Reducing False Alarms in Searches for Gravitational Waves from Coalescing Binary Systems

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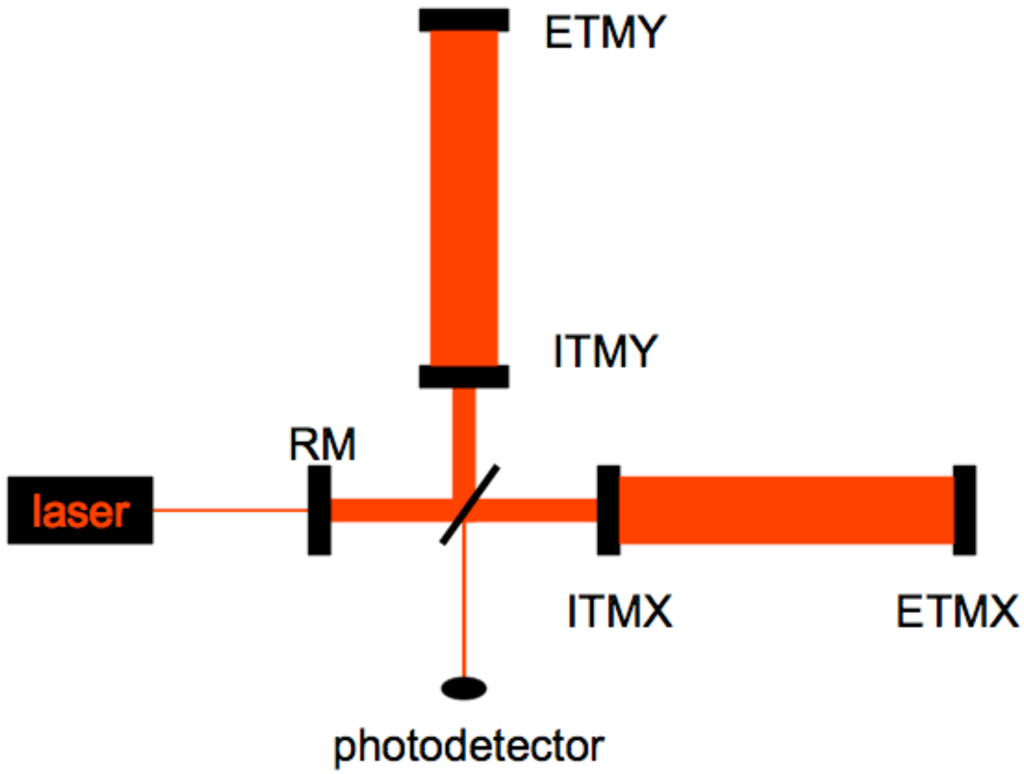
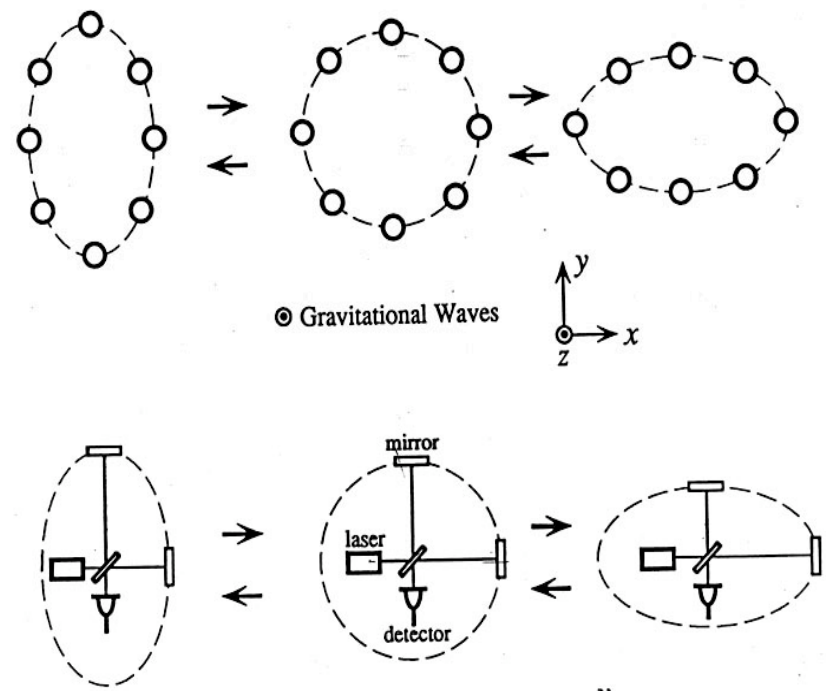
Outline

- LIGO
- Sources of Gravitational Waves
- Data Analysis for Coalescing Binary Systems
- Methods to Reduce False Alarms - χ^2 Veto, r^2 Test
- LIGO S3 Primordial Black Hole Search
- Conclusions

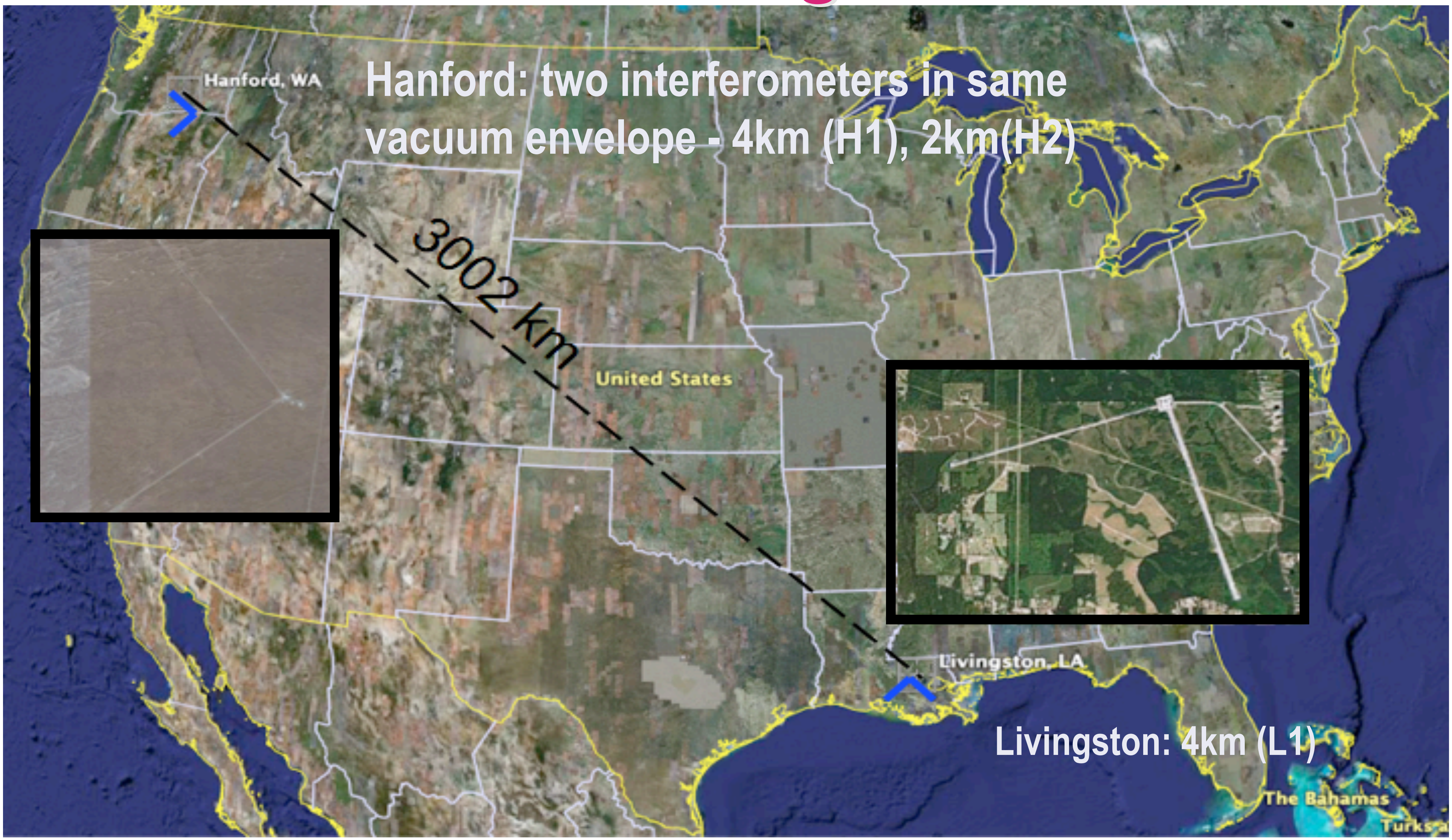
Laser Interferometer Gravitational Wave Observatory (LIGO)





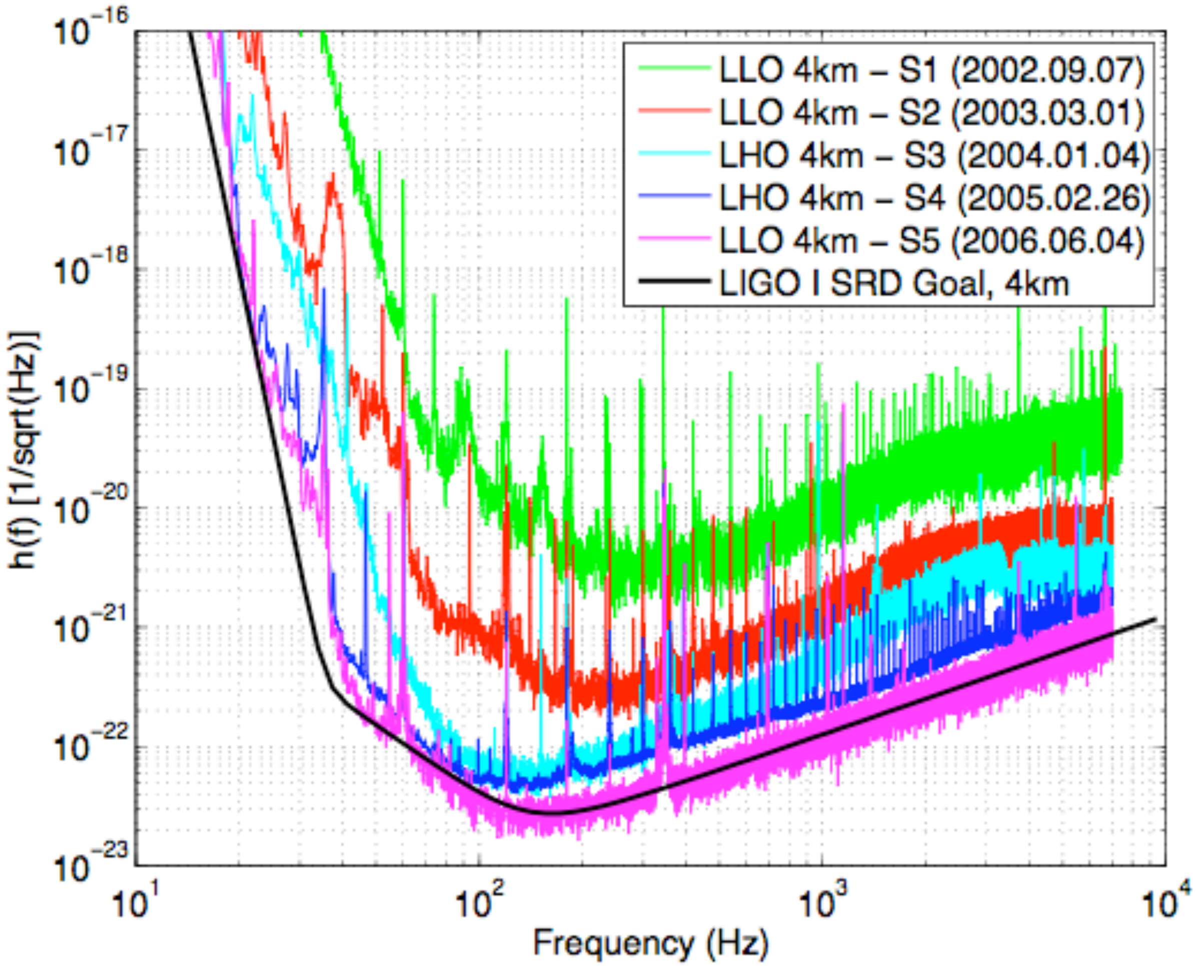
$$s(t) = [\Delta L_x - \Delta L_y]/L$$

LIGO Sites
lsc.org



Generated with Google Earth™

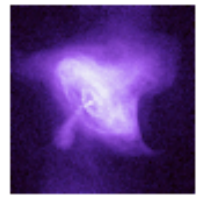
Improved Sensitivity, LIGO Science Runs



- *S1* Aug ‘02 - Sept ‘02
- *S2* Feb ‘03 - April ‘03
- *S3* Oct ‘03 - Jan ‘04
- *S4* Feb ‘05 - March ’05
- *S5* Nov ‘05 - current

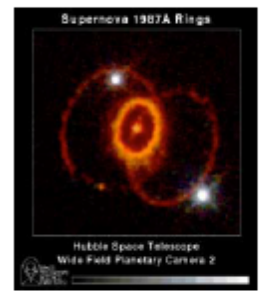
Sources of Gravitational Waves

- *periodic signals*: pulsars

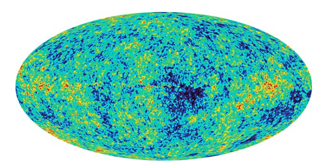


Crab pulsar (NASA, Chandra Observatory)

- *burst signals*: supernovae, gamma ray bursts

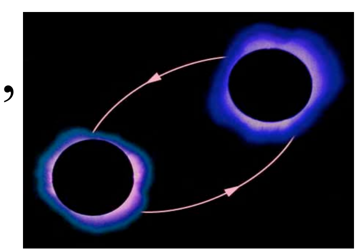


- *stochastic background*: early universe,
  unresolved sources



NASA, WMAP

- *compact binary coalescing (CBC) systems*: neutron stars,
  black holes



Coalescing Binary Systems

- General Relativity predicts the decay of the binary orbit due to the emission of gravitational radiation.

- Waveforms can be well approximated by 2nd order post-Newtonian expansion.

Non -spinning waveforms parameterized by:
  » masses: m_1,m_2, total mass M, or reduced mass μ
  » orbital phase ϕ & orientation ι
  » position in the sky: θ, ϕ

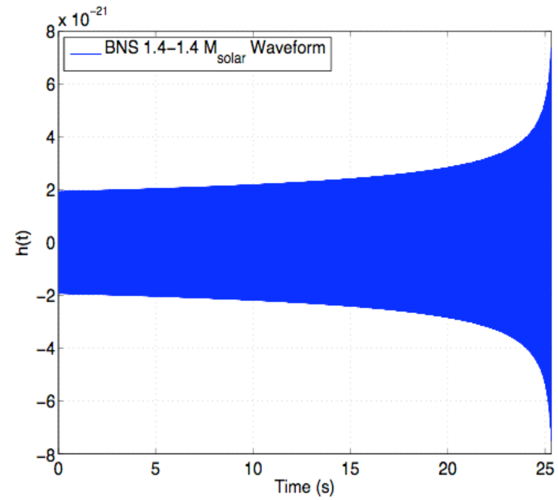
$$F_+ = -\frac{1}{2}(1+\cos^2\theta)\cos 2\phi$$

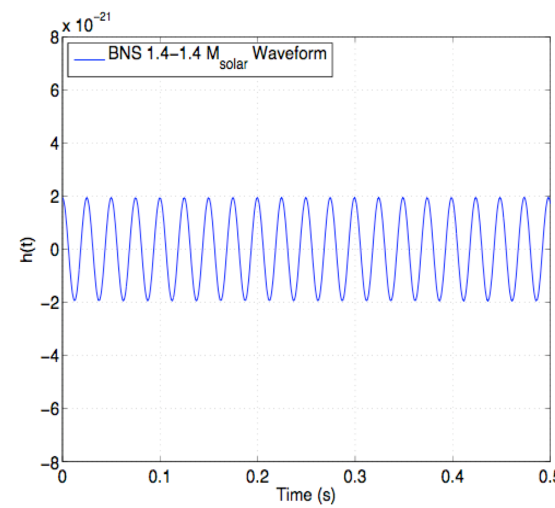
$$h(t) = F_+ h_+(t) + F_\times h_\times(t)$$

$$F_\times = \cos\theta \sin 2\phi$$

$$h_+(t) = \frac{1+\cos^2\iota}{2}\left(\frac{G\mathcal{M}}{c^2 D}\right)\left(\frac{t_c - t}{5G\mathcal{M}/c^3}\right)^{1/4} \times \cos\iota[2\phi_c - 2\phi(t - t_c; \mathcal{M}, \mu)]$$

$$h_\times(t) = \cos\iota\left(\frac{G\mathcal{M}}{c^2 D}\right)\left(\frac{t_c - t}{5G\mathcal{M}/c^3}\right)^{1/4} \times \sin\iota[2\phi_c - 2\phi(t - t_c; \mathcal{M}, \mu)]$$





Coalescing Binary Systems II

- Effective Distance:

$$D_{\text{eff}} = \frac{D}{\sqrt{F_+^2(1+\cos^2\iota)^2/4 + F_\times^2(\cos\iota)^2}}$$

- Chirp Mass:

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

- Symmetric Mass ratio η:

$$\eta = \frac{m_1 m_2}{(m_1+m_2)^2} = \frac{\mu}{\mathcal{M}}$$

Matched Filtering

- Data stream searched using matched filtering between data & template waveform: $s(t) = n(t) + h(t)$

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

Effective Distance:

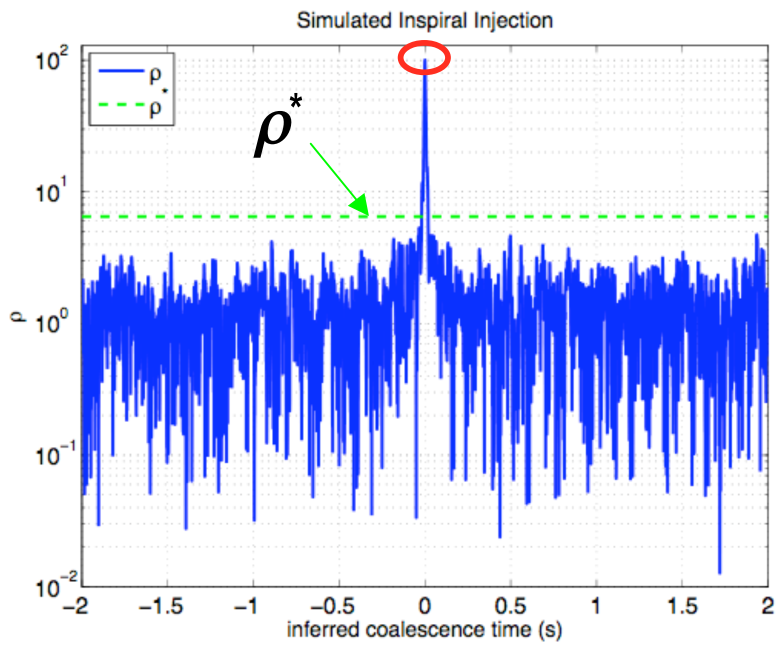
$$D_{\rm eff} = (1{\rm Mpc})\frac{\sigma}{\rho}$$

- Characteristic Amplitude:

$$\sigma^2 = 4\int_0^\infty \frac{|\tilde{h}(f)|^2}{S(f)} df$$

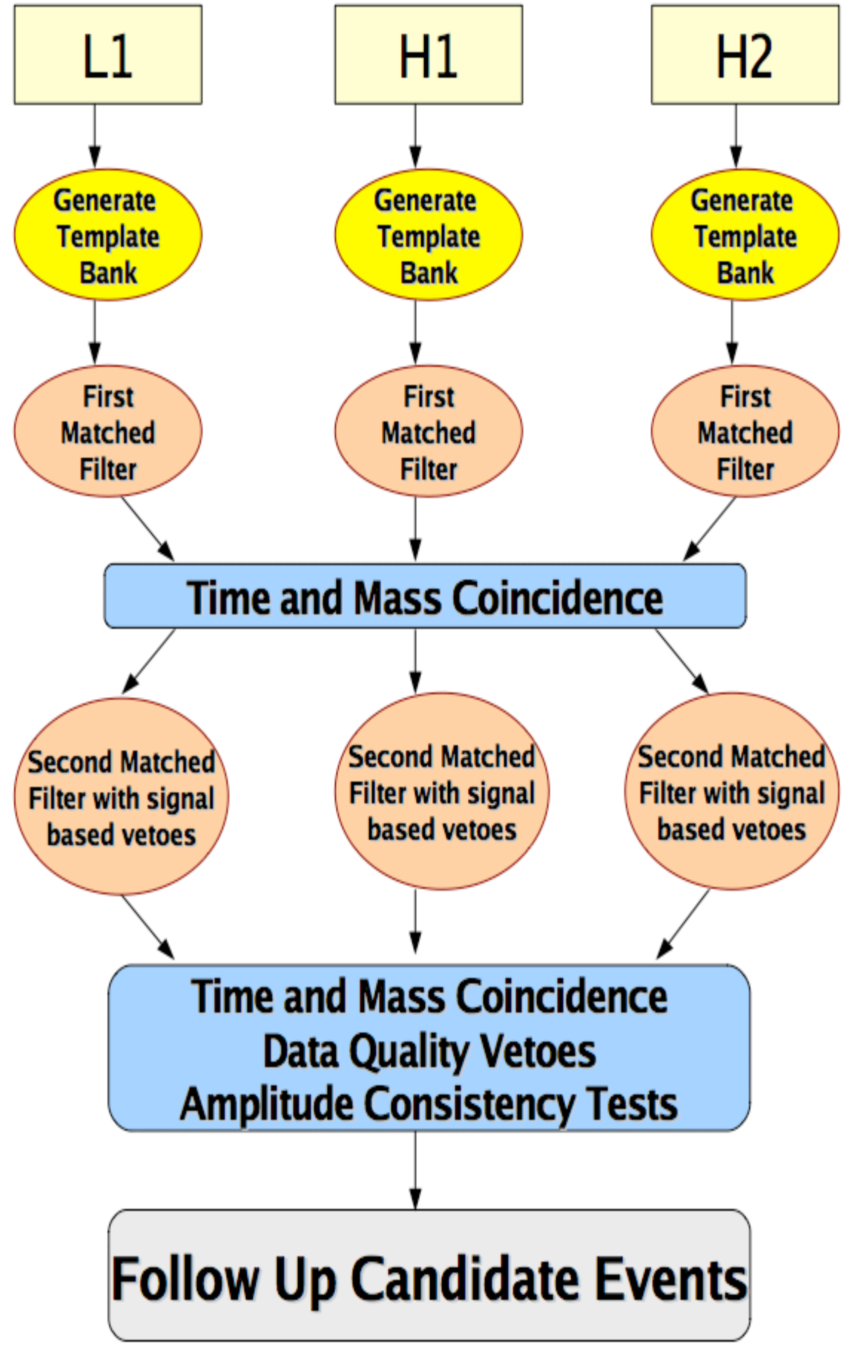
- Signal to Noise Ratio (SNR): $\rho(t) = \frac{|z(t)|}{\sigma}$

- Inspiral Trigger: $\rho = \frac{|z_{\max}|}{\sigma}$ & $\rho > \rho^*$



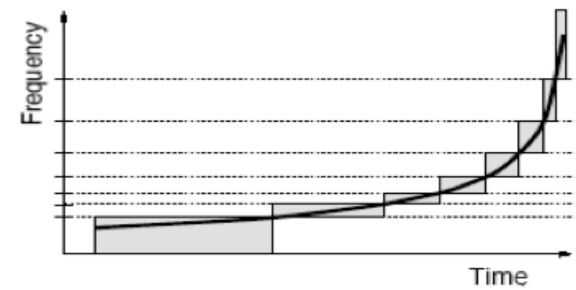
Inspiral Coincidence Pipeline

- Data Collection
- Template Bank Generation: h(f)
- Matched Filter I: z(t), ρ(t), ask $\rho > \rho^*$
- 1st Coincidence (time, η, M_c)
- Matched Filter 2: χ^2, r^2 Test
- 2nd Coincidence (time, η, M_c)
- Follow Up



Methods to Reduce False Alarms I: χ^2 Veto

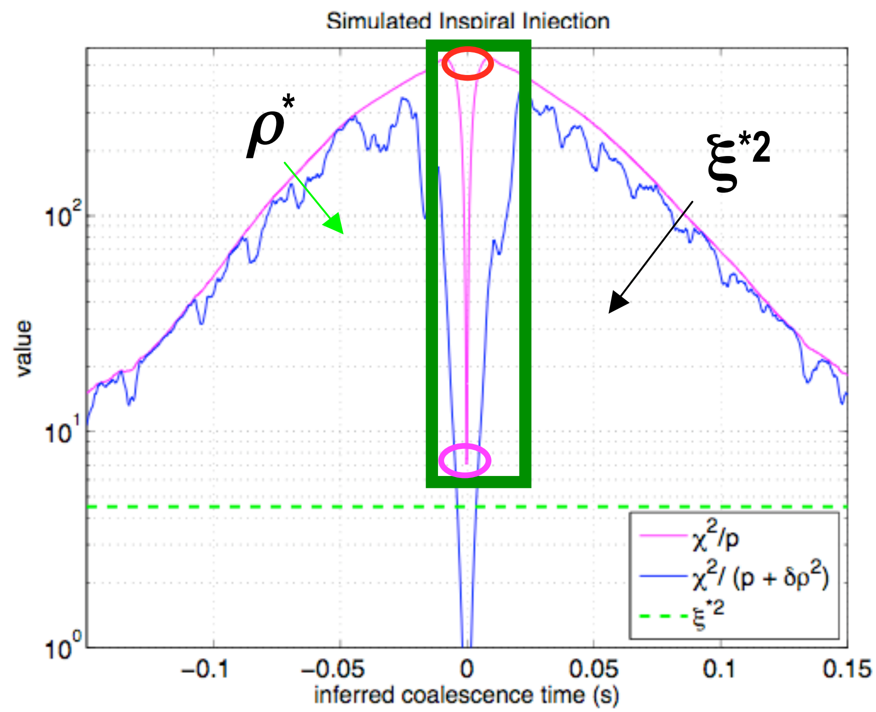
$$\chi^2(t) = p\sum_{i=1}^{p}|\rho_i(t) - \rho(t)/p|^2$$



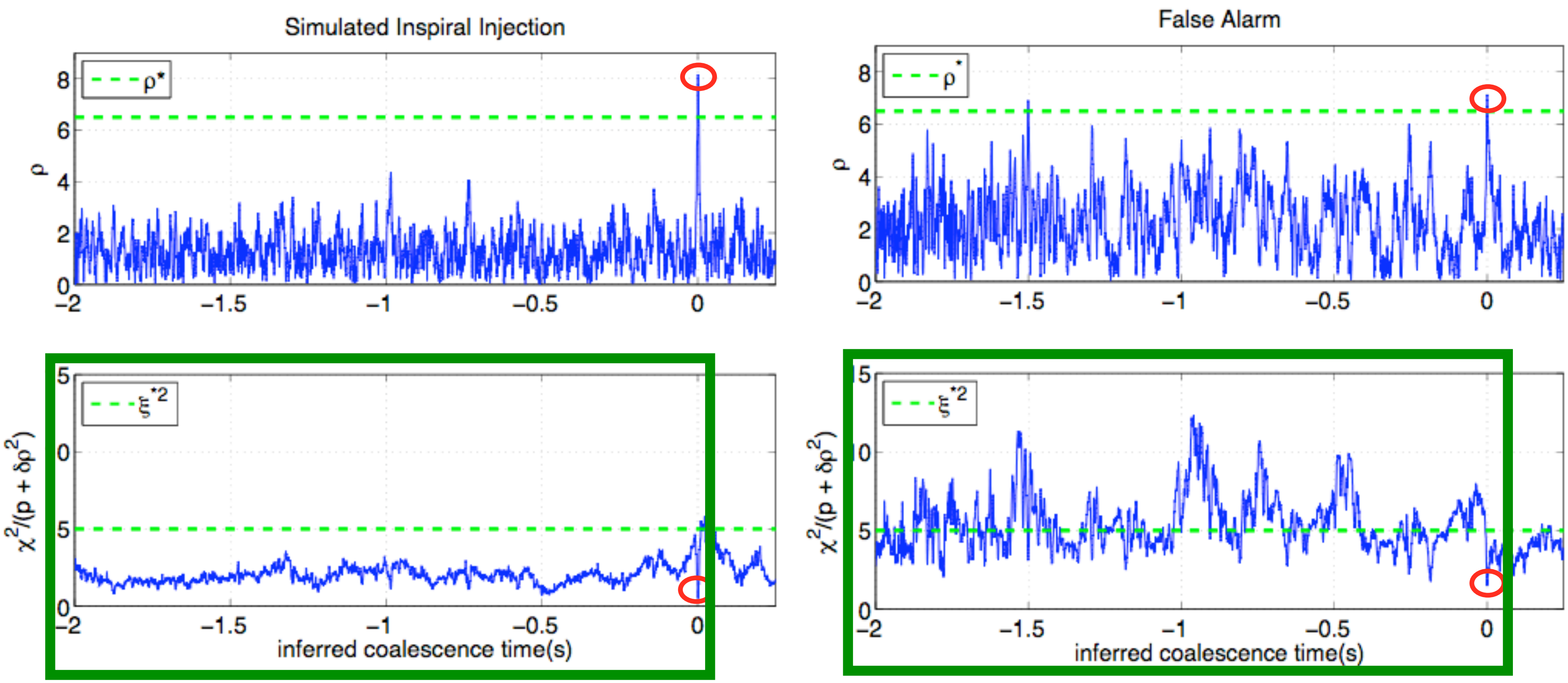
$$\xi^2 = \frac{\chi^2}{p+\delta\rho^2} \quad , \quad r^2 = \frac{\chi^2}{p}$$

Inspiral Trigger:

$$\rho > \rho^* \quad \& \quad \frac{\chi^2}{p+\delta\rho^2} < \xi^{*2}$$

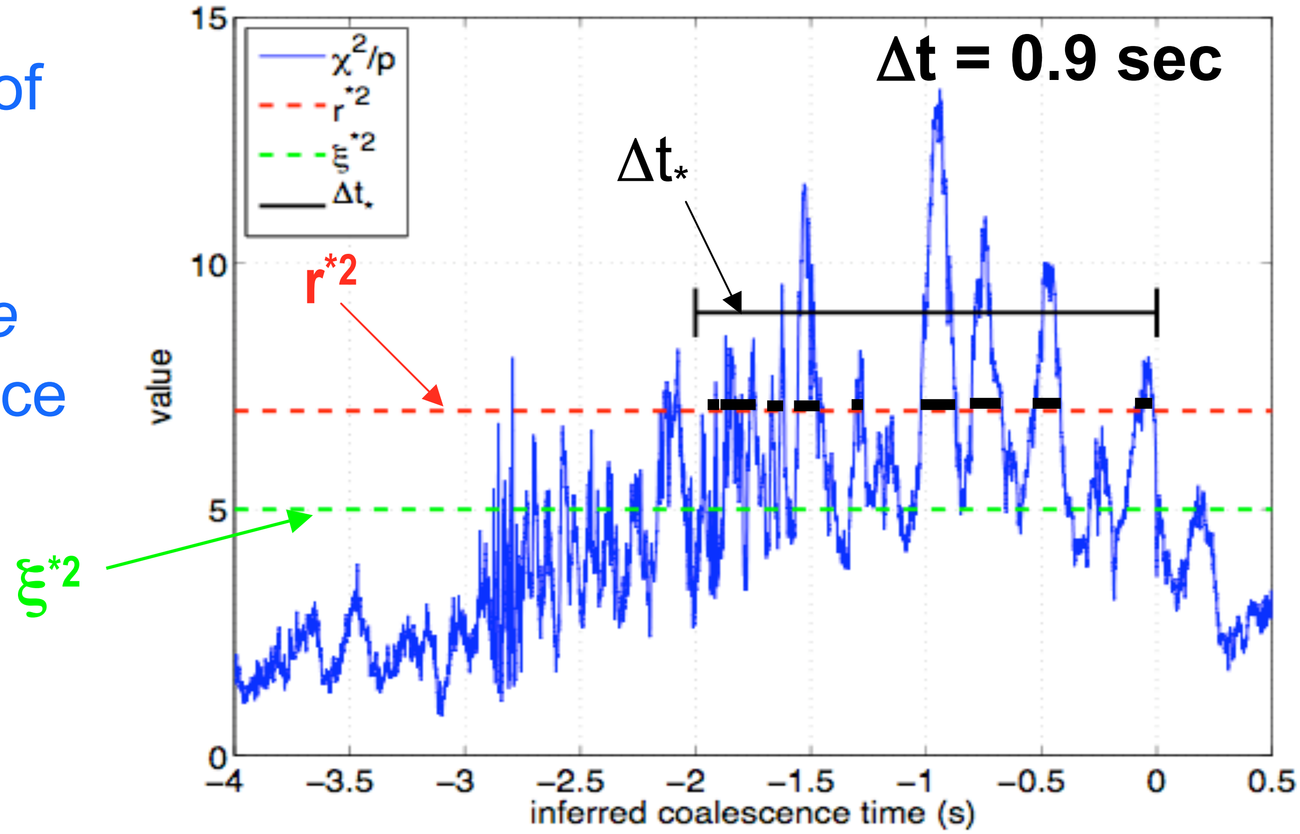


Simulated Waveform vs False Alarm

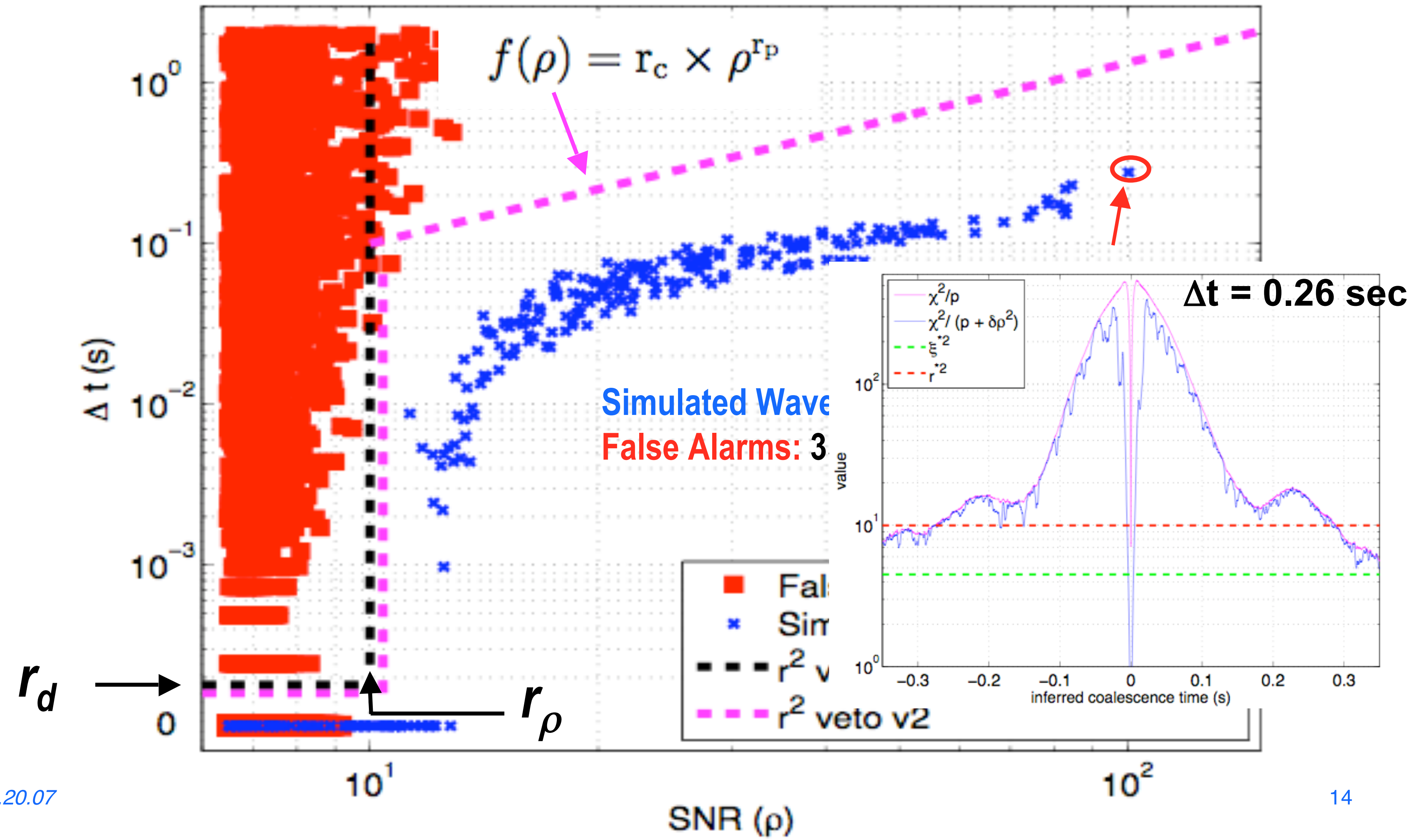


Methods to Reduce False Alarms II: r^2 Test

- Use the r^2 time series (χ^2/p) as a method to search for excess noise.
- Impose a higher r^2 threshold (r^{*2}) than the search employs.
  - » Count the number of time samples (Δt) above r^{*2} in a time interval (Δt_*) *before* inferred coalescence



Methods to Reduce False Alarms II
r^2 Test Result: S4 BNS Search



r^2 Test Results:
Searches performed by CBC Group in the LSC

r^2 Test Results for LIGO CBC Searches

	r^2 veto version	Falsely Dismissed Injections (%)	Vetoed False Alarms (%)
S3BNS	1	0.001	43.0
S3PBH	1	0.0	26.5
S4BNS	1	0.0	35.0
S4PBH	1	0.0	35.0
S5BNS (epoch 1)	2	0.001	26.9
S5BBH (epoch 1)	2	0.12	19.1

- r^2 test is included in current LIGO searches:
  S5 Low Mass ($M < 35M_{SOL}$) 1 year

S3 Primordial Black Hole (PBH) Search I

- Black hole composed with mass < 1.0 M_{SOL} is believed to be a primordial black hole (PBH).

- They are compact objects may have formed in the early, highly compressed stages of the universe immediately following the big bang.

- Speculated to be part of the galactic halo or constituent of dark matter (small fraction).

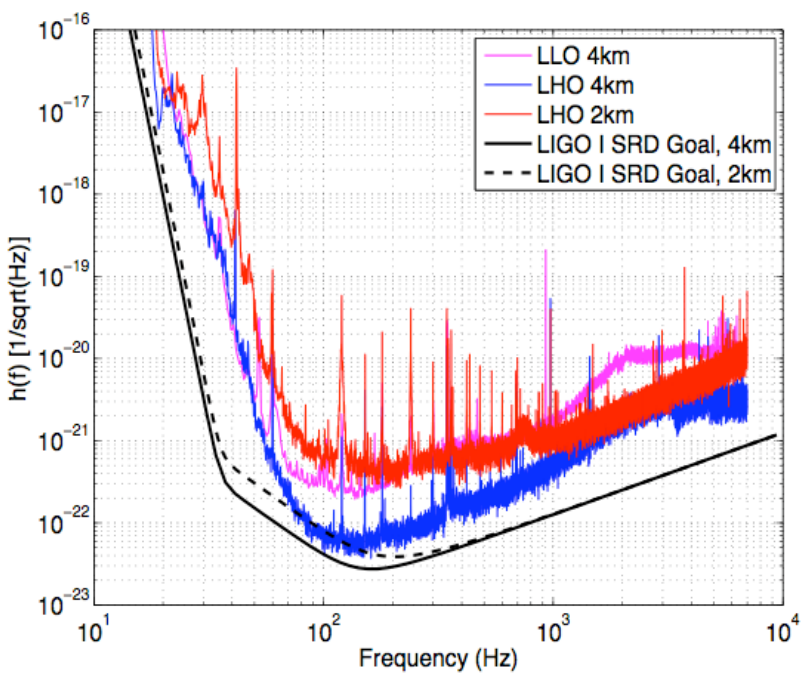
- Binary system composed of two PBH's will emit gravitational waves that may be detectable by LIGO.

- A PBH binary composed of 2 x 0.35 M_{SOL} objects would have a coalescence frequency of 2023Hz and would spend about 22 seconds in LIGO's sensitive band.

S3 PBH Search II

- Target Sources:

$m_{\text{min}}(M_\odot)$	$m_{\text{max}}(M_\odot)$	$f_L(\text{Hz})$	N_b	$D_{\text{max}}(\text{s})$
0.35	1.0	100	4500	22.1



S3: October 3 - January 09: 2004

	S3
H1-H2-L1 times	184 (167) hrs
H1-H2 times	604 (548) hrs
Total times	788 (715) hrs

* Numbers in () represent time left after data used for tuning search.

S3 PBH Search III - Tuning

- Coincidence Windows

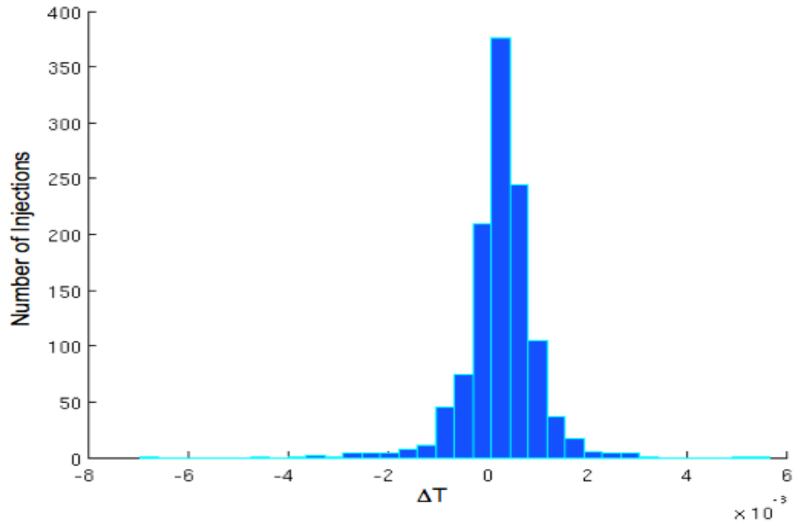
$$\eta = \frac{m_1 m_2}{(m_1 + m_2)^2} \qquad \mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

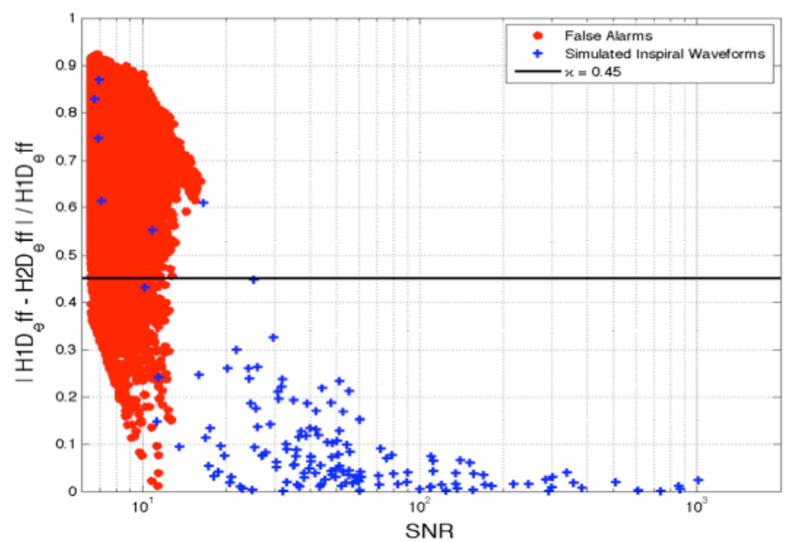
- H1H2 Effective Distance Cut

$$\frac{|\mathrm{H1}D_{\mathrm{eff}} - \mathrm{H2}D_{\mathrm{eff}}|}{\mathrm{H1}D_{\mathrm{eff}}} < \kappa \quad , \kappa = 0.45$$

- Parameters Selected:

ΔT (milliseconds)	$\Delta\mathcal{M}_c$ ($M_\odot$)	$\Delta\eta$
4×2	0.002×2	0.06





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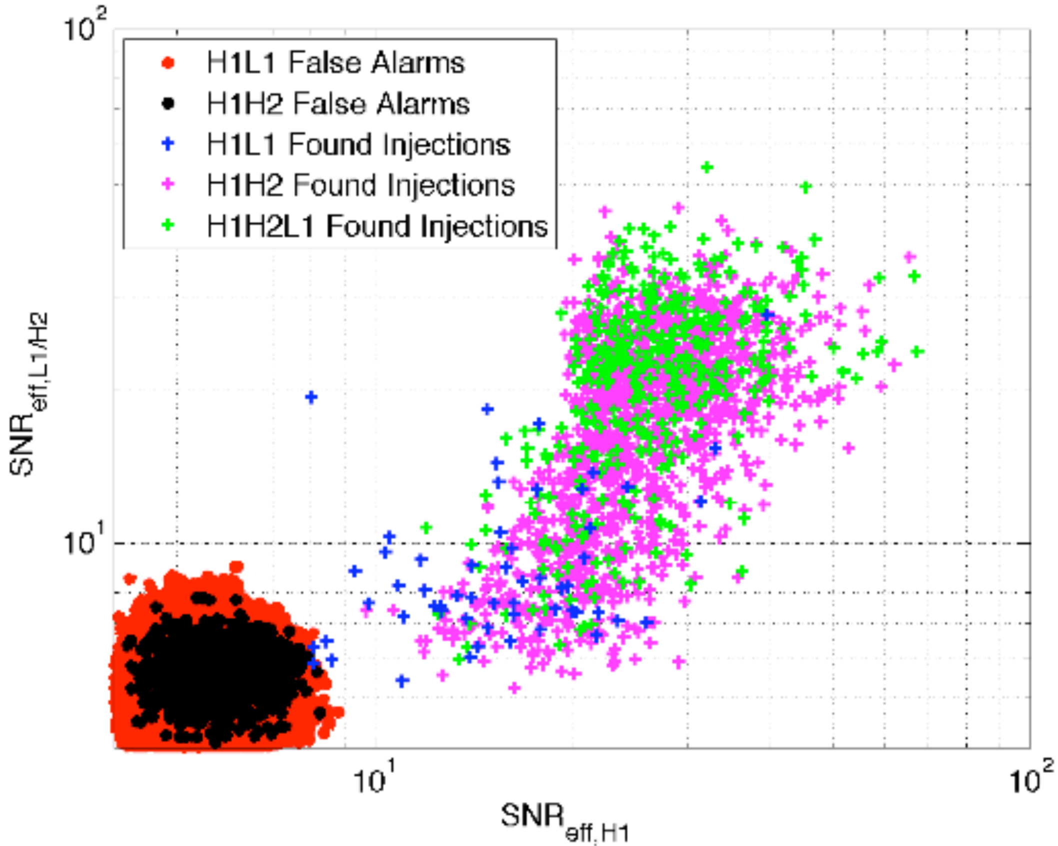
S3 PBH Search IV - Tuning

- Effective SNR:

$$\rho^2_{\text{eff}} = \frac{\rho^2}{\sqrt{\left(\frac{\chi^2}{2p-2}\right)\left(1+\frac{\rho^2}{250}\right)}},$$

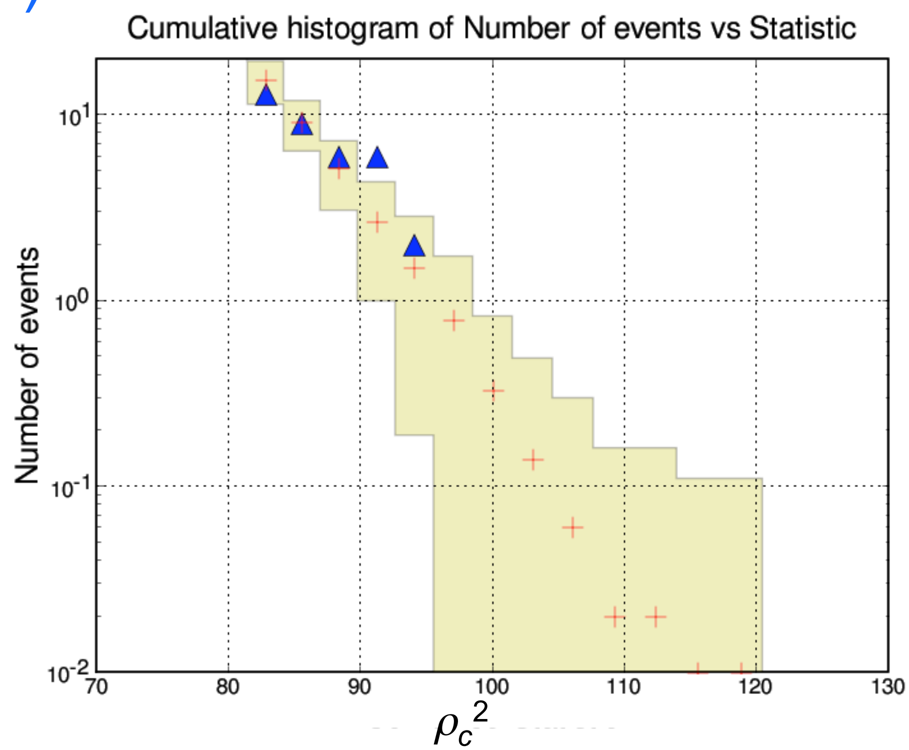
- Combined SNR:

$$(\rho_c)^2_{\text{PBH}} = \sum_i^N \rho^2_{\text{eff,i}}$$



S3 PBH Search V: Result

- No triple coincident foreground candidate events or background events were found.
- Number of double coincidences found (▲) consistent with measured background (+).



Conclusions

- r^2 test greatly reduces rate of false alarms in LIGO CBC searches.
- The r^2 test be incorporated into future LIGO searches: S5 Low Mass ($M < 35M_{SOL}$) 1 year.
- A search for primordial black hole binary systems ($M < 1M_{SOL}$) in LIGO's S3 run was performed with results consistent with measured background.

Thank You!

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LSU-LIGO Group: Chad, Ravi, Rupal, Prof. Warren Johnson, Jake, Dr. Myungkee Sung,
Prof. Joseph Giaime, Shyang, Andy W., Jeff, Dr. Romain Gouaty

CBC Group: Dr. Duncan Brown, Dr. Stephen Fairhurst, Dr. Eirini Messaritaki,
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LSC: Prof. Peter Shawhan, Prof. Alan Weinstein, Prof. Laura Cadonati, Dr. John Whelan,
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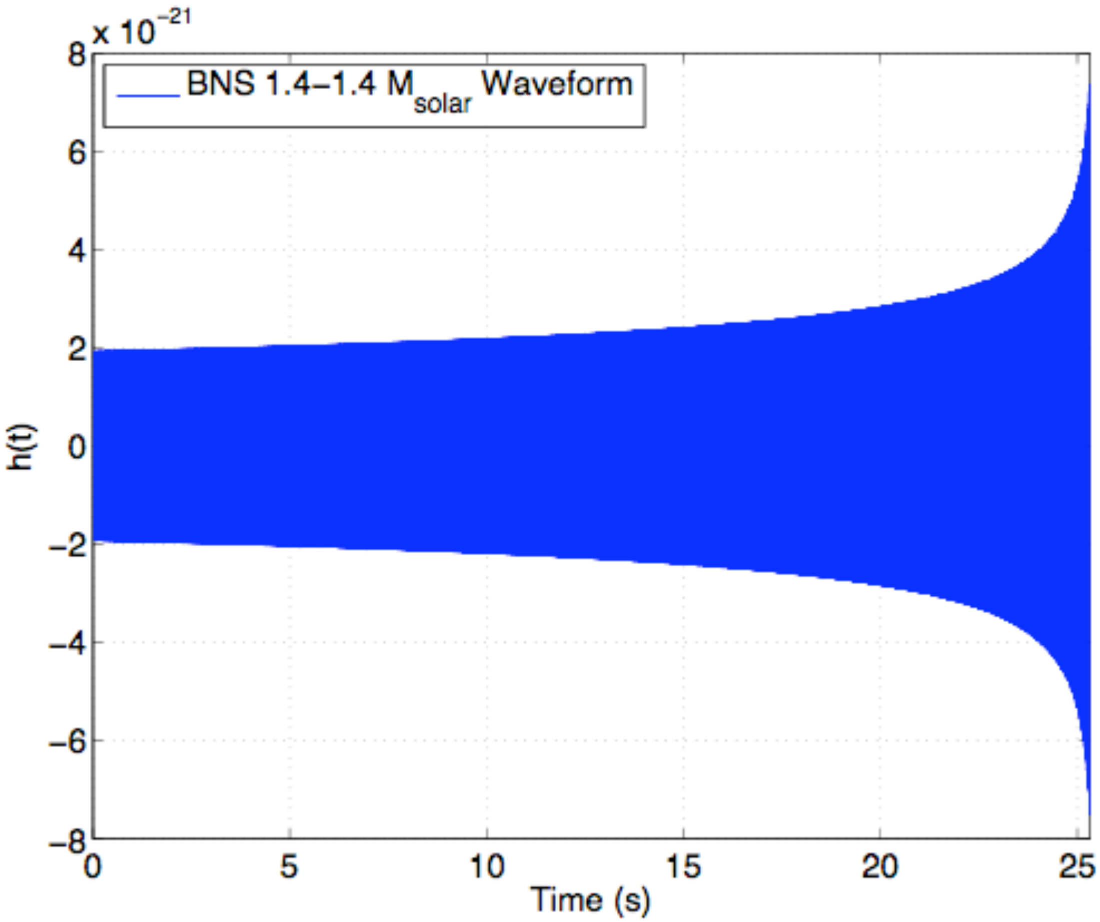
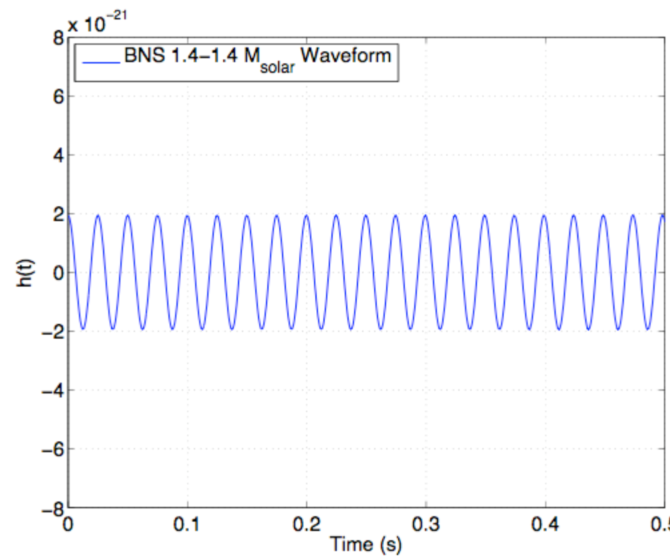
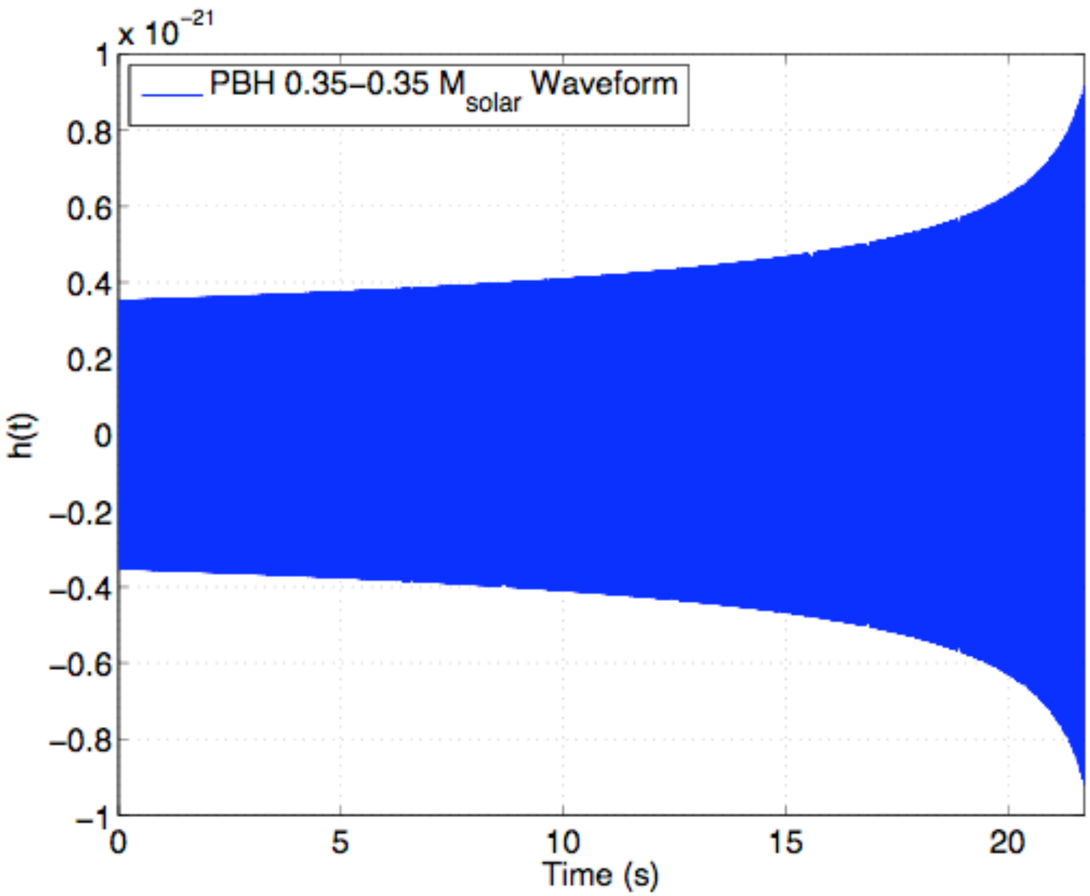
Extra Slides

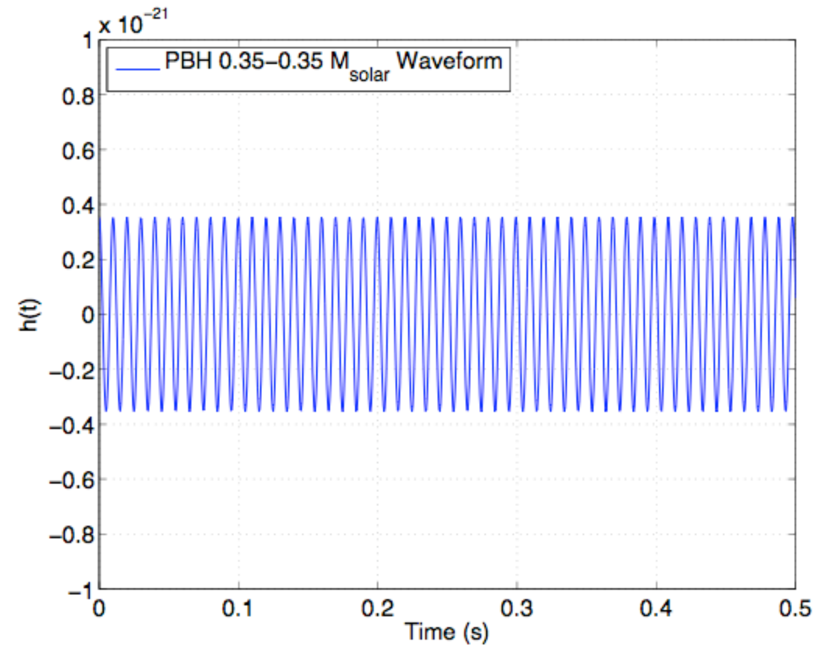
BNS Waveform



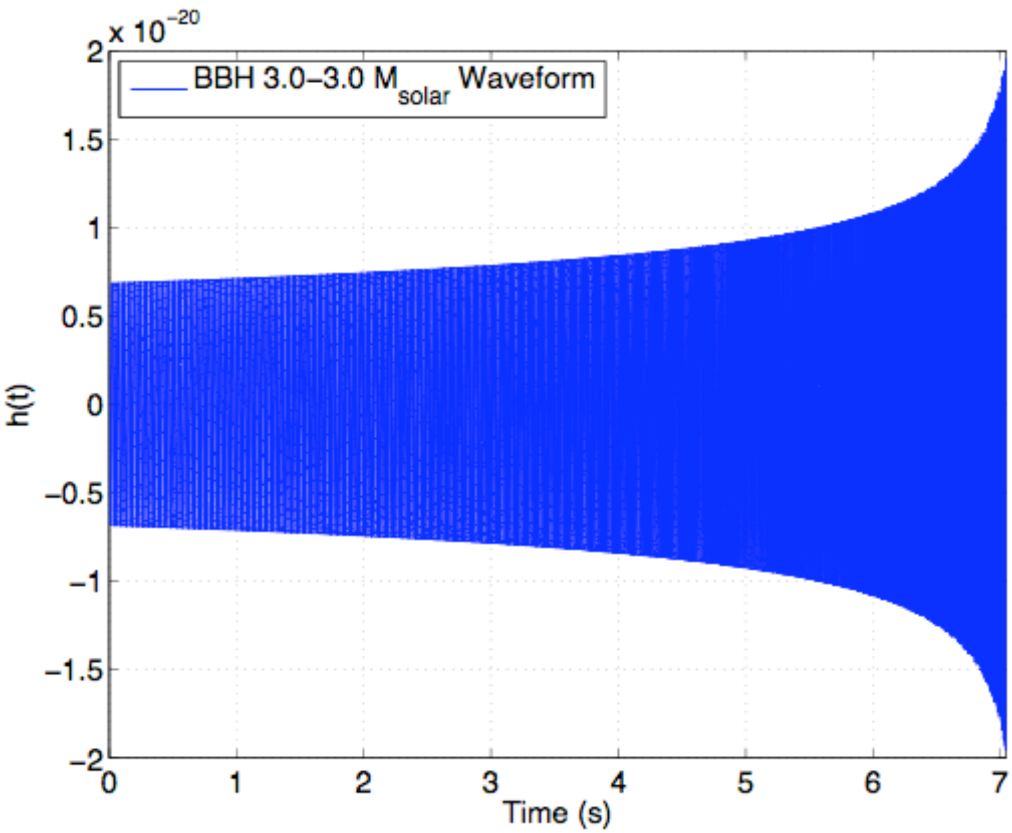


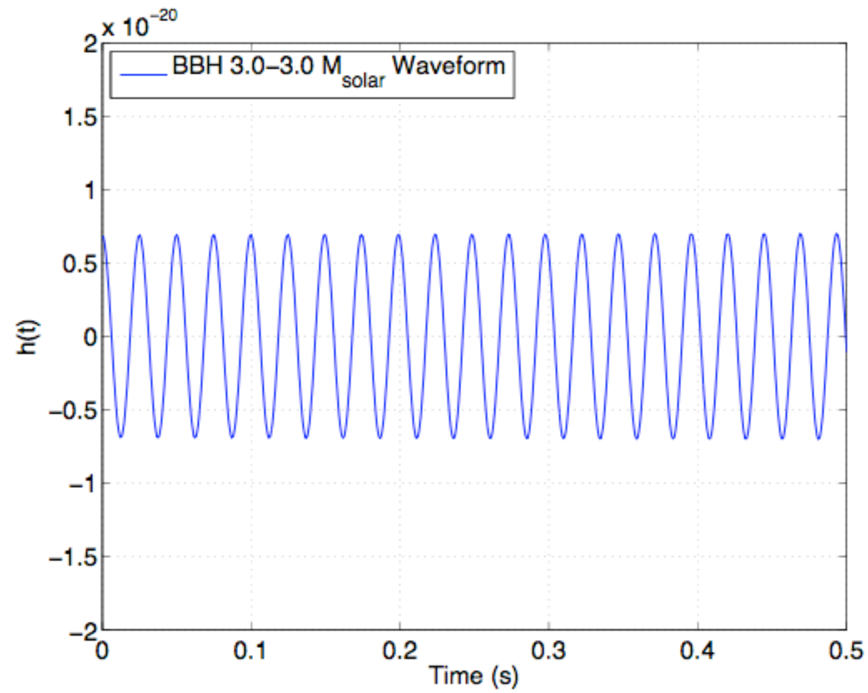
PBH Waveform



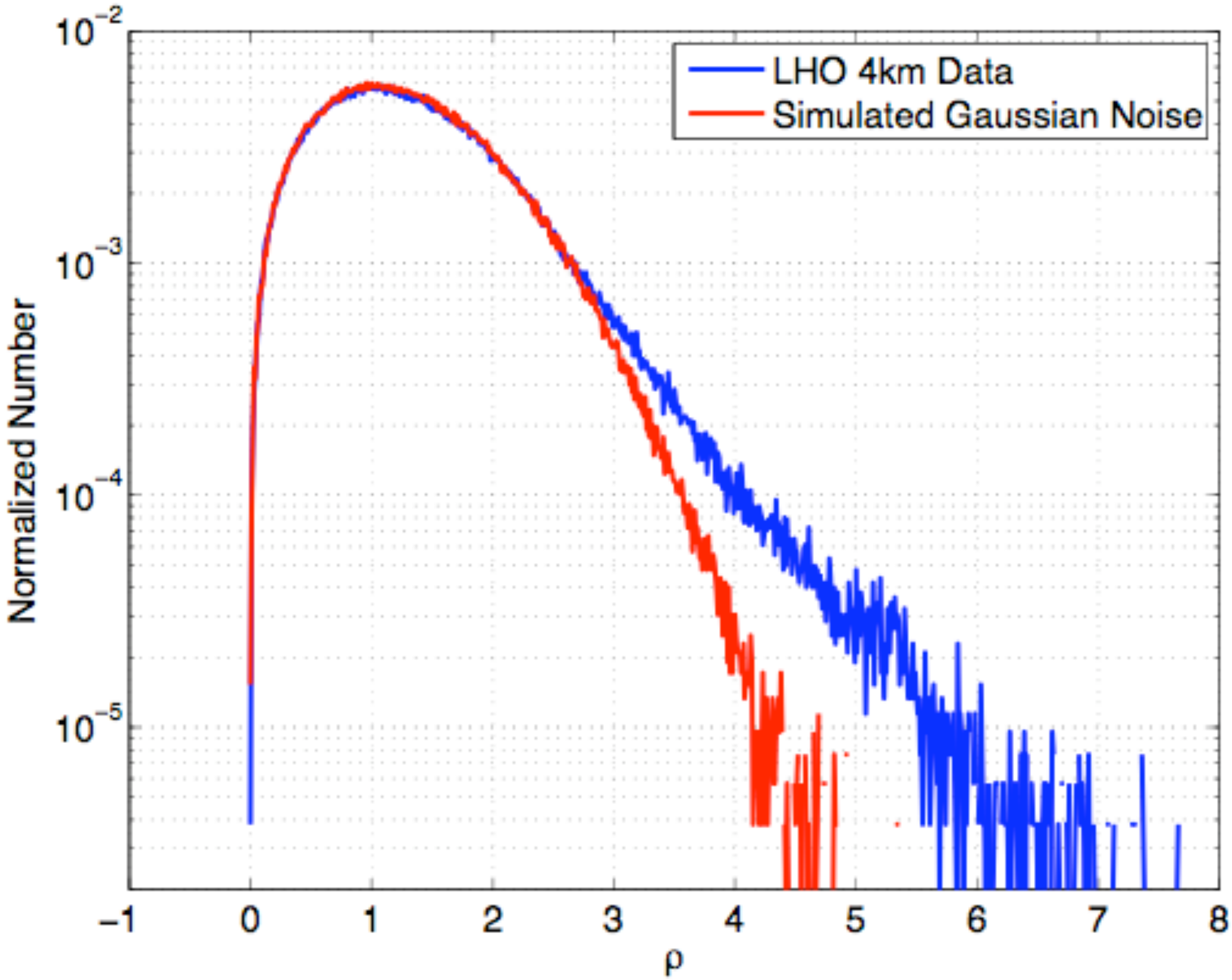


BBH Waveform



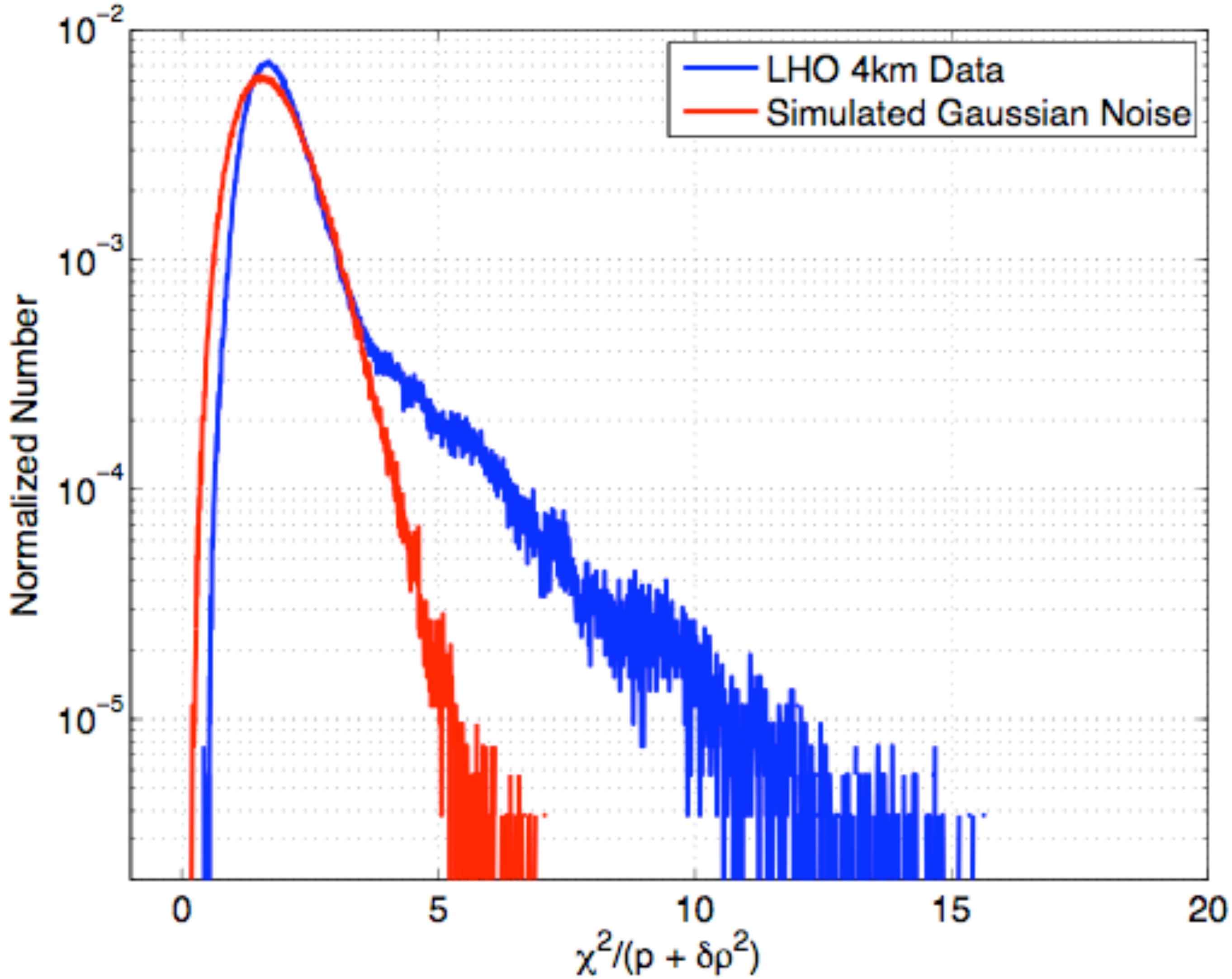


SNR



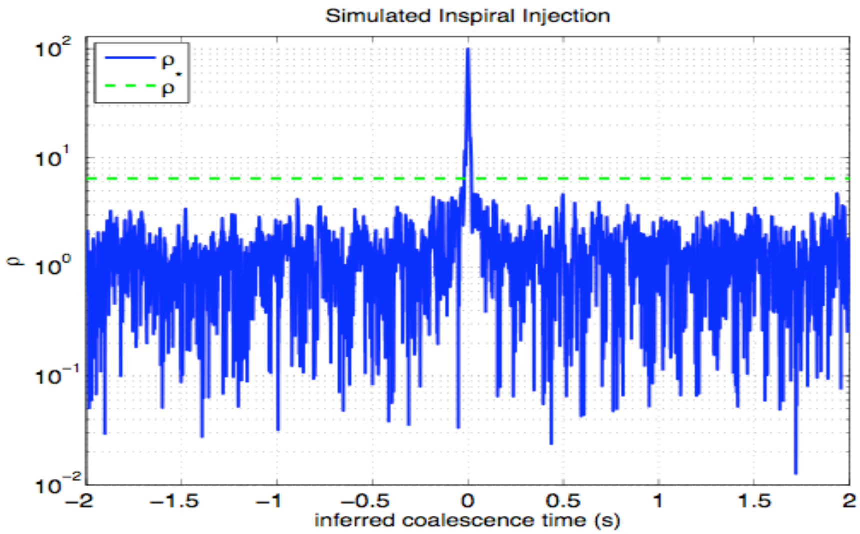
LHO 4km Data
Simulated Gaussian Noise
Normalized Number
10^{-2}
10^{-3}
10^{-4}
10^{-5}
−1
0
1
2
3
4
5
6
7
8
ρ

\xi^2

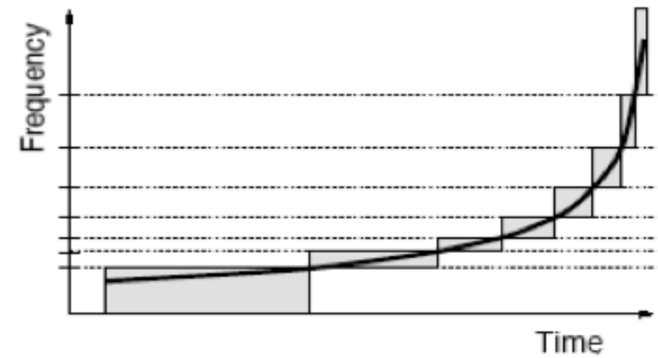


LHO 4km Data
Simulated Gaussian Noise
Normalized Number
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
5
10
15
20
$\chi^2/(p + \delta\rho^2)$

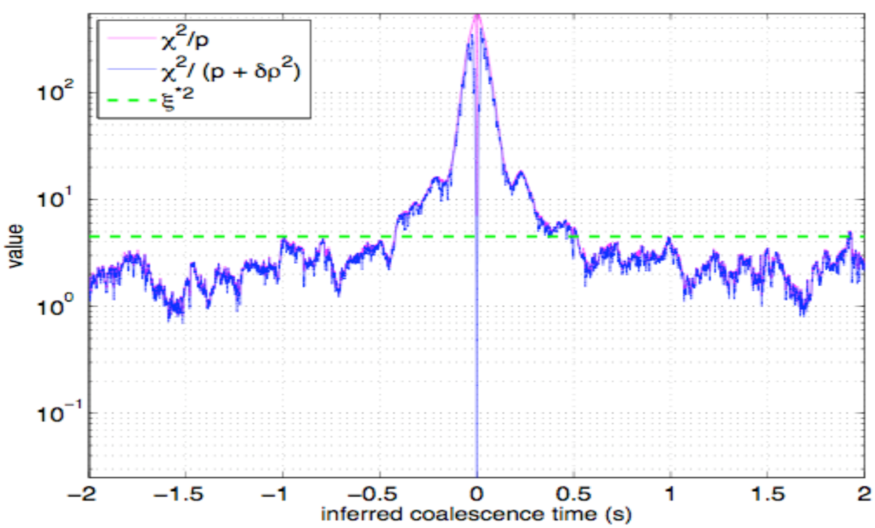
Injection



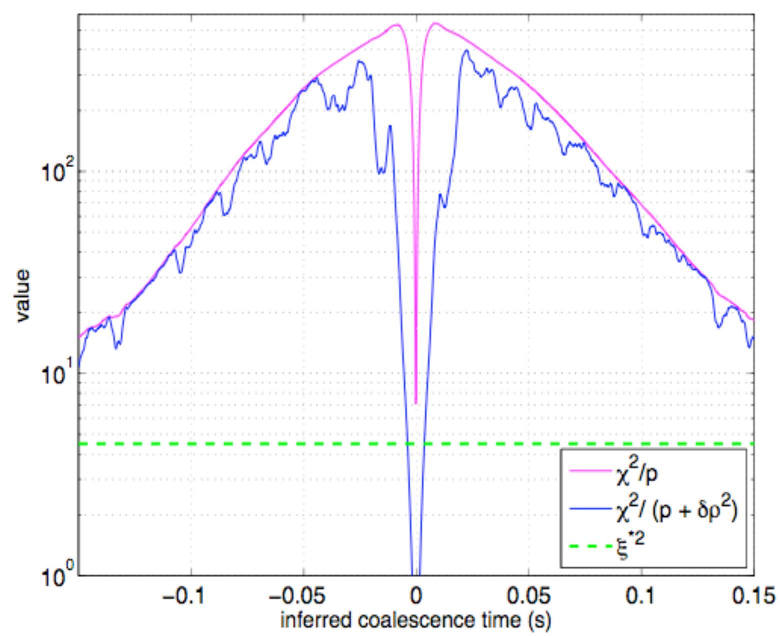
Simulated Inspiral Injection
ρ
ρ*
inferred coalescence time (s)



Frequency
Time

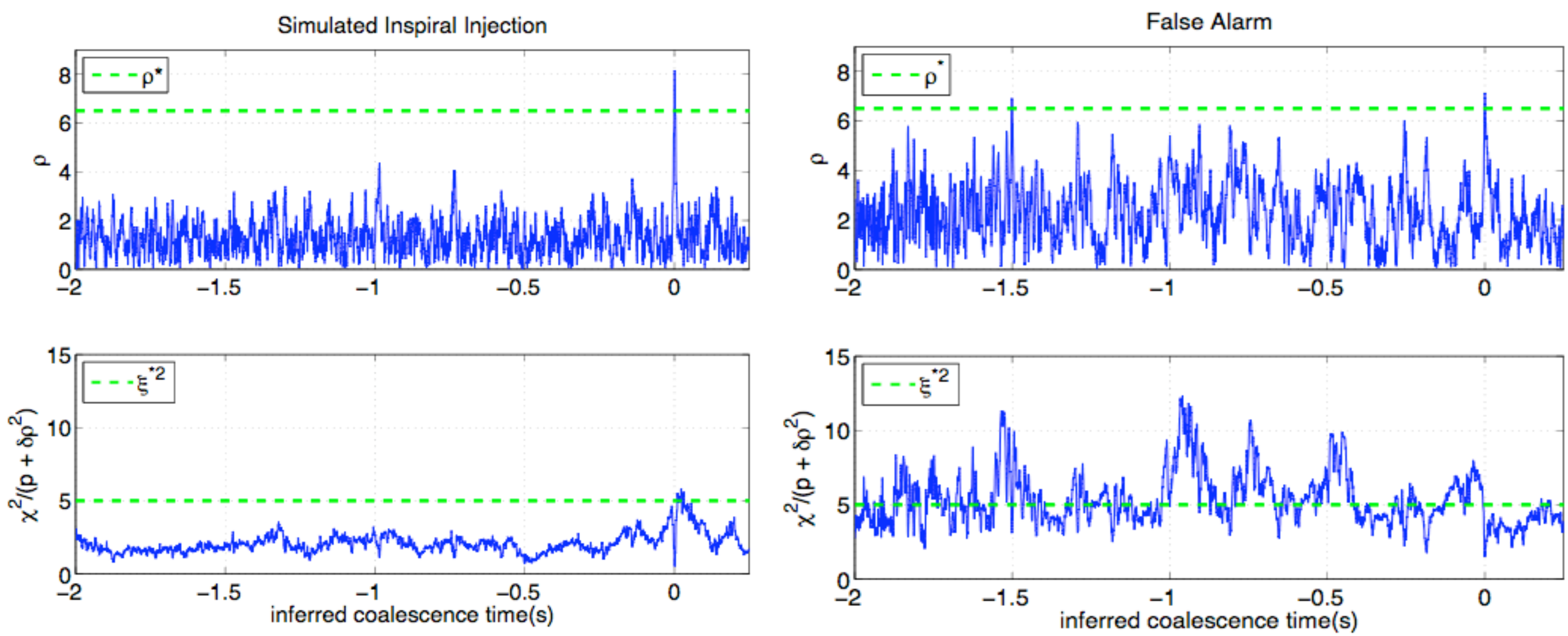


χ²/p
χ²/ (p + δρ²)
ξ*2
value
inferred coalescence time (s)

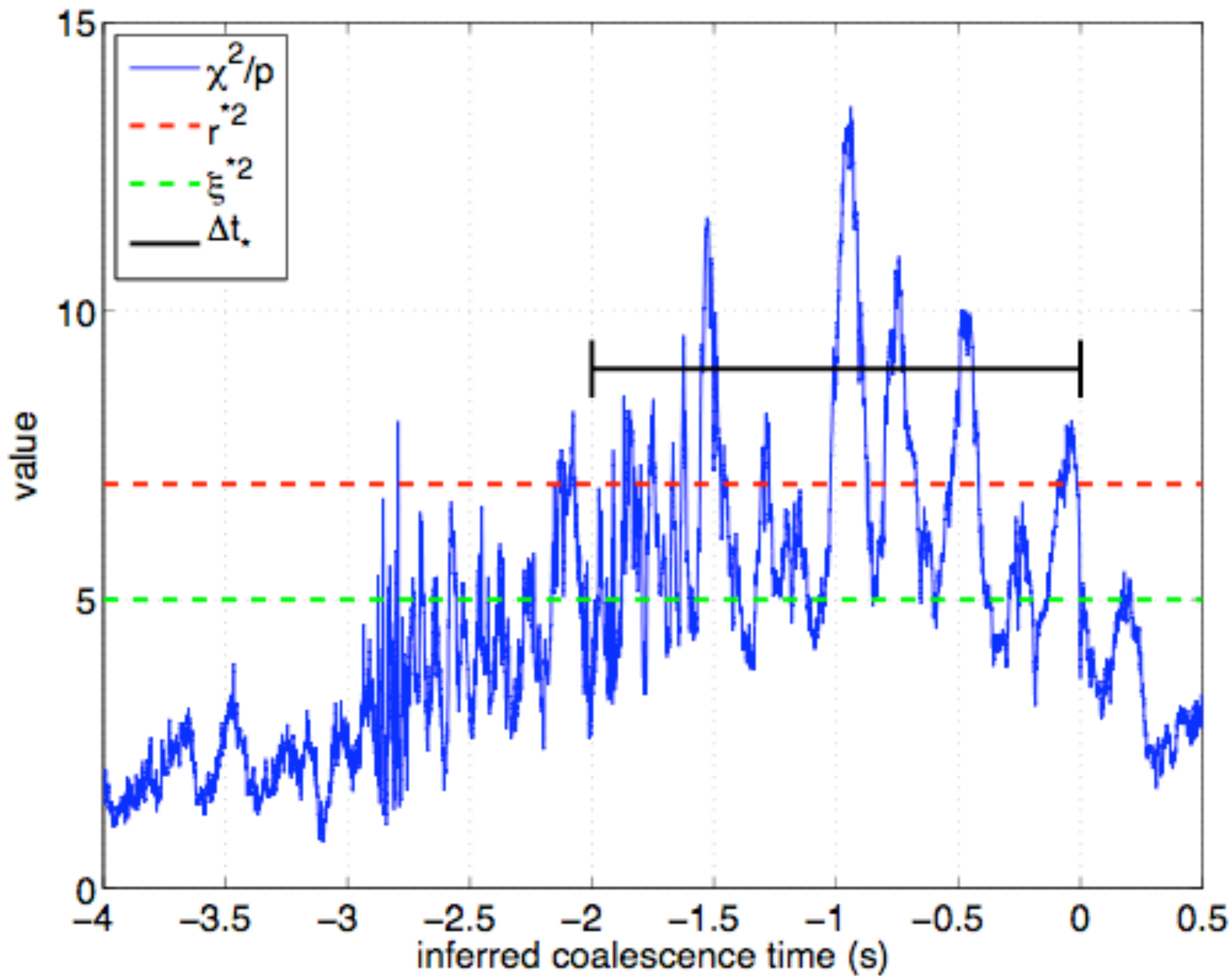


χ²/p
χ²/ (p + δρ²)
ξ*2
value
inferred coalescence time (s)

Injection vs Trigger

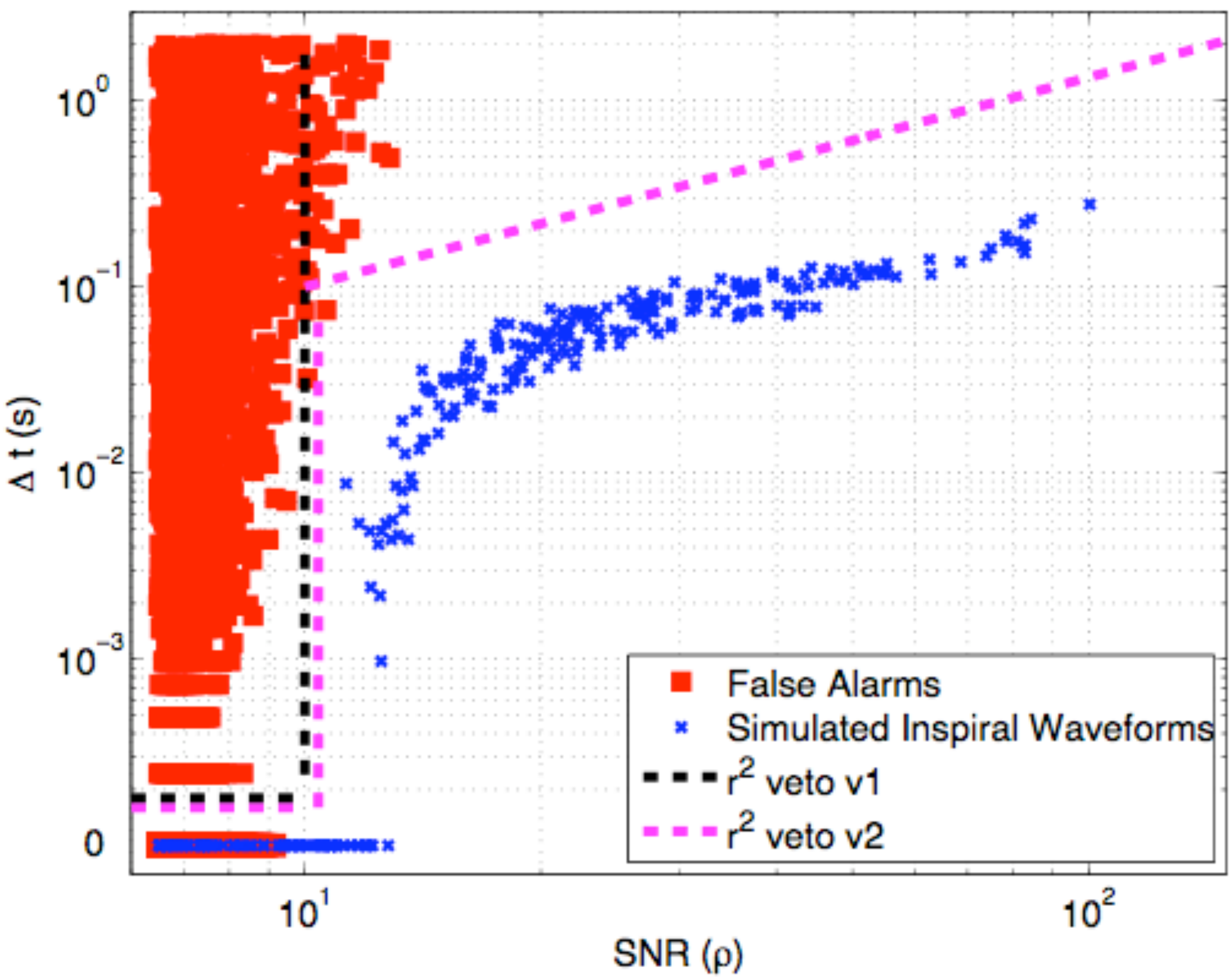


r^2 test



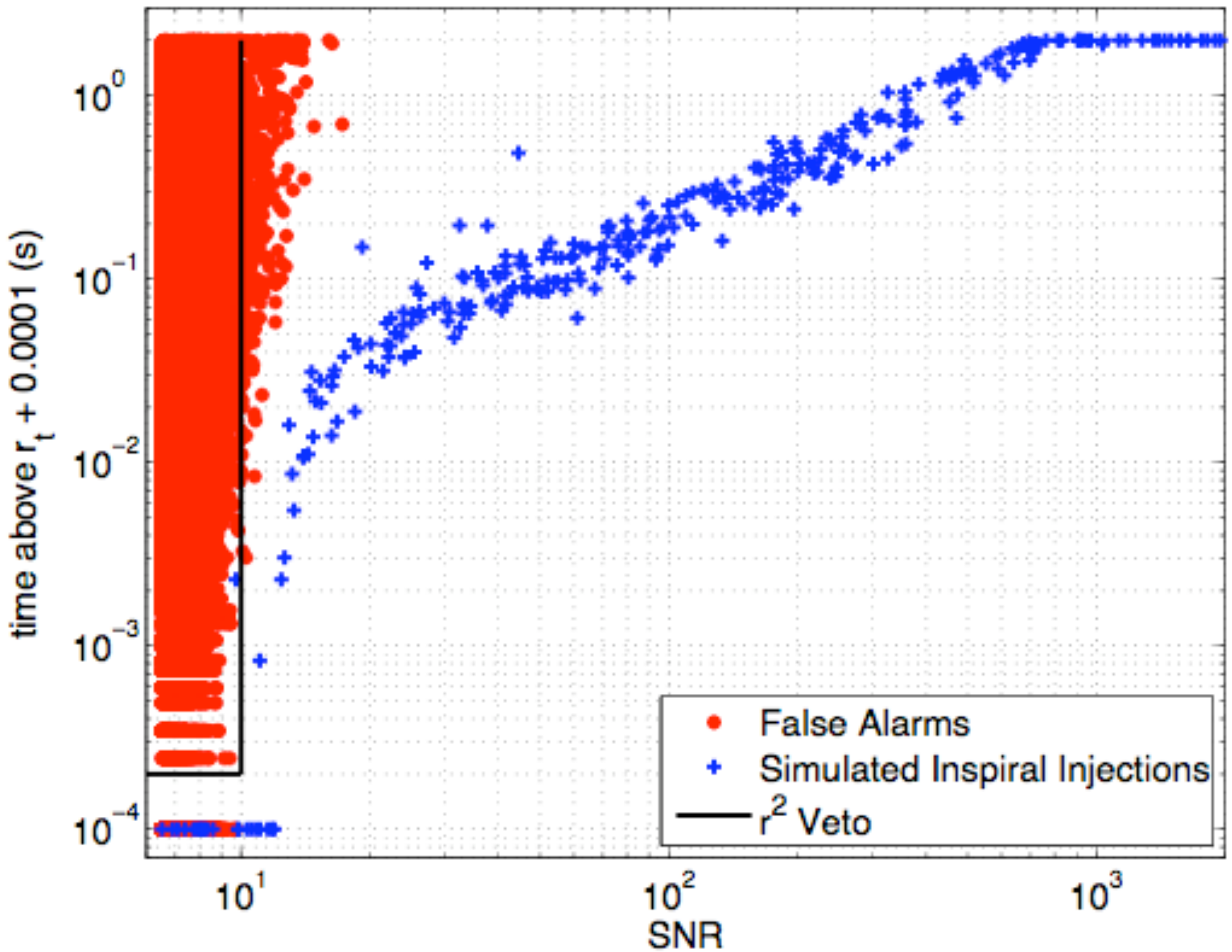
15
10
5
0
value
−4
−3.5
−3
−2.5
−2
−1.5
−1
−0.5
0
0.5
inferred coalescence time (s)
χ²/p
r*²
ξ*²
Δt*

r^2 example



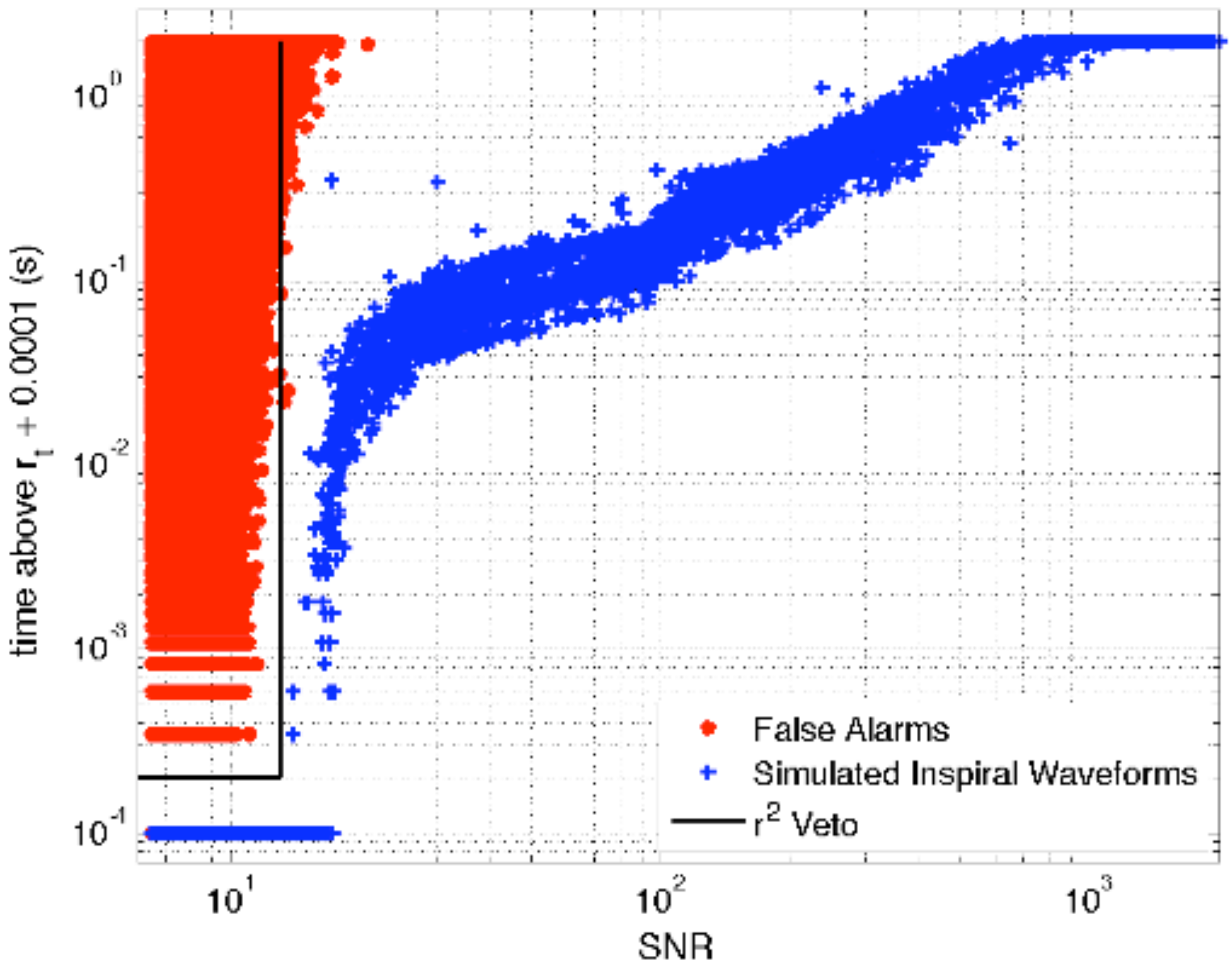
10^0
10^{-1}
10^{-2}
10^{-3}
0
Δ t (s)
10^1
10^2
SNR (ρ)
False Alarms
Simulated Inspiral Waveforms
r^2 veto v1
r^2 veto v2

r^2 - S3 BNS



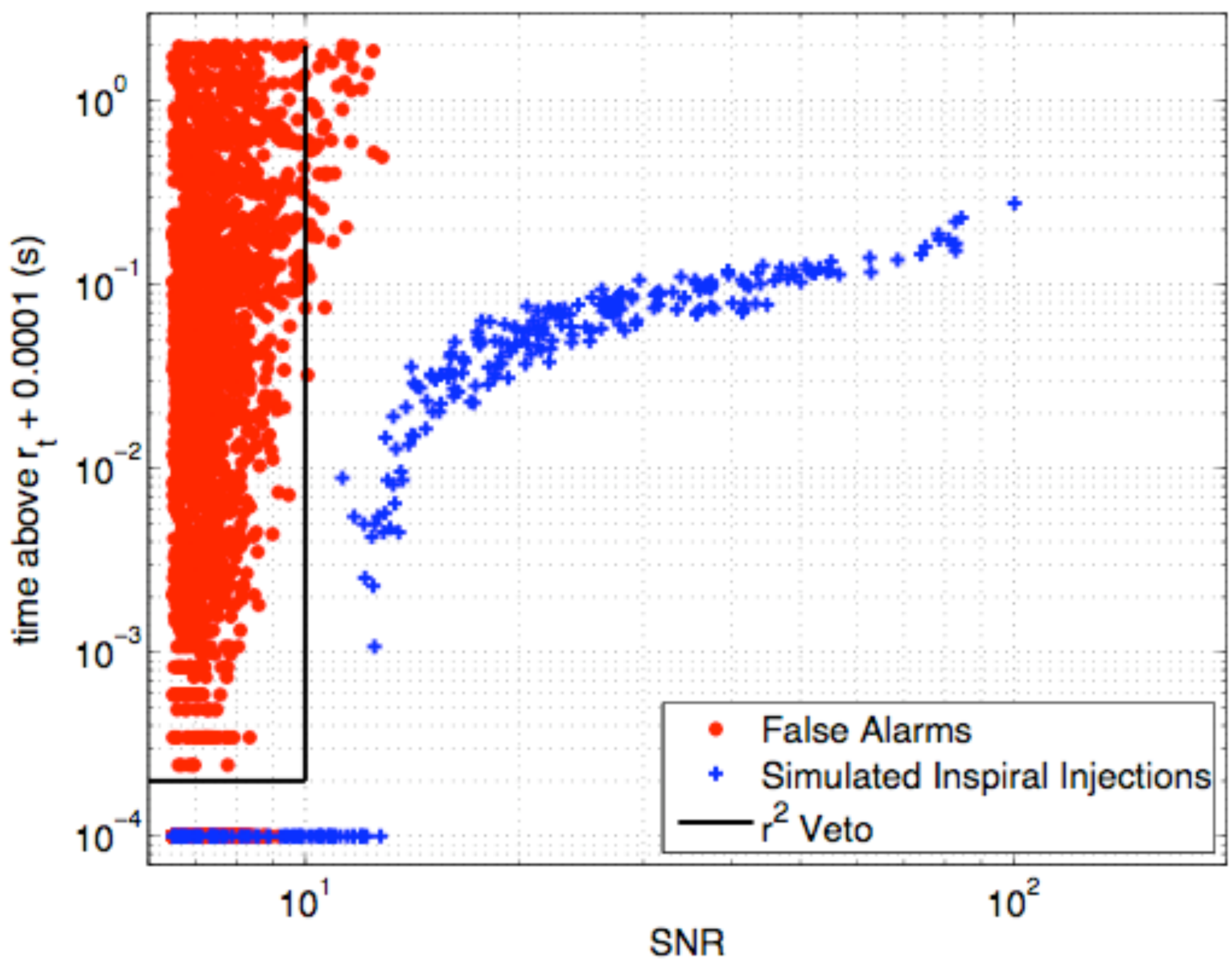
time above r_t + 0.0001 (s)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3
SNR
False Alarms
Simulated Inspiral Injections
r^2 Veto

r^2 - S3 PBH



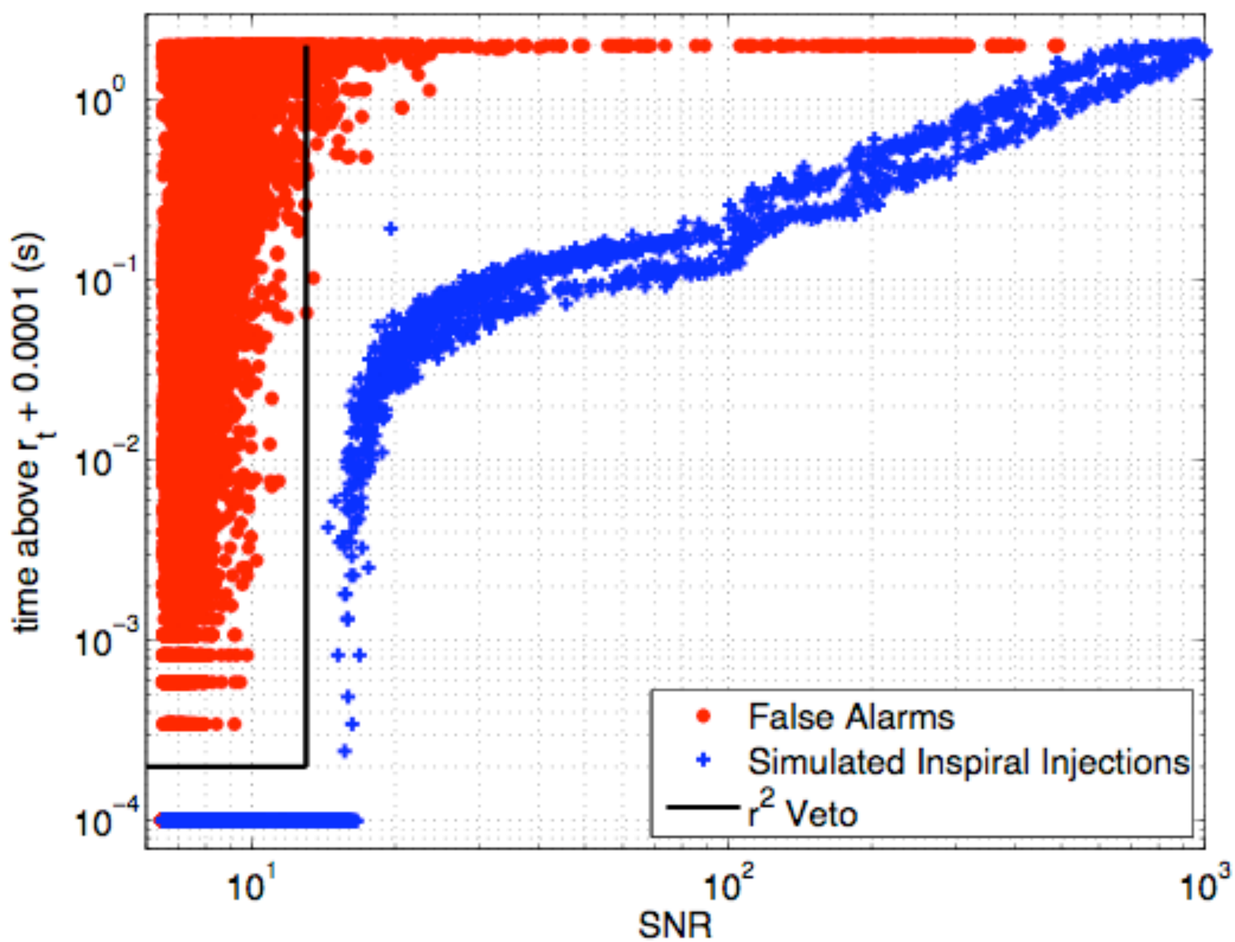
time above r_t + 0.0001 (s)
SNR
False Alarms
Simulated Inspiral Waveforms
r^2 Veto

r^2 - S4 BNS



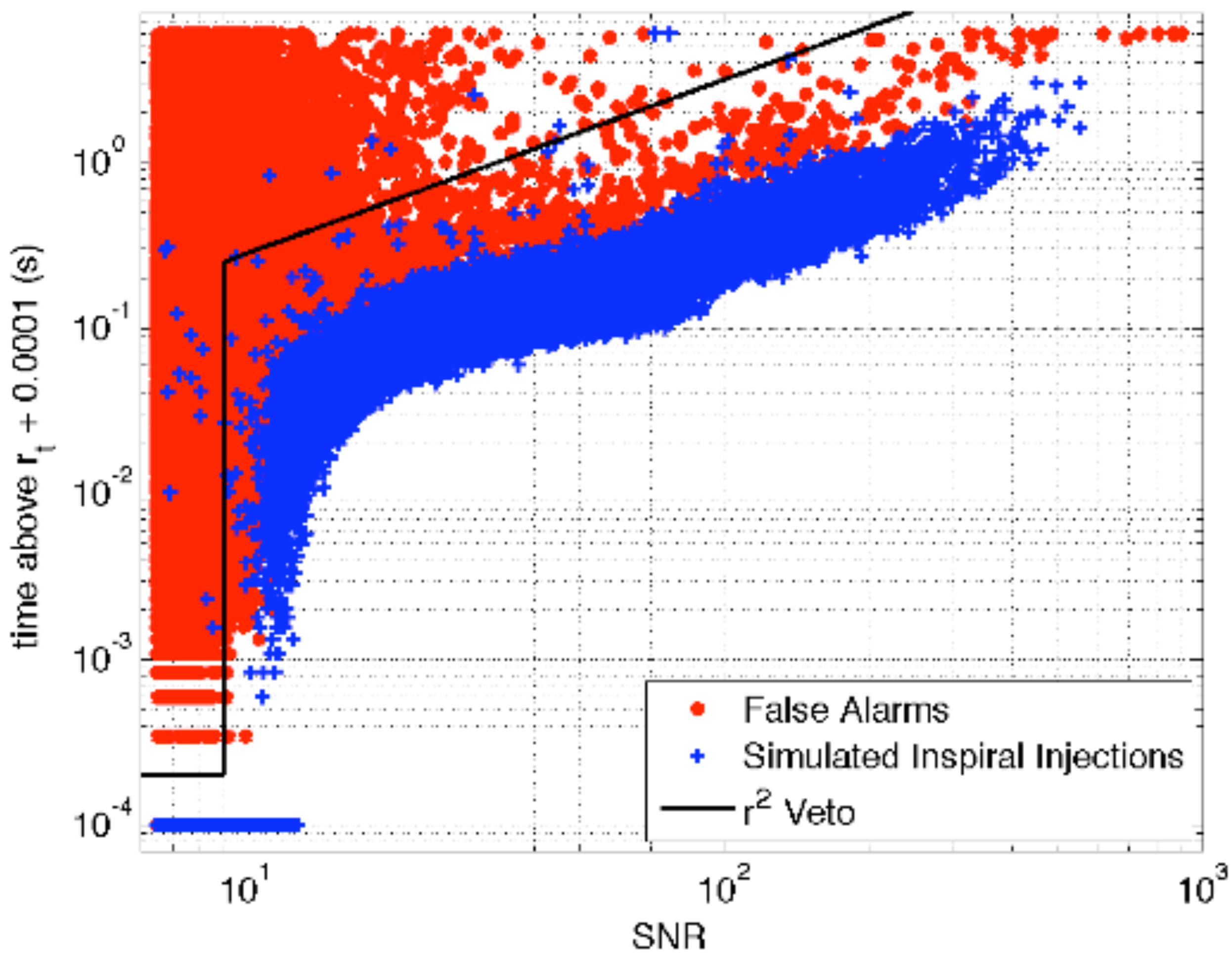
time above r_t + 0.0001 (s)
10^0
10^-1
10^-2
10^-3
10^-4
10^1
10^2
SNR
False Alarms
Simulated Inspiral Injections
r^2 Veto

r^2 - S4 PBH

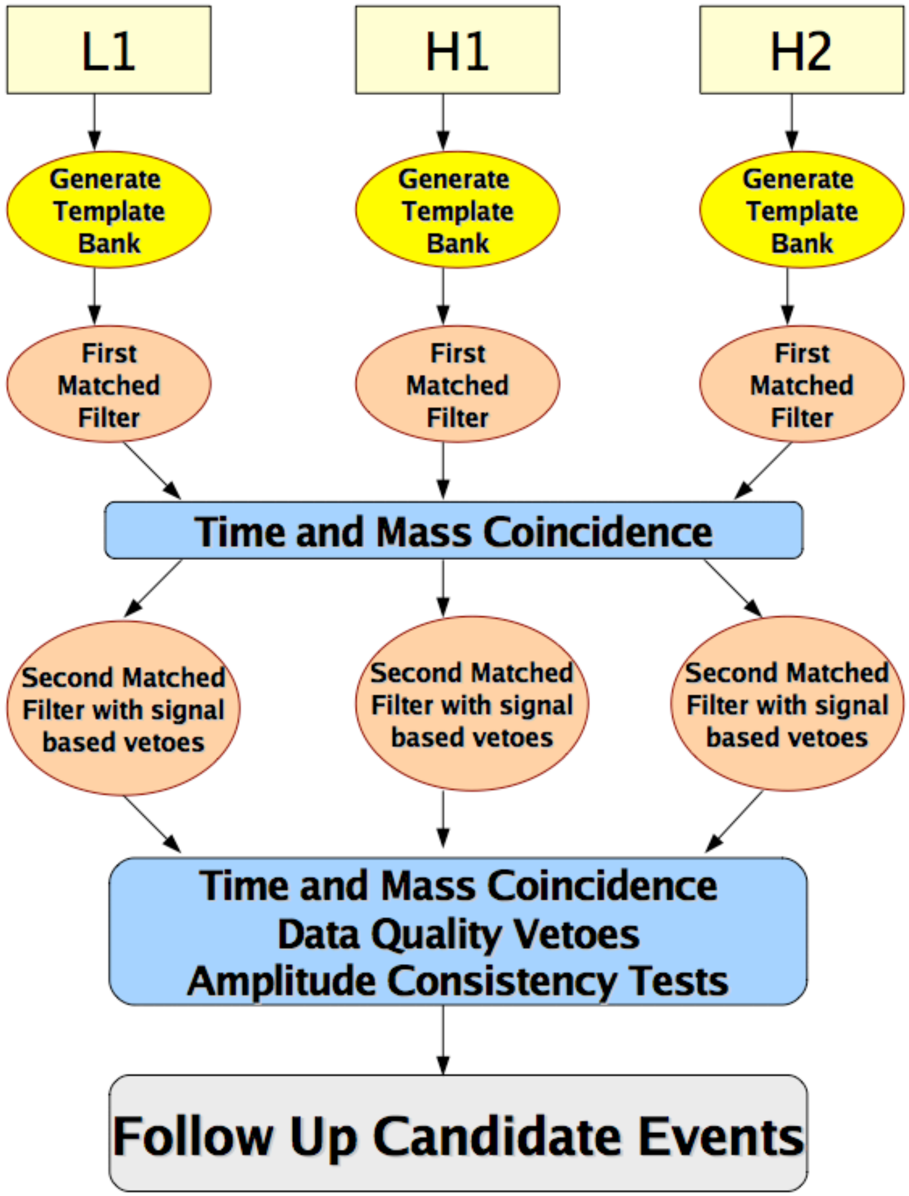


time above r_t + 0.0001 (s)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3
SNR
False Alarms
Simulated Inspiral Injections
r^2 Veto

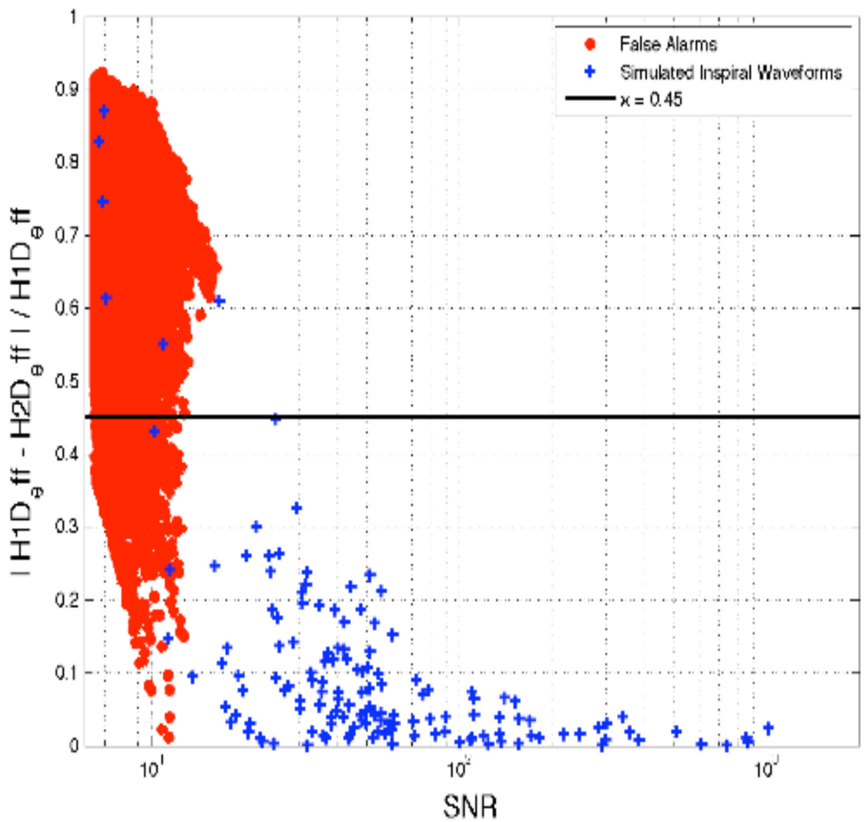
r^2 - S5 BBH epoch 1

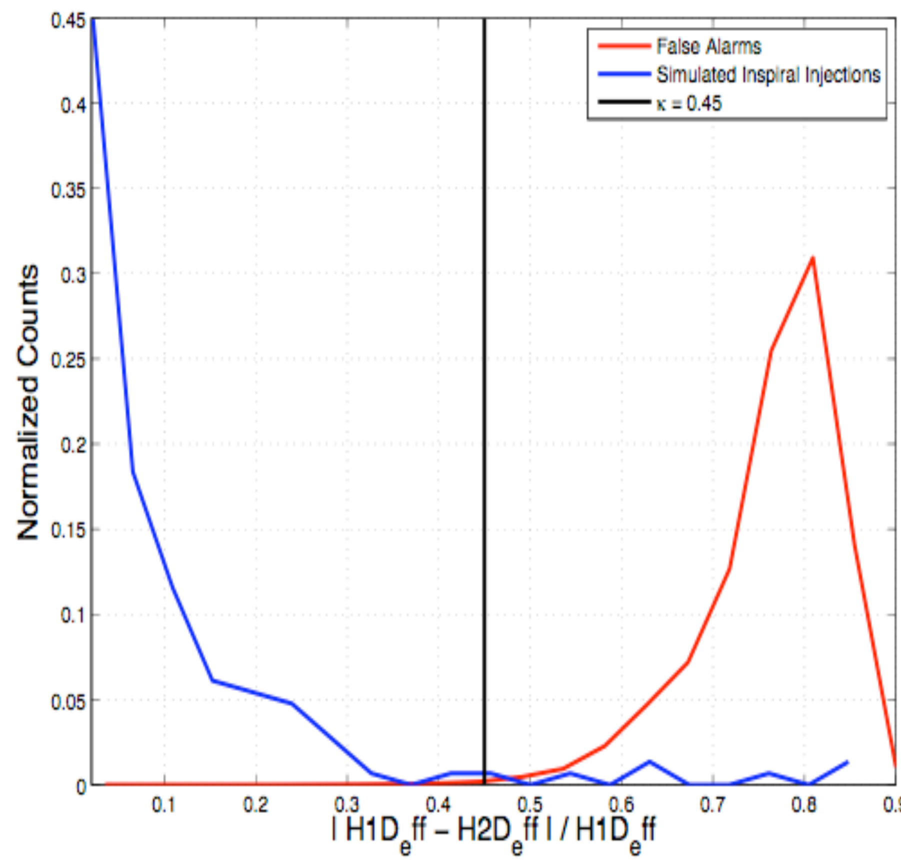


Pipeline

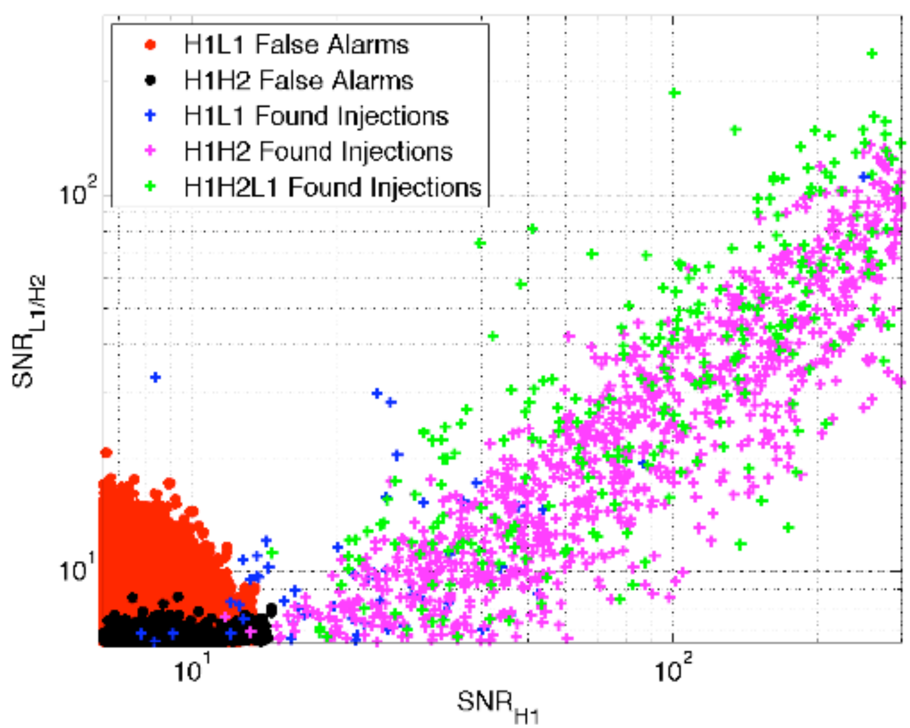

L1
H1
H2
Generate Template Bank
Generate Template Bank
Generate Template Bank
First Matched Filter
First Matched Filter
First Matched Filter
Time and Mass Coincidence
Second Matched Filter with signal based vetoes
Second Matched Filter with signal based vetoes
Second Matched Filter with signal based vetoes
Time and Mass Coincidence
Data Quality Vetoes
Amplitude Consistency Tests
Follow Up Candidate Events

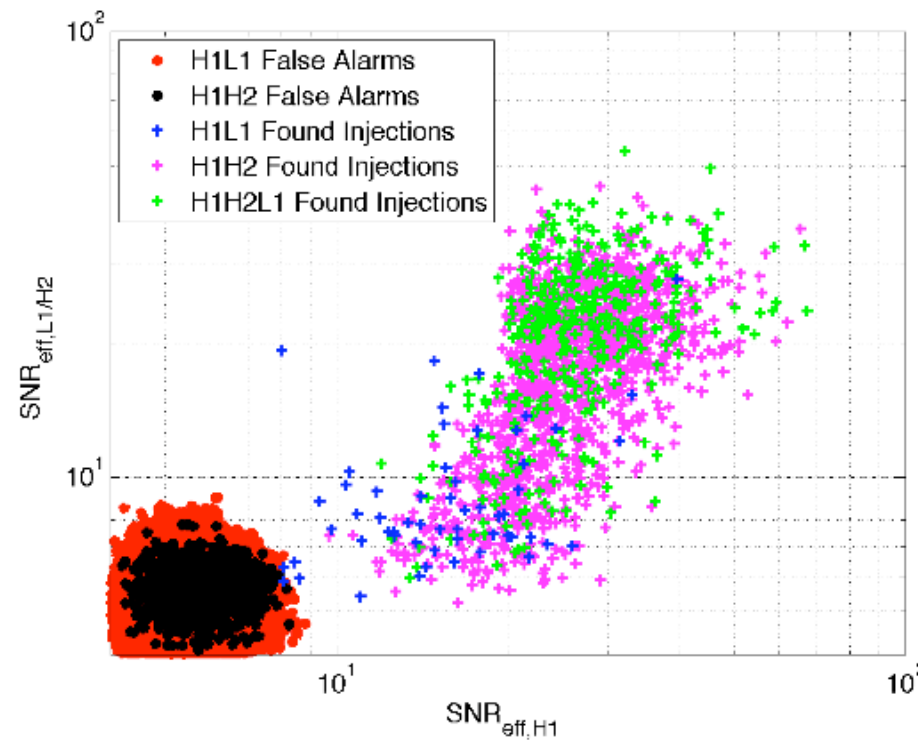
S3 PBH - Effective Distance Cut





Effective SNR - S3 PBH





Tuning - S3PBH