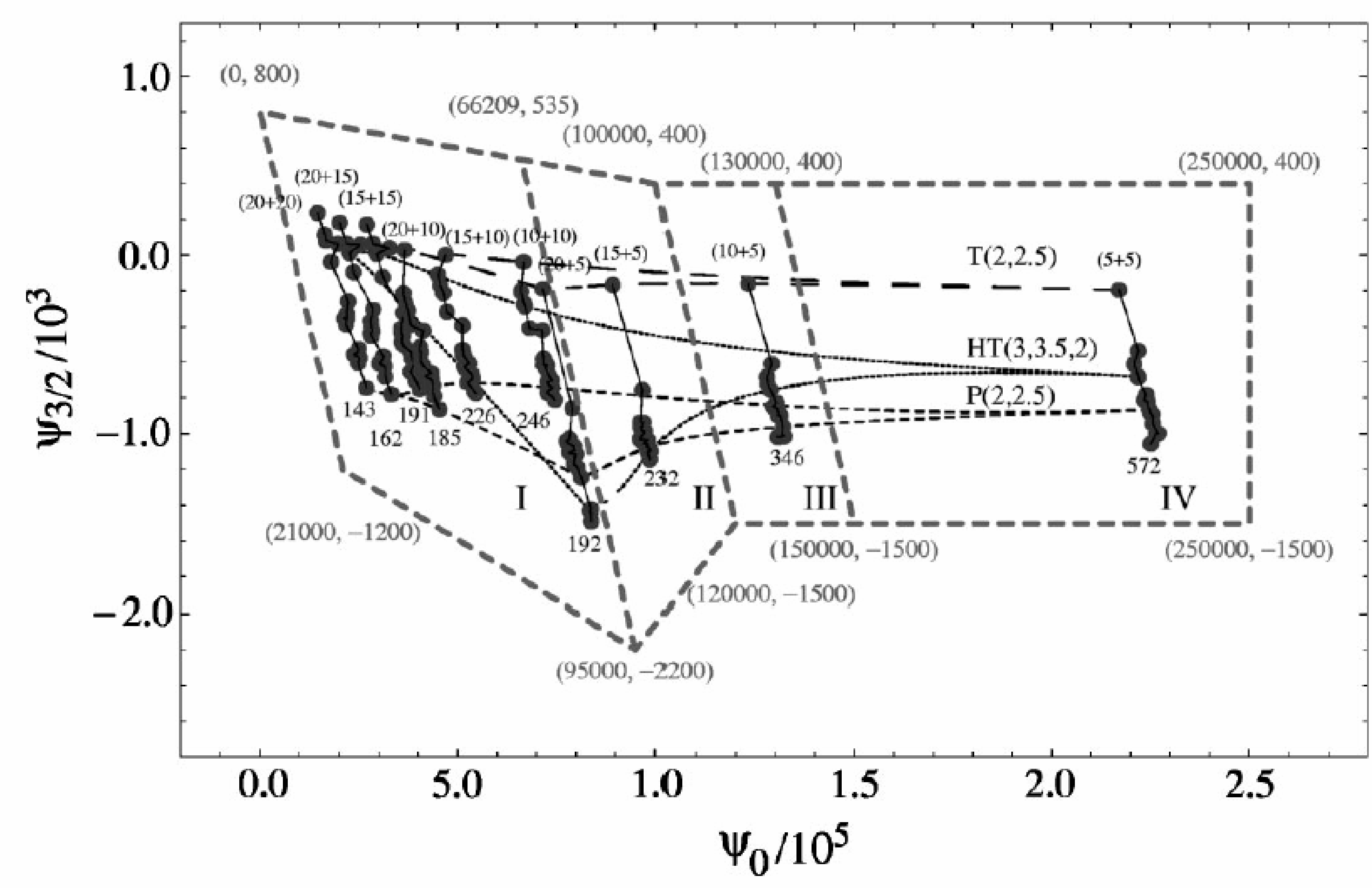
Use matched filtering with "BCV detection template family"

- 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 !