Searching for Gravitational Waves from the Coalescence of High Mass Black Hole Binaries

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Introduction

- Moving towards Advanced LIGO
  - Hardware: Optics, Lasers, Seismic Isolation, Suspensions
  - Software: Data Acquisition, Data Analysis
- CBC-BBH group is developing the GSTLAL analysis pipeline for BBH detection at aLIGO
  - iLIGO: iHOPE
  - aLIGO: aHOPE, GSTLAL

LIGO

Objectives

- Run high-statistics simulation to evaluate the sensitivity of the GSTLAL analysis pipeline
- Test the readiness of the GSTLAL analysis pipeline for advanced LIGO
  - » Include aligned spins
  - » Push down cut off frequency to 30 Hz
  - » Expand the mass range

GSTLAL Analysis Pipeline

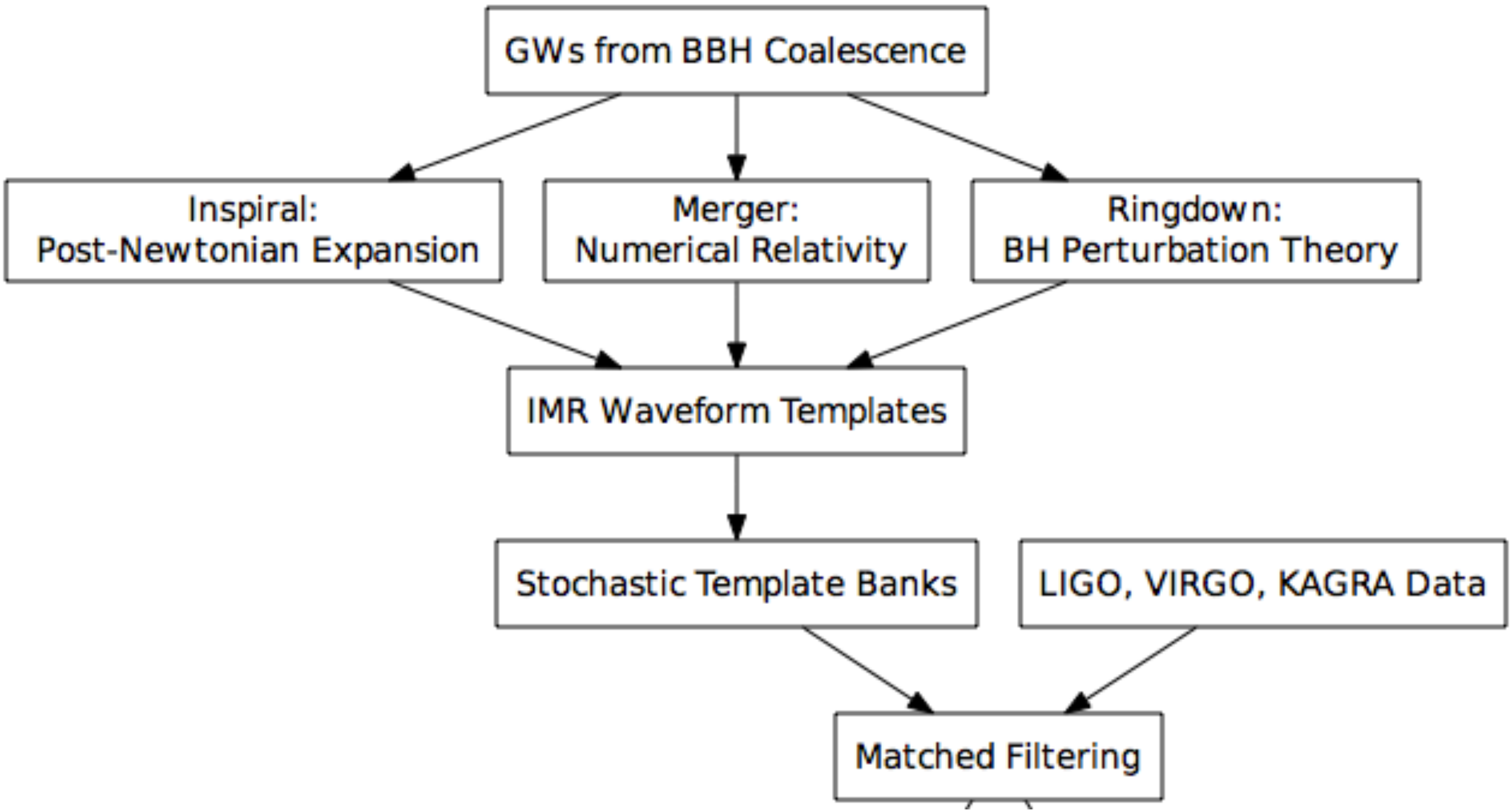
Distinguishing Feature:

- Low latency: compare with E&M searches

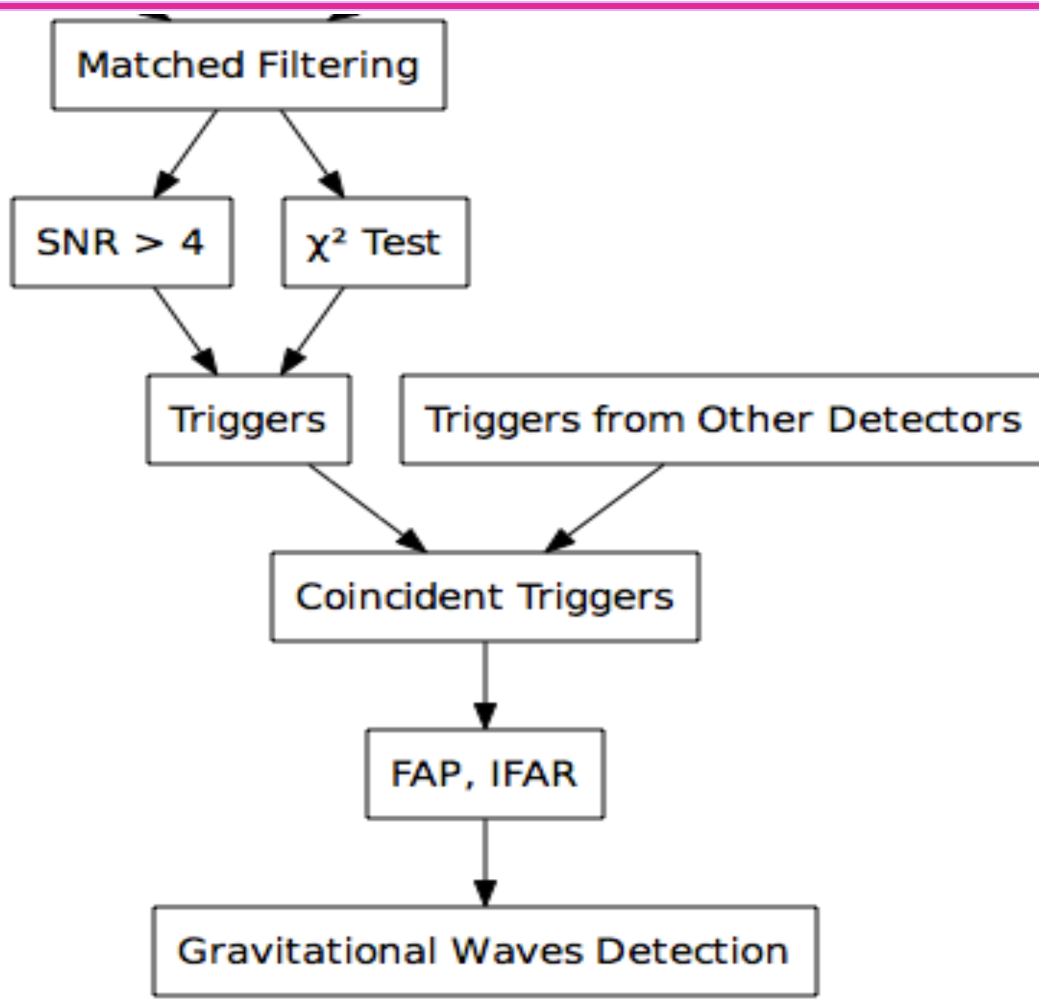
Improvements:

- IMR waveforms rather than SpinTaylor
- Includes aligned spins
- (Future: To include precessing spins)

GSTLAL Analysis Pipeline Flowchart



GSTLAL Analysis Pipeline Flowchart



Matched Filtering

- Motivation: optimal detection technique for known modulated sinusoidal data, with Gaussian and stationary detector noise
- Output: Signal-to-noise ratio

$$\rho(t) \equiv \frac{|z(t)|}{\sigma} \qquad \sigma = \sqrt{\langle \tilde{h} \,|\, \tilde{h} \rangle} = \sqrt{4 \int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n(f)}\, df}$$

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

Coping with "glitches"

- Not perfect detectors have "glitches": non-Gaussian, non-stationary detector noise fluctuations
- χ^2 test: compares data with template + Gaussian noise
- Computed simultaneously with SNR in GSTLAL

Significance of Coincident Triggers

- Final discriminator: false alarm probability (FAP): probability of identifying noise as signals at a likelihood L when the data contain only noise

$$\mathcal{L}(\rho_1, \chi_1^2, \ldots \rho_D, \chi_D^2, \bar{\theta}) = \frac{P(\rho_1, \chi_1^2, \ldots \rho_D, \chi_D^2, \bar{\theta}|s)}{P(\rho_1, \chi_1^2, \ldots \rho_D, \chi_D^2, \bar{\theta}|n)}$$

- FAP is calculated from SNR and χ^2
- In practice, use inverse false alarm rate (IFAR)

Testing GSTLAL pipeline

- Stochastic template banks: specified mass range and spin range
- Injections: simulated signals + recolored S6 data
- Pipeline runs
- Evaluate the pipeline efficiency through injection accuracy, missed and found plots, horizon distance, SNR vs. χ^2 , FAP

Pipeline Run Status – Banks

	Shape	Number of Templates	Component Mass	Total Mass	Mass Ratio	F-low	Spin
Sq1	square	13713	[4.9, 22]	[9.8, 44]	[1, 4]	20Hz	[-0.9, 0.9]
Sq2	square	27430	[4.9, 22]	[9.8, 44]	[1, 4]	20Hz	[-0.9, 0.9]
Sq3	square	18370	[4.9, 22]	[9.8, 44]	[1, 4]	20Hz	[-0.2, 0.9]
Sq4	square	12237	[4.9, 22]	[9.8, 44]	[1, 4]	30Hz	[-0.9, 0.9]
Trape5	trapezoid	32289	[1, 44]	[9.8, 44]	[1, 4]	30Hz	[-0.9, 0.9]
Trape6	trapezoid	100713	[1, 44]	[9.8, 44]	[1, 4]	20Hz	[-0.9, 0.9]
LgSq	square	13561	[4.9, 55]	[9.8, 110]	[1, 4]	30Hz	[-0.9, 0.9]
LgTrape	trapezoid	32597	[1, 110]	[9.8, 110]	[1, 4]	30Hz	[-0.9, 0.9]

Pipeline Run Status – Dailies

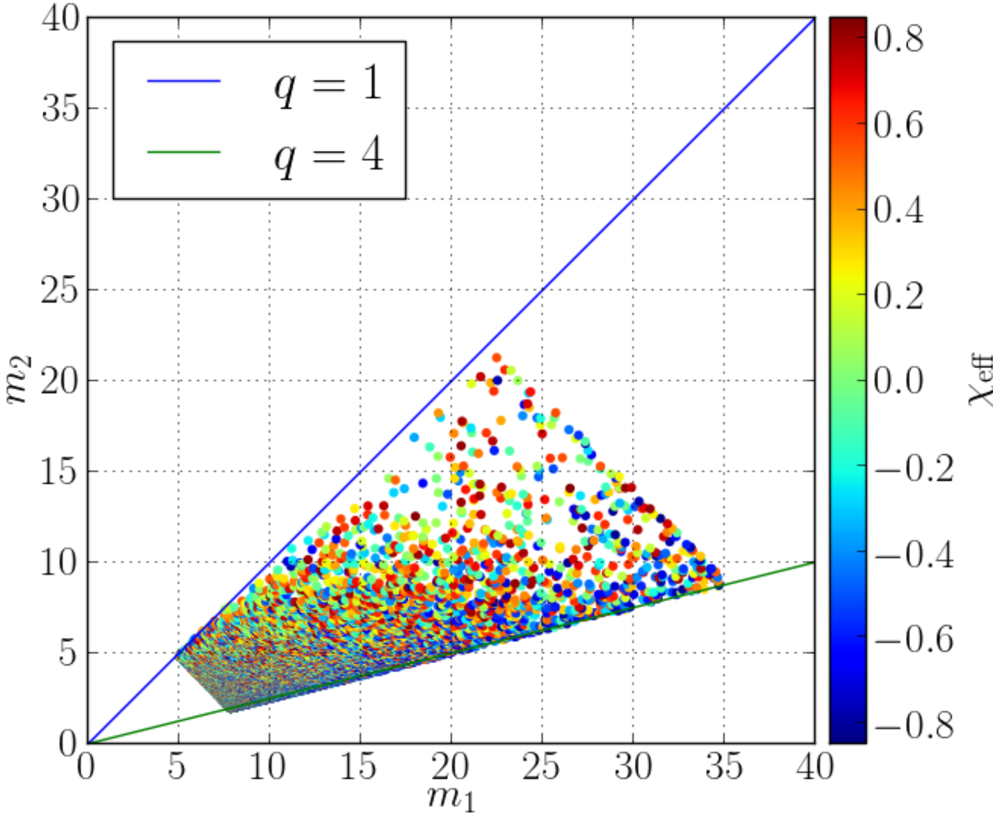
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Sq1	√	X	X	X	X	X	X
Sq2	√	√	√	√	√	√	√
Sq3	√	X	X	X	X	X	X
Sq4	√	X	X	X	X	X	X
Trape5	√	√	√	√	√	√	√
Trape6	X	X	X	X	X	X	X
LgSq	√	△	△	△	△	△	△
LgTrape	√	△	△	△	△	△	△

Table 4.2: GSTLAL daily runs status (√: Finished; ○: Running; △: Planning; X: No plan to run.)

Ex: Day 1 Run with Trape5 Bank

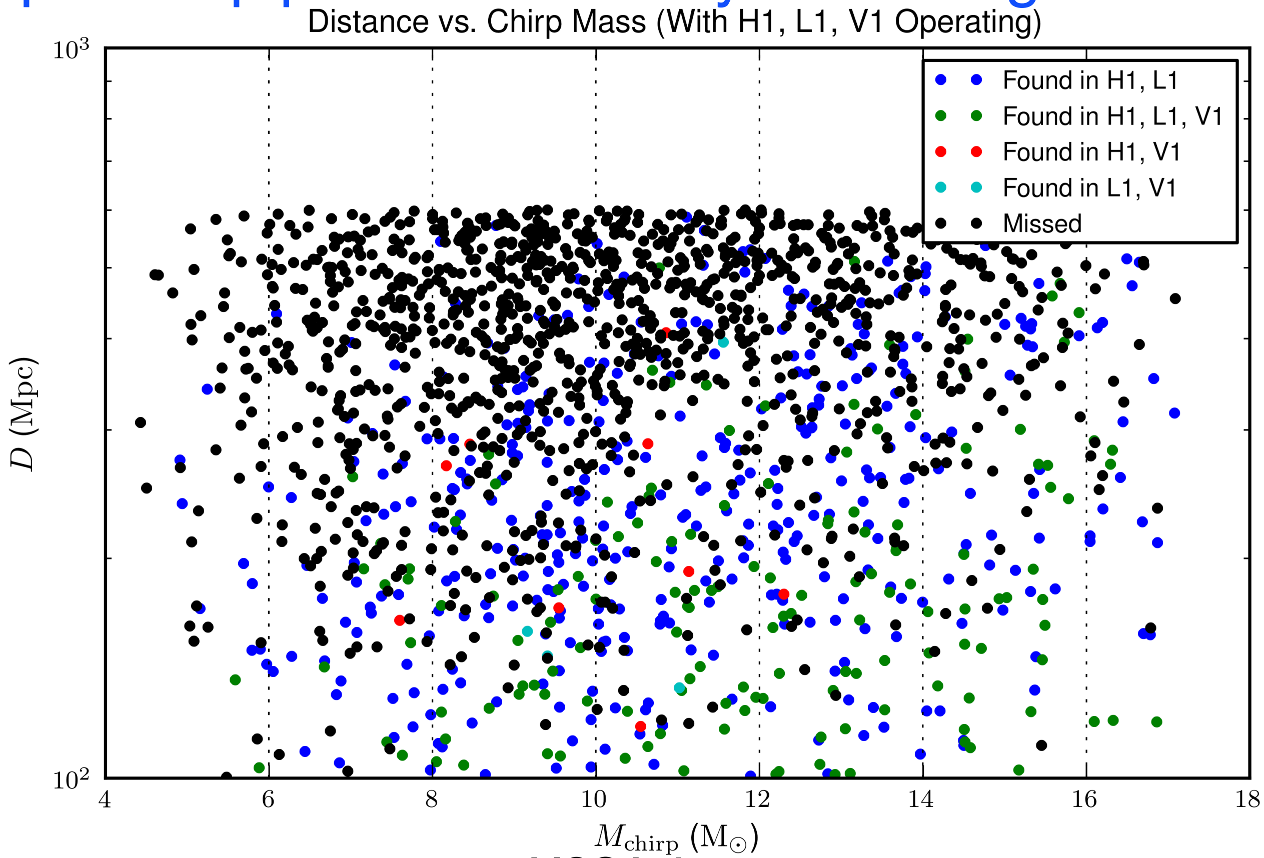
2 Table 2. BANK PARAMETERS SUMMARY

BANK PARAMETERS	VALUE
Number of Templates	32289
Approximant	IMRPhenomB
Noise Model	aLIGOZeroDetHighPower
Mass1 Range	[1, 44]
Mass2 Range	[1, 44]
Total Mass Range	[9.8, 44]
Mass Ratio Range	[1, 4]
Spin1 Range	[-0.9, 0.9]
Spin2 Range	[-0.9, 0.9]
Cut Off Frequency	30



Ex: Missed and Found

- Aids in diagnosing the pipeline and providing the expected pipeline sensitivity to real signals

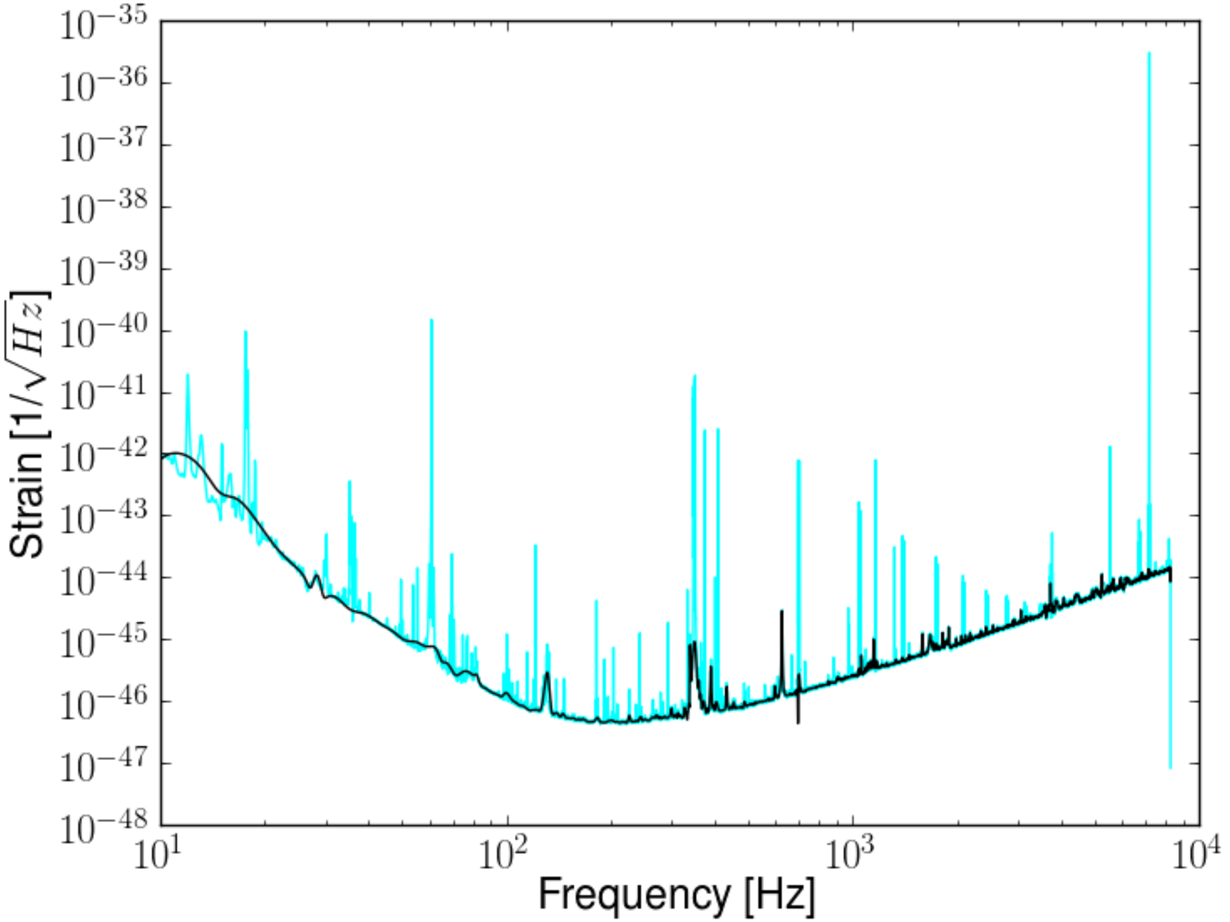


Ex: Horizon Distance

- Useful search sanity check
- Horizon distance: where a CBC system will produce a signal with expected SNR of 8
- Mean Sensitive Distance: horizon distance averaged over all sky position and orientation angles
- To evaluate the sensitivity:
  - » Compute theoretical horizon distances
  - » Compare with real pipeline run horizon distances

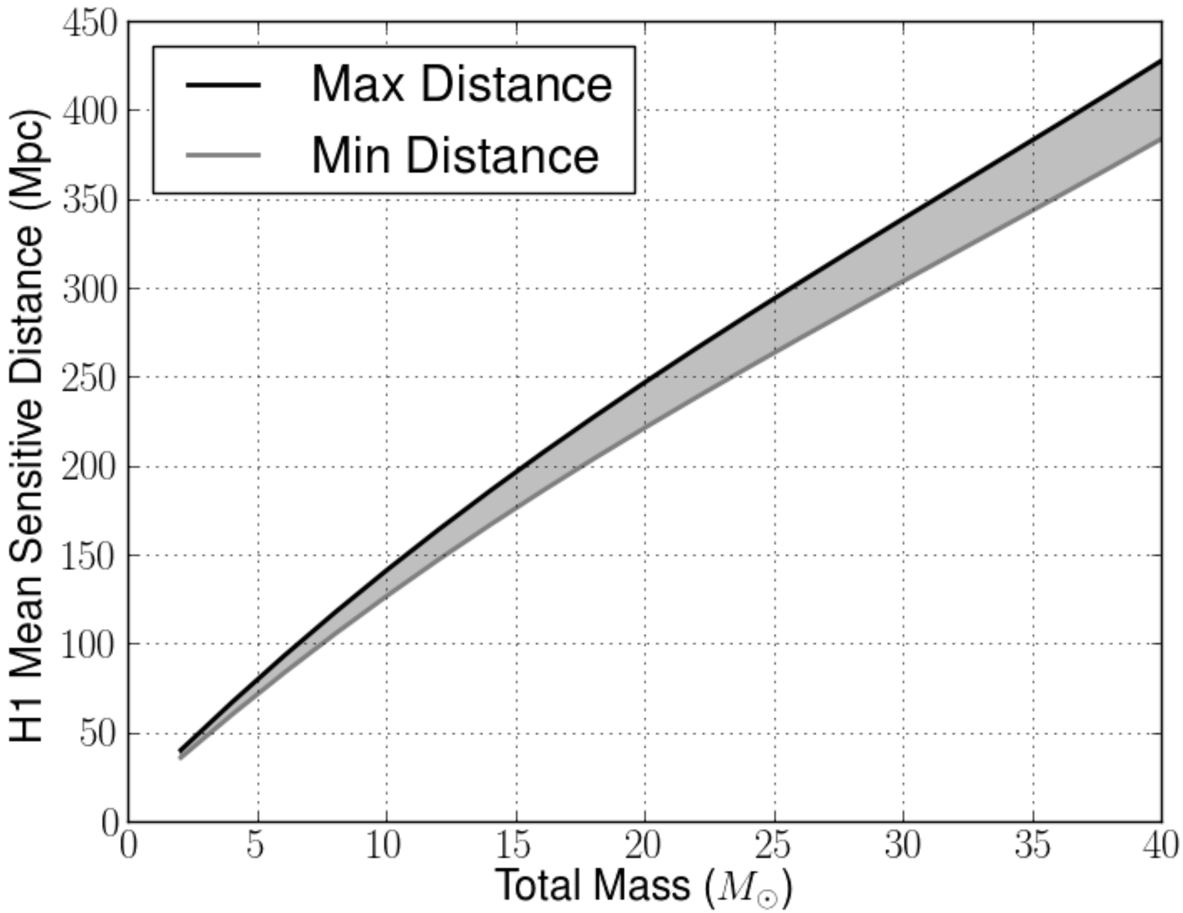
Ex: Pipeline Efficiency

- PSD function for horizon distance calculation



Ex: Pipeline Efficiency

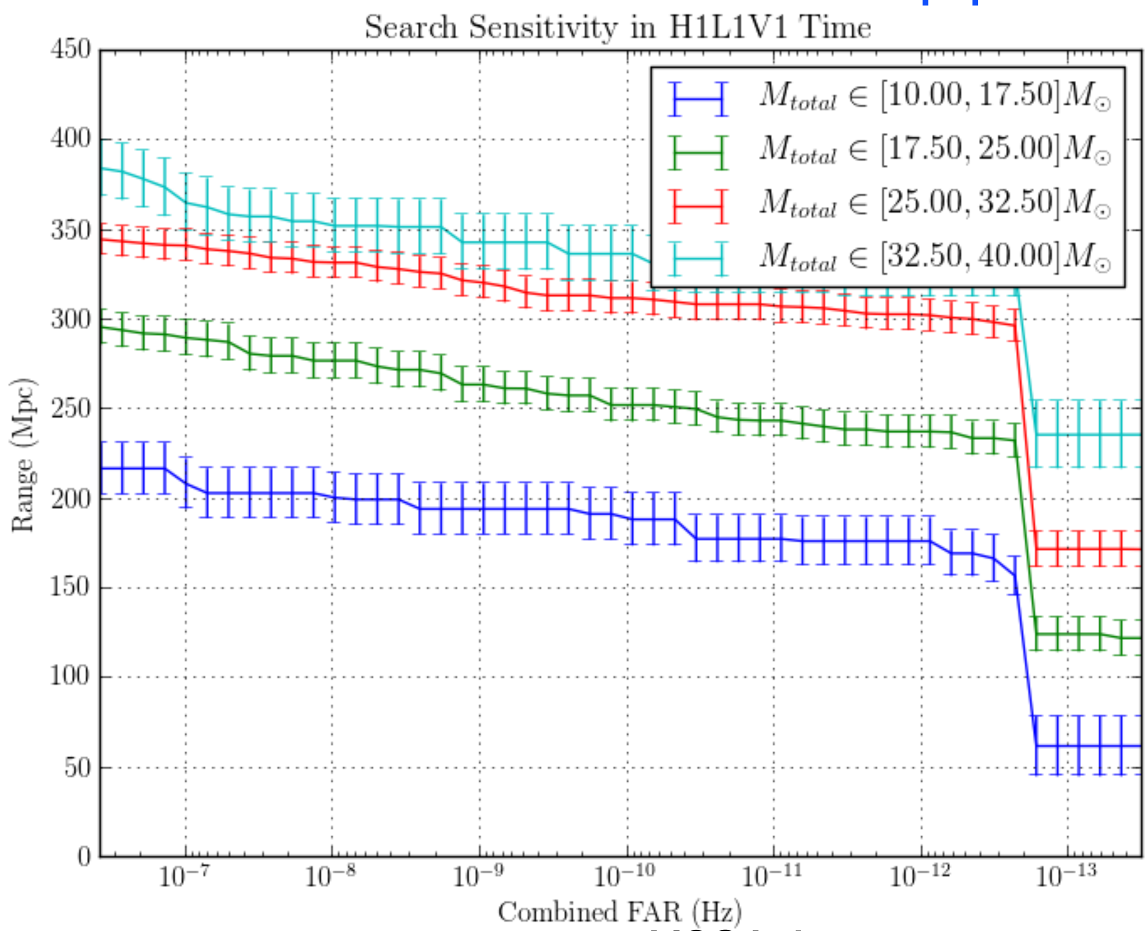
- Theoretical mean sensitive distance



Check: look at 15 solar masses

Ex: Pipeline Efficiency

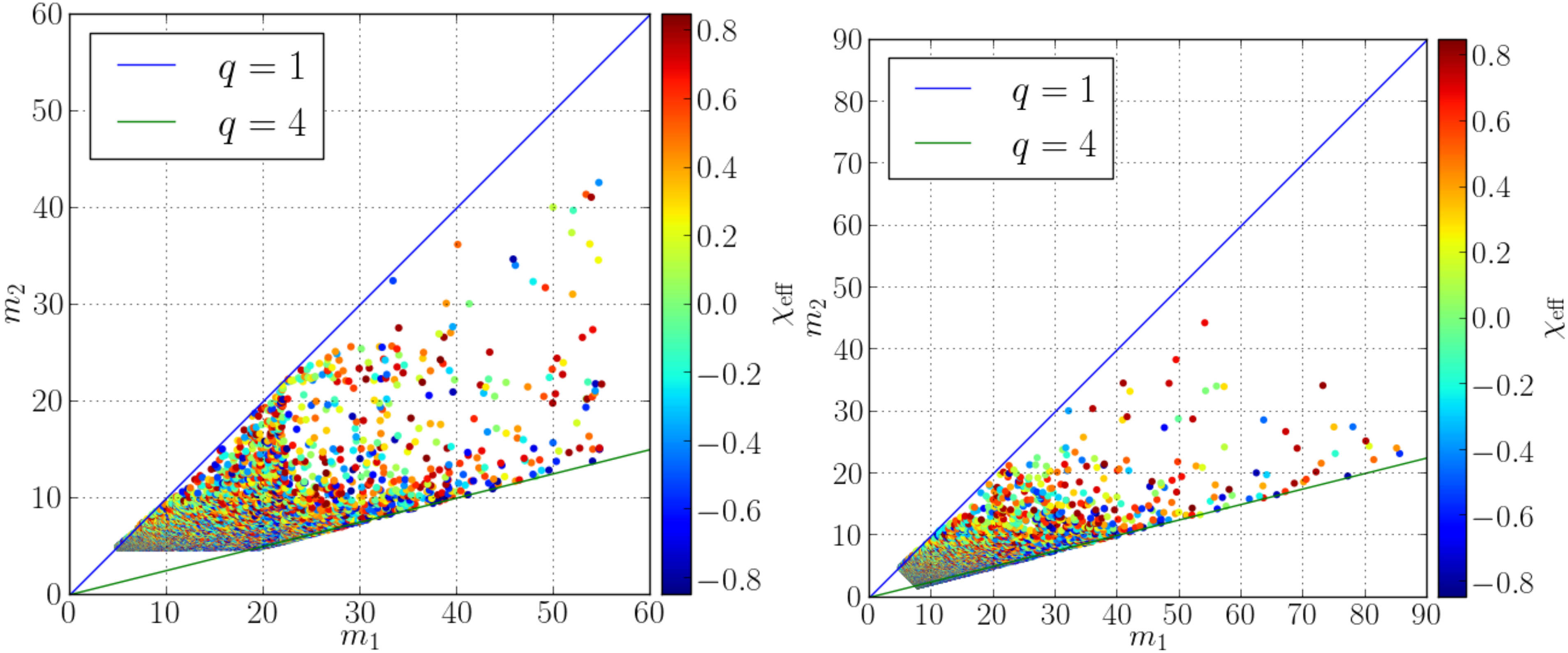
- Mean sensitive distance from pipeline runs



Check: look at 15 solar masses

Expanding BBH Mass Range

- Pushing up to 100 solar masses, down to 6 solar masses
- Had problems, need to adjust injection distance



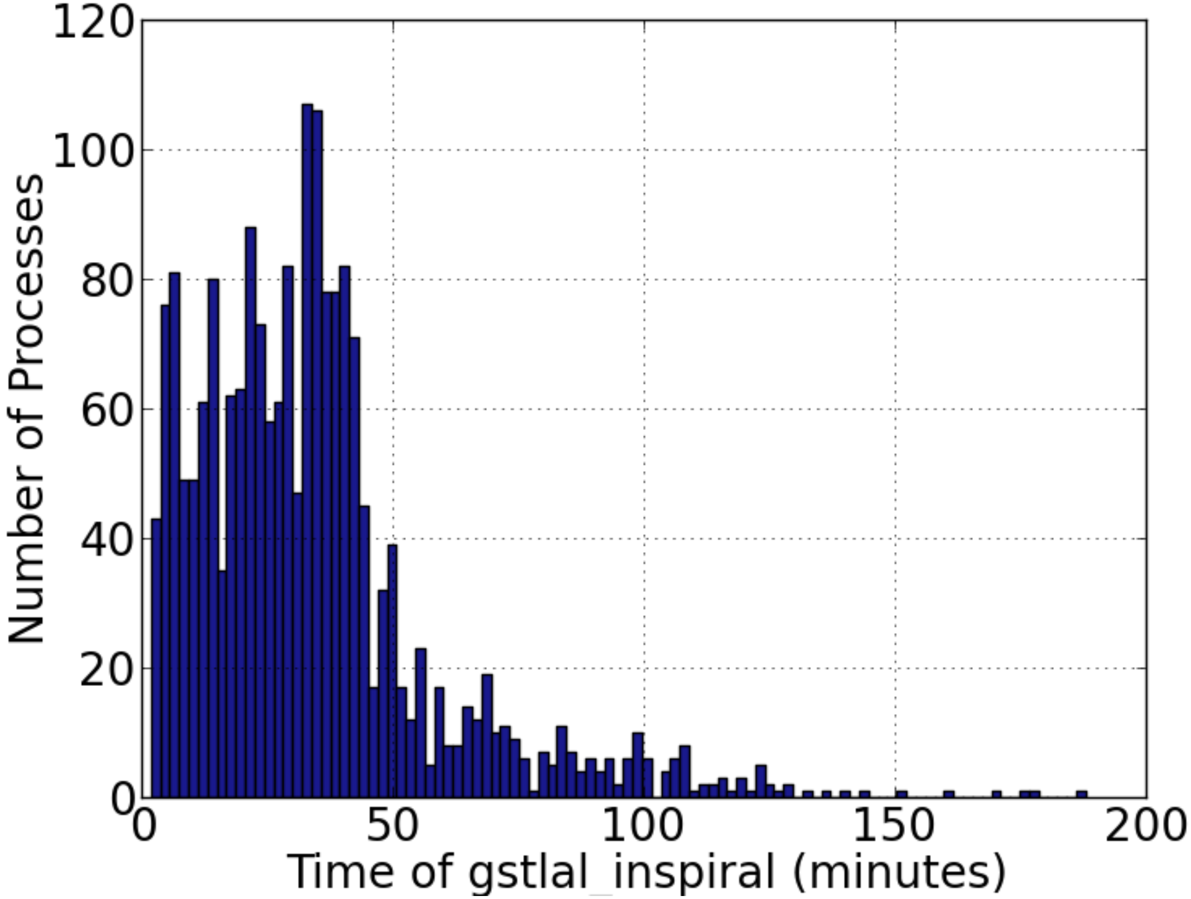
Timing Analysis

- A pipeline has many processes, which in turn have many jobs
- Different jobs of the same process take different time to finish


PROCESS
(#OCCURANCE) [MAX D+HH:MM]
gstlal_reference_psd
(14) [0+00:28]
gstlal_svd_bank
(4521) [0+00:06]
gstlal_plot_psd_horizon
(1) [0+00:03]
gstlal_inspiral
(1960) [0+03:08]
gstlal_inspiral_calc_likelihood
(140) [0+00:38]
lalapps_run_sqlite
(424) [0+00:16]
ligolw_sqlite
(150) [0+00:28]
gstlal_inspiral_marginalize_likelihood
(4) [0+00:53]
ligolw_inspinjfind
(3) [0+00:00]
gstlal_compute_far_from_snr_chisq_histograms
(1) [0+00:00]
gstlal_inspiral_plot_background
(1) [0+00:05]
gstlal_inspiral_plot_sensitivity
(1) [0+00:01]
gstlal_inspiral_plotsummary
(1) [0+00:03]
gstlal_s5_pbh_summary_page
(2) [0+00:01]

Timing Analysis

- Histogram of gstlal_inspiral



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Conclusion

- We have successfully proved the effectiveness of the GSTLAL analysis pipeline, down to 30 Hz cut off frequency, with aligned spins included, and the whole mass range covered

- There is still optimization work to do regarding the pipeline's performance and timeliness, but soon, GSTLAL will be ready for aLIGO

Future Work

- Combine dailies into weeklies, weeklies into monthlies, etc.
  - » Weeklies: combine daily coincident triggers and backgrounds together. Can better estimate backgrounds and separate them.
  - » Monthlies, yearlies: collections of weeklies for better visualization
- Figure out reasons for outliers
- Compare existing runs with runs using Gaussian noise
- Tune the pipeline parameters for better accuracy and faster run time

Acknowledgements

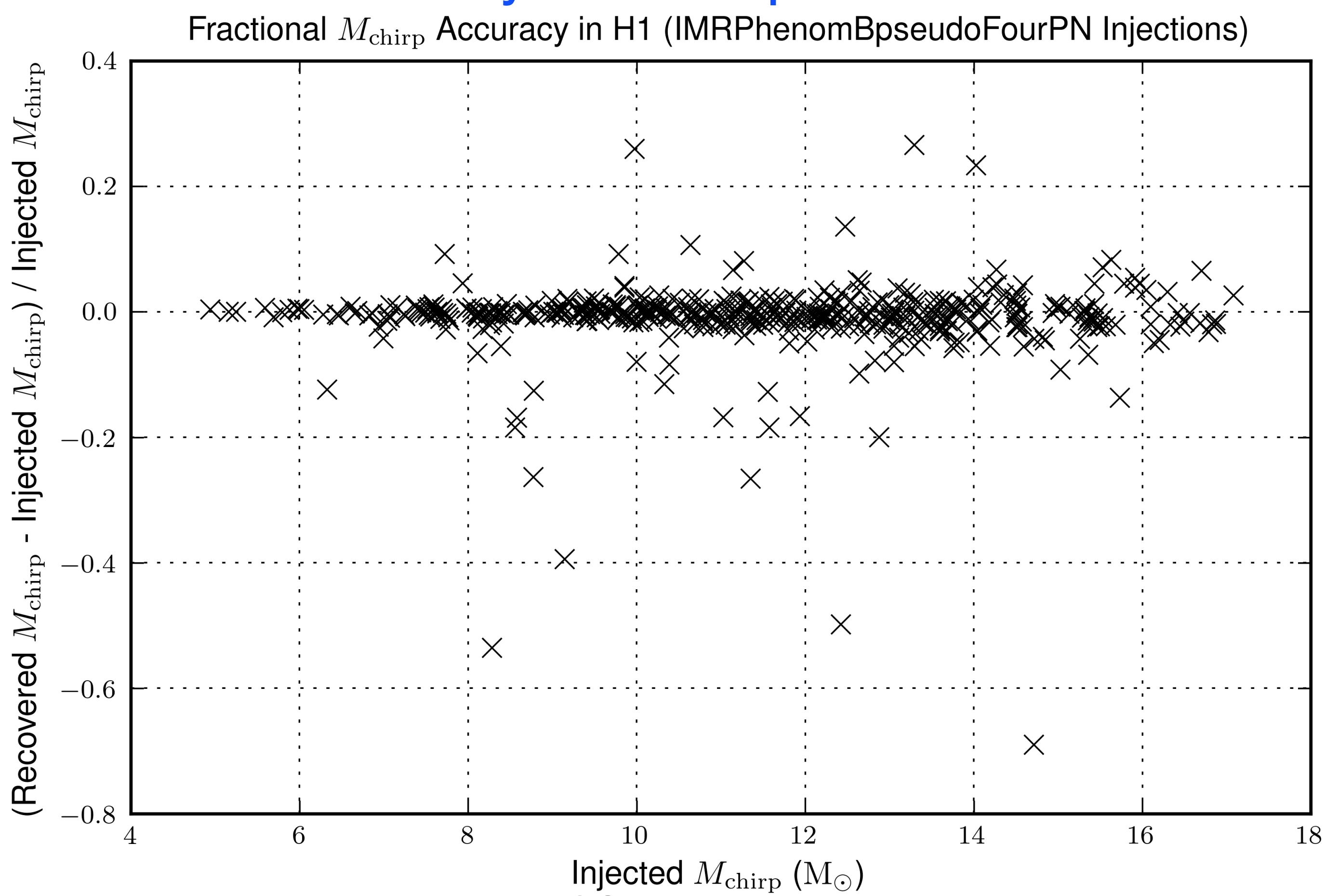
- Prof. Alan Weinstein, Tjonnie Li, Surabhi Sachdev
- LIGO Scientific Collaboration
- Caltech SURF
- NSF

Thank you!

Backup Slides

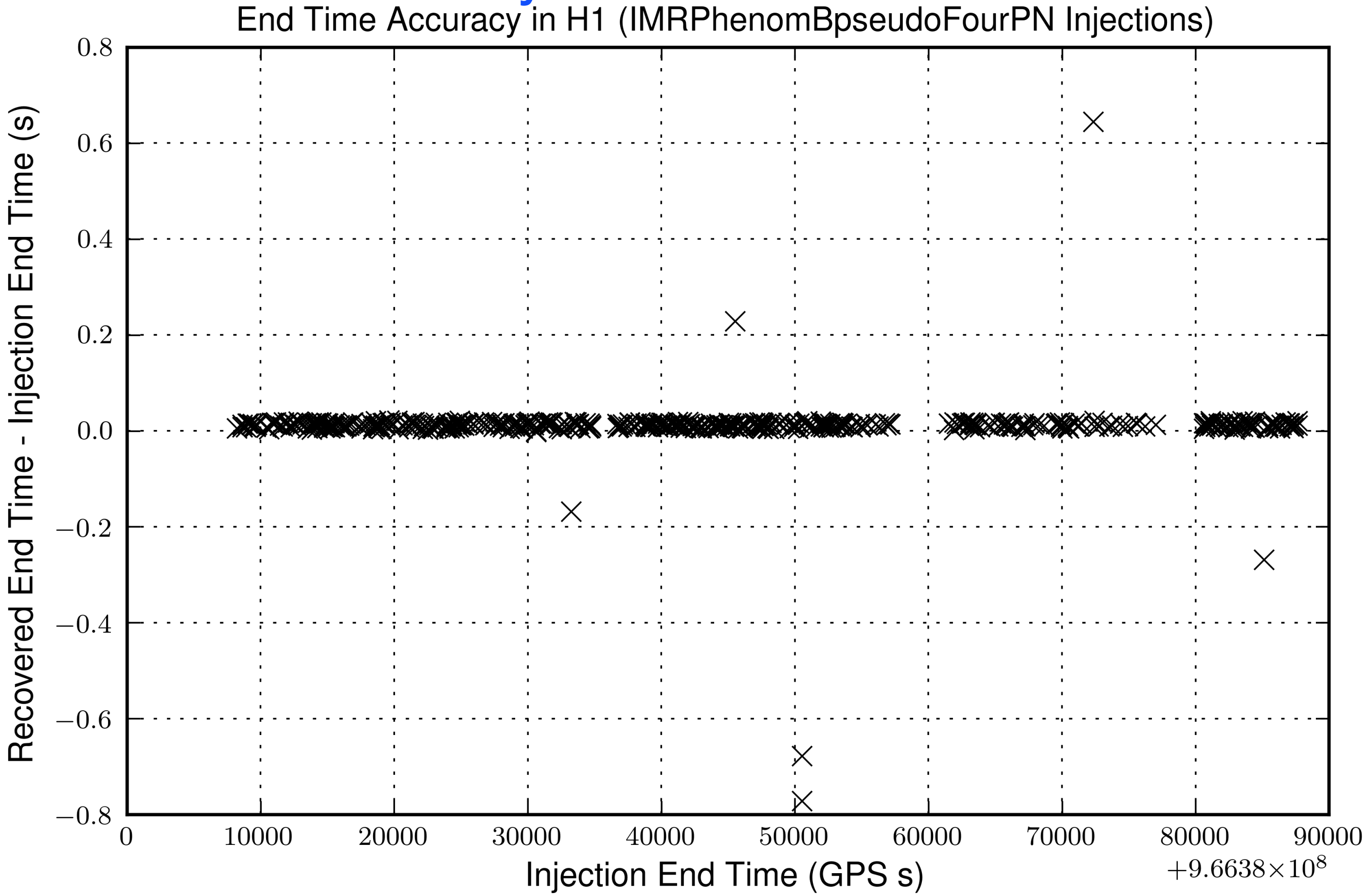
Ex: Injection Accuracy

- Successful recovery of mchirp



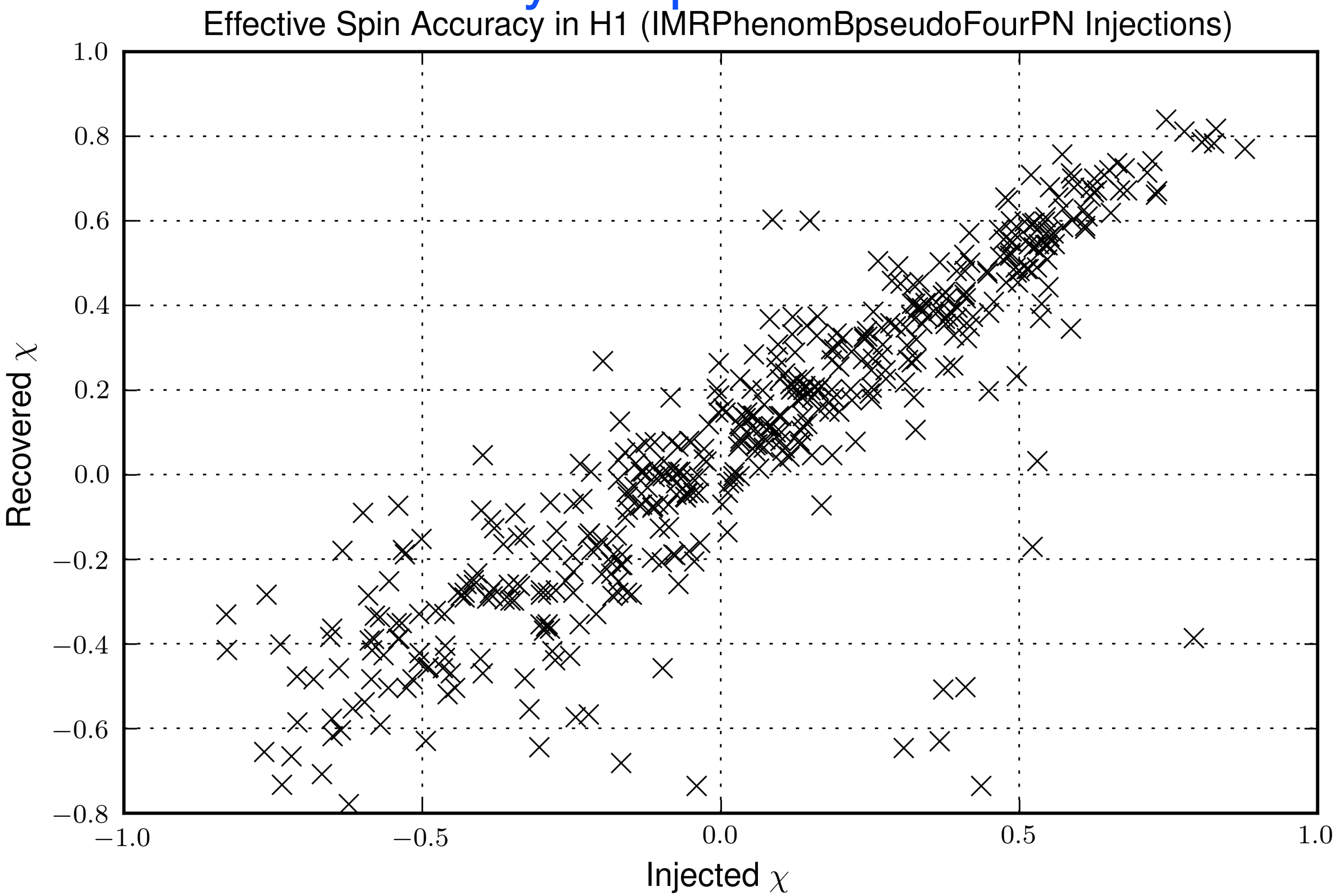
Ex: Injection Accuracy

- Successful recovery of time



Ex: Injection Accuracy

- Successful recovery of spins



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Ex: Missed and Found Table

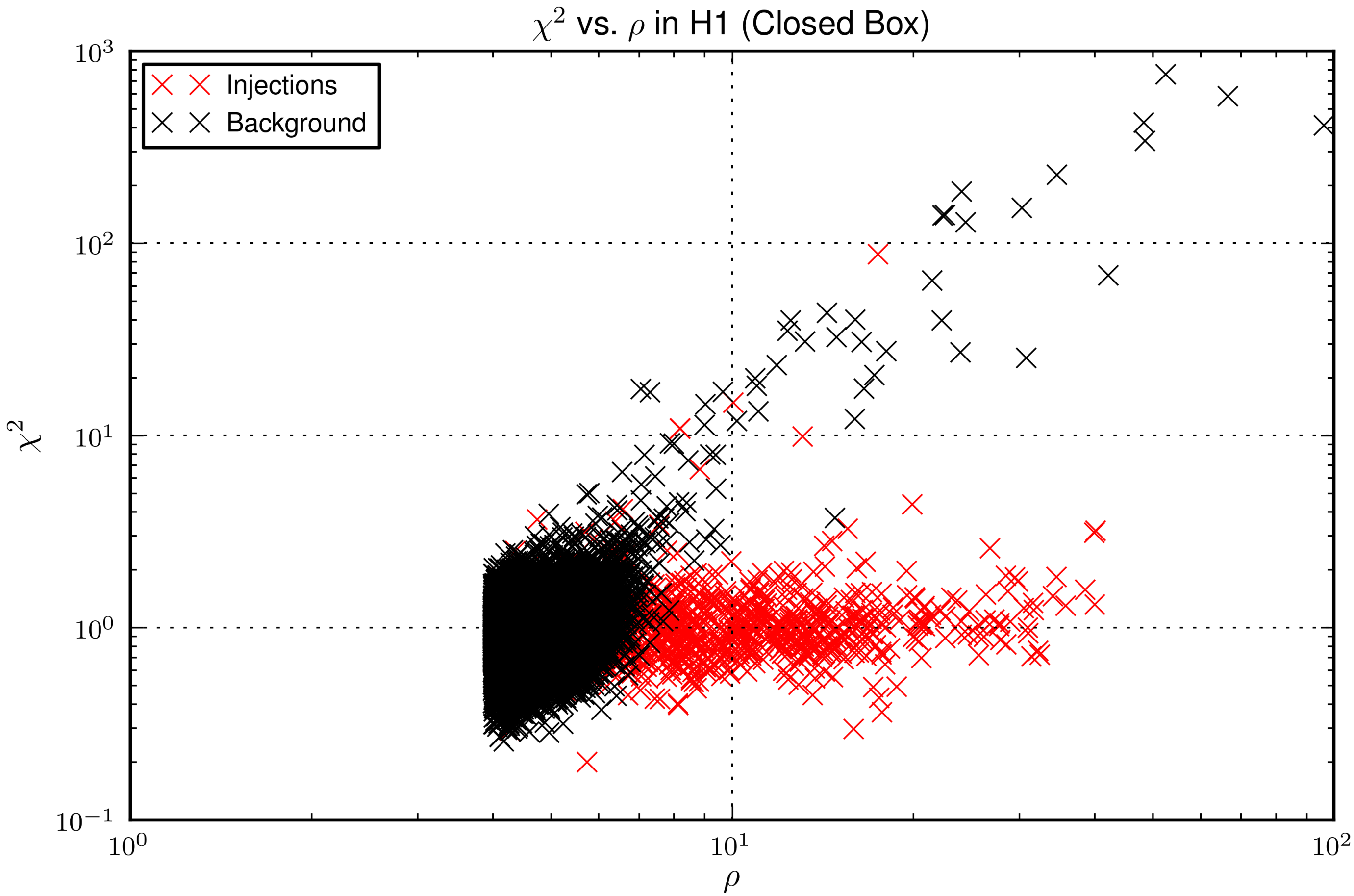
5 Table 2. INJECTION SUMMARY TABLE

ON INSTRUMENTS	PARTICIPATING INSTRUMENTS	MISSED/FOUND
H1V1	H1V1	FOUND: 35
H1V1	---	MISSED: 374
H1L1V1	H1L1	FOUND: 404
H1L1V1	H1L1V1	FOUND: 151
H1L1V1	H1V1	FOUND: 9
H1L1V1	L1V1	FOUND: 6
H1L1V1	---	MISSED: 1096
H1L1	H1L1	FOUND: 16
H1L1	---	MISSED: 26
L1V1	L1V1	FOUND: 26
L1V1	---	MISSED: 206

5 Table 2. Summary of missed and found injections broken up by detector time

Ex: Detection Statistics

- Well separated signals and backgrounds



Ex: Detection Statistics

- FAP calculated from SNR and χ^2