# Search for gravitational waves from Compact Binary Coalescence in LIGO data

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# Plan

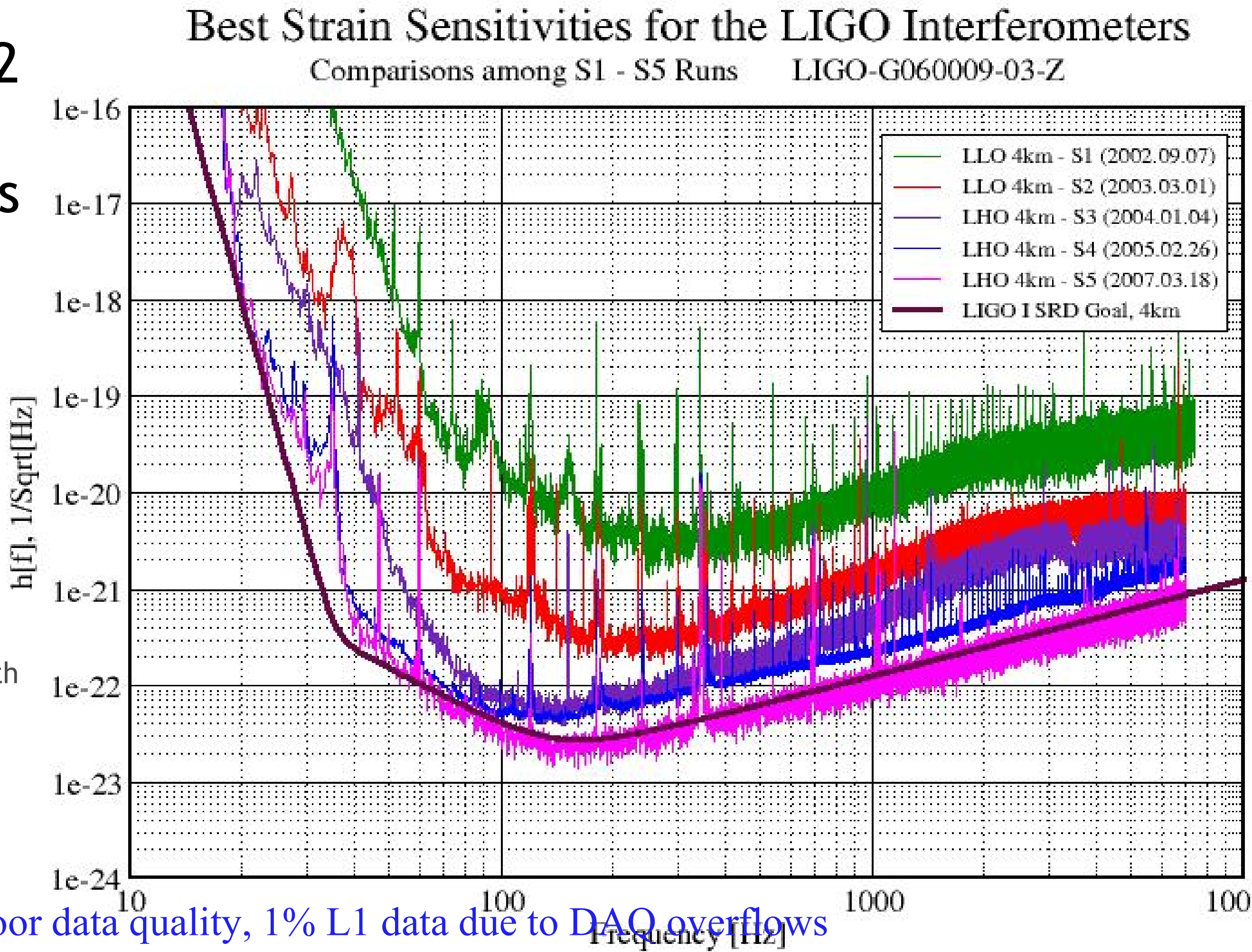
- S3 and S4 searches
  - Overview of the searches
    - Target waveforms : BNS, BBH, PBH
    - Data in LIGO S3 and S4 science runs
  - The search
    - Horizon distances
    - Search pipeline
    - Background estimation
  - S3 and S4 search results
    - Upperlimits on rate of CBC from S4 search
- Current searches
  - Pipeline enhancements
  - S5 CBC search status

# *The LIGO data*

For S3, H1 and H2 constraint
In S4, all combinations of coincident times.

*S3 science run :*
31st October 2003 to 9th January 2004.

S4 science run :
22nd February 2005 to 24th March 2005.


Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1 - S5 Runs LIGO-G060009-03-Z

S3, data quality flags
5% H1/H2 data removed due to poor data quality, 1% L1 data due to DAQ overflows
In S4, 10% of H1/H2 data removed due to transients.

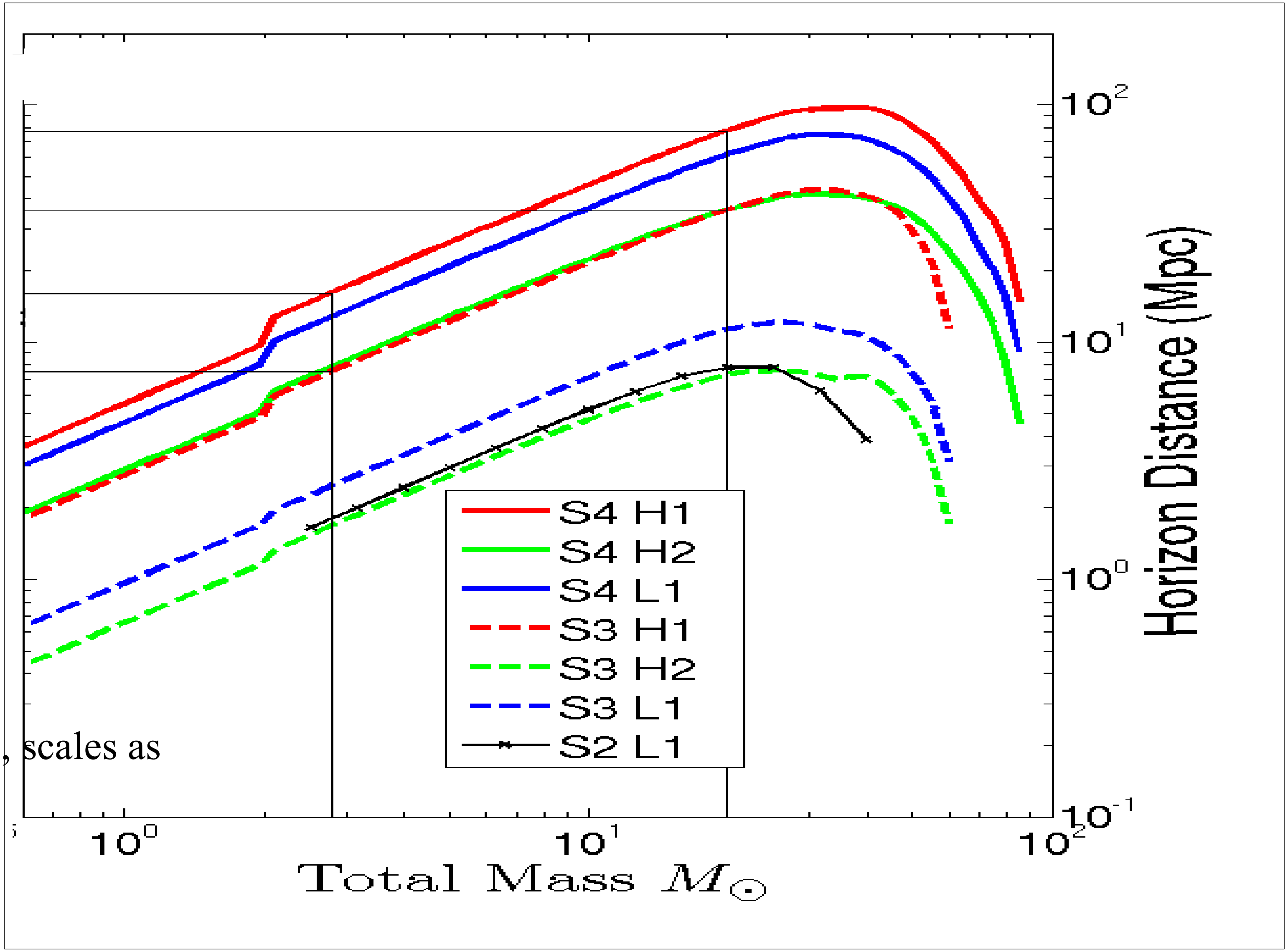
# *Expected inspiral horizon distance*

***The inspiral horizon distance*** is the distance at which an optimally oriented and located binary system can be seen with a given signal to noise ratio:

$$D_\rho(Mpc) = \frac{A}{1\mathrm{Mpc} \times \rho} \times f(m_1, m_2) \times \int_{F_L}^{f_{cut}} \frac{f^{-7/3}}{S_h(f)} df$$

It is a measure of the range of detection based on real data. This is not the search.

It is useful for a sanity check of the search algorithms.



For asymmetric systems, scales as

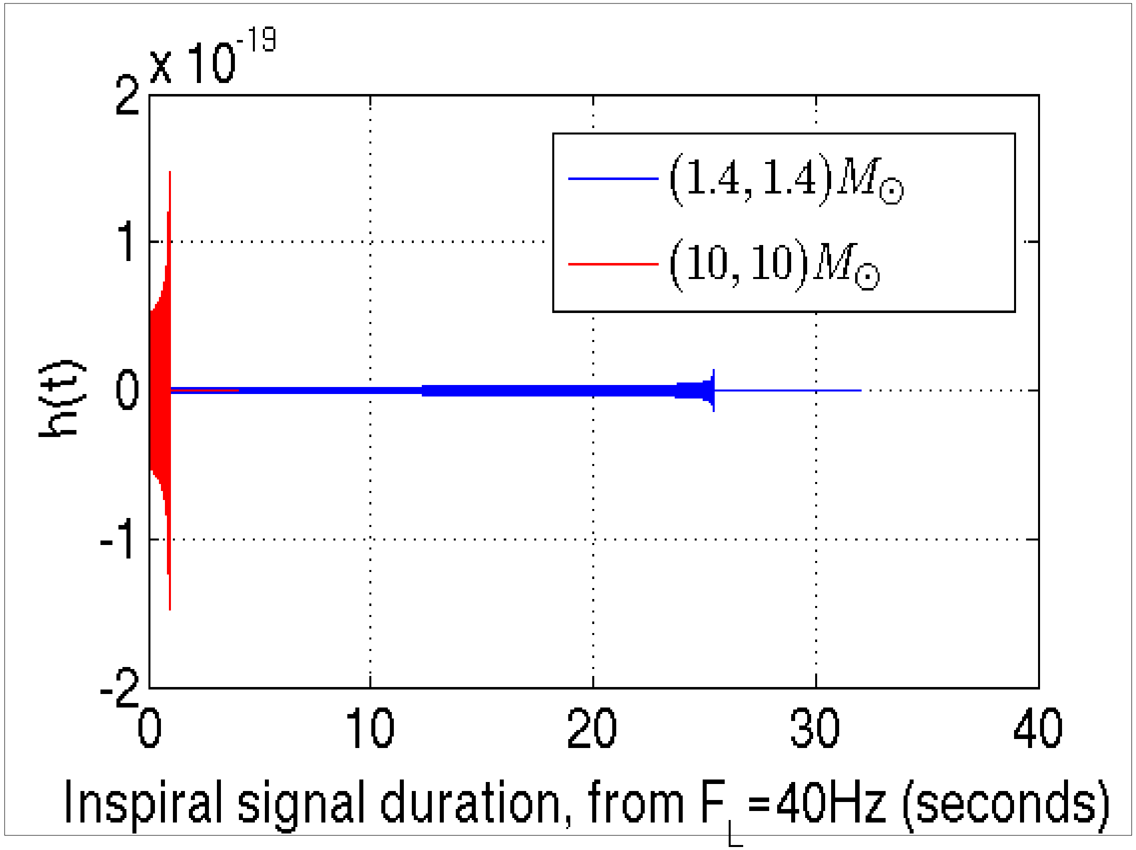
$$\frac{\sqrt{q_m}}{q_m + 1}$$

# Target waveforms

The gravitational-wave signal can be modeled well in the adiabatic regime, and represented by :

$$h(t) = \frac{1Mpc}{D_{\rm eff}}\left[h_c(t)\cos\Phi + h_s(t)\sin\Phi\right]$$

- The **amplitude** and **duration** of $h_{c,s}(t)$ depend on the masses, $\mathbf{m_1}$ and $\mathbf{m_2}$, and the lower cut-off frequency $F_L$
- No spin effects.
- $D_{\rm eff}$ contains the physical distance and orientation of the binary system.



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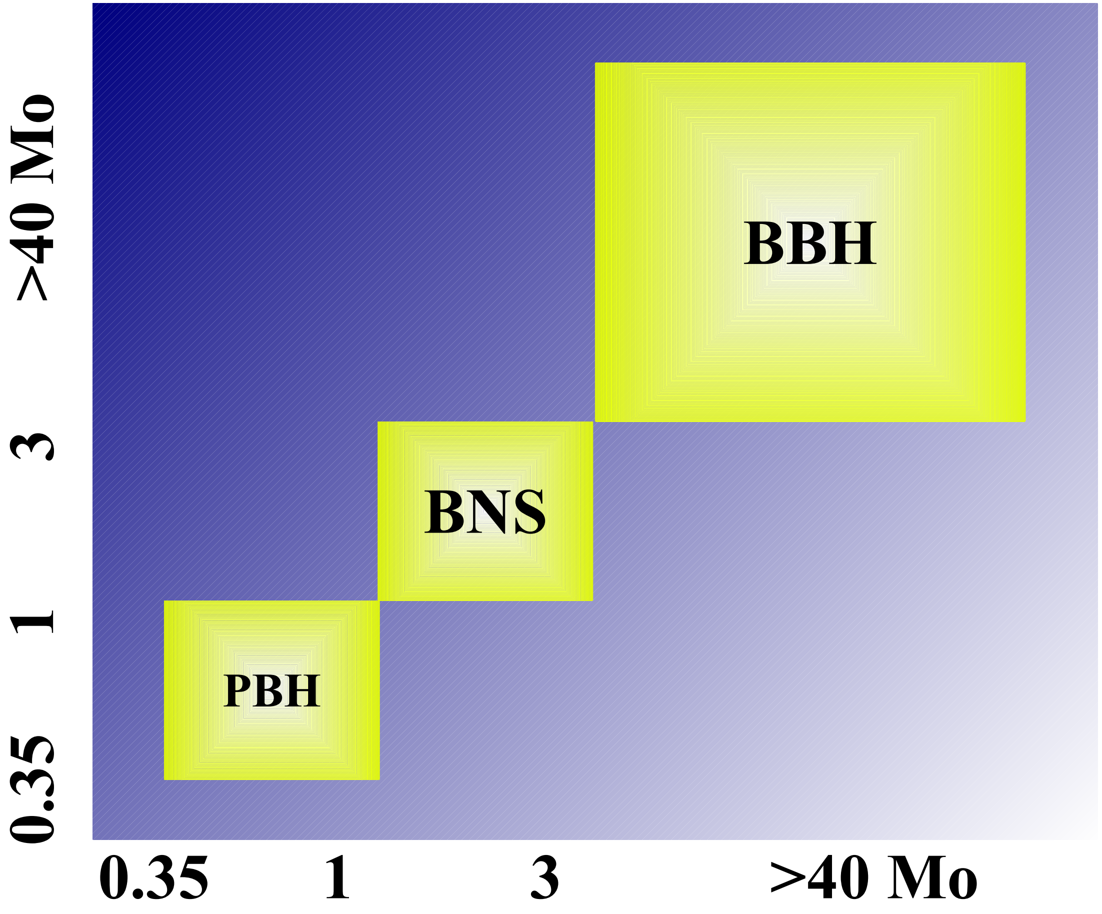
# *Different searches*

- We searched for inspiraling compact binaries:
  - Primordial Black Holes binaries (***PBH* binaries**) : $m_1$, $m_2$ in [0.35, 1.0]$M_\odot$
  - Binary neutron stars (***BNS***): $m_1$, $m_2$ in [1.0, 3.0]$M_\odot$ .
  - Binary Black Holes (***BBH***) : $m_1$, $m_2$ in [3.0, 80.0]$M_\odot$ with total mass less than 80$M_\odot$.

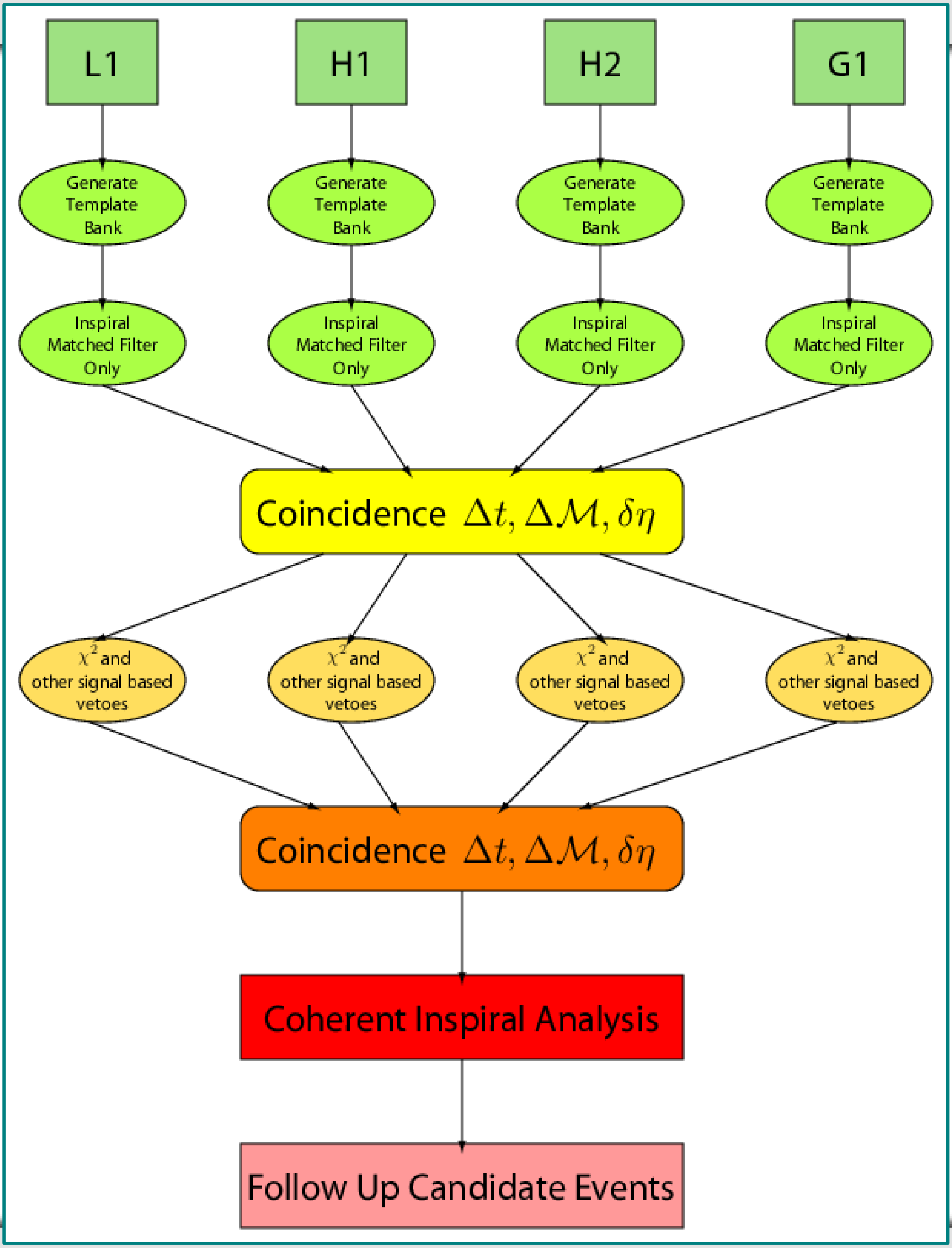


Driven by technical issues in the analysis methods.

# *Search pipeline and Coincidence*

***Coincidence at the input stage***:
A list of time intervals where at least two detectors operate in science mode.

***Coincidence at the output stage:***
We keep triggers that are coincident in time and mass parameters. The coincidence reduces the rate of triggers and increases the confidence in detection.



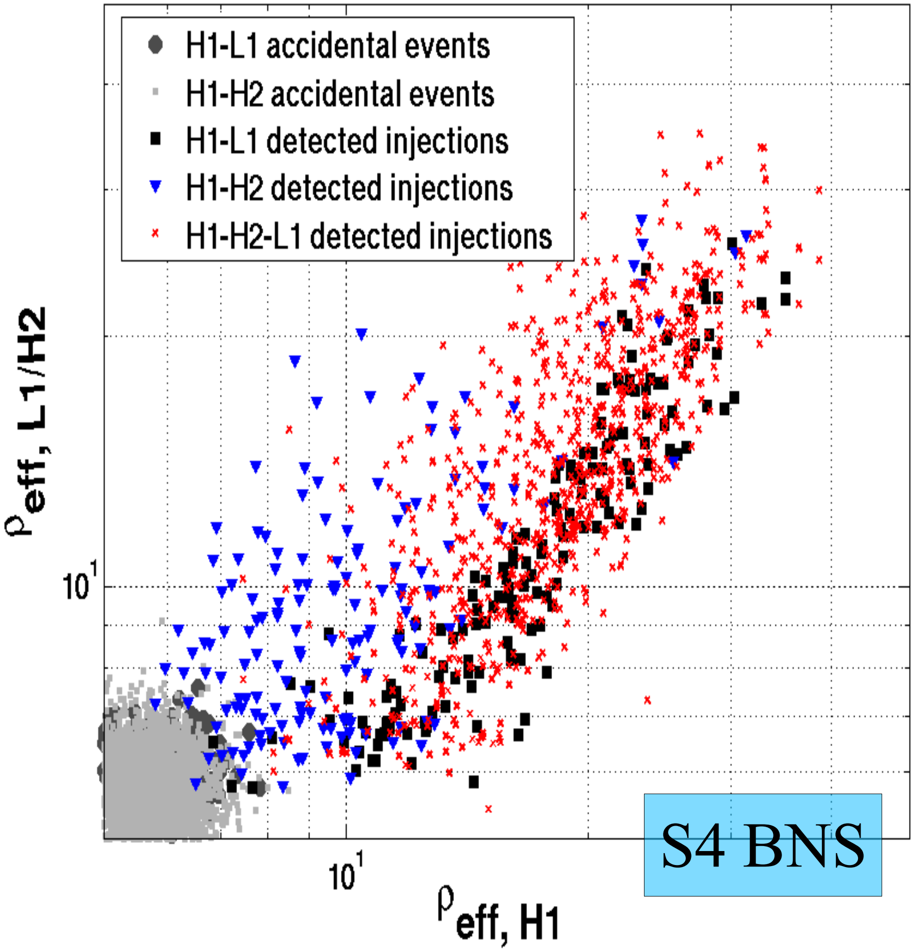
# *Background and simulations*

The search requires the pipeline to be used in 3 different ways:

1-Injections: we can tune the search parameters such as coincidence windows to be sure not to miss any real GW event.

2-Background estimation: we time-shift the data from the different detectors so as to estimate the accidental rate of triggers. Each search used 100 time-shifts.

3-Results: Finally, we analyse the data (no injections, no time shifts). The resulting triggers constitute the ***in-time coincident triggers, or candidate events.***



# *Difference between PBH binary, BNS and BBH search*

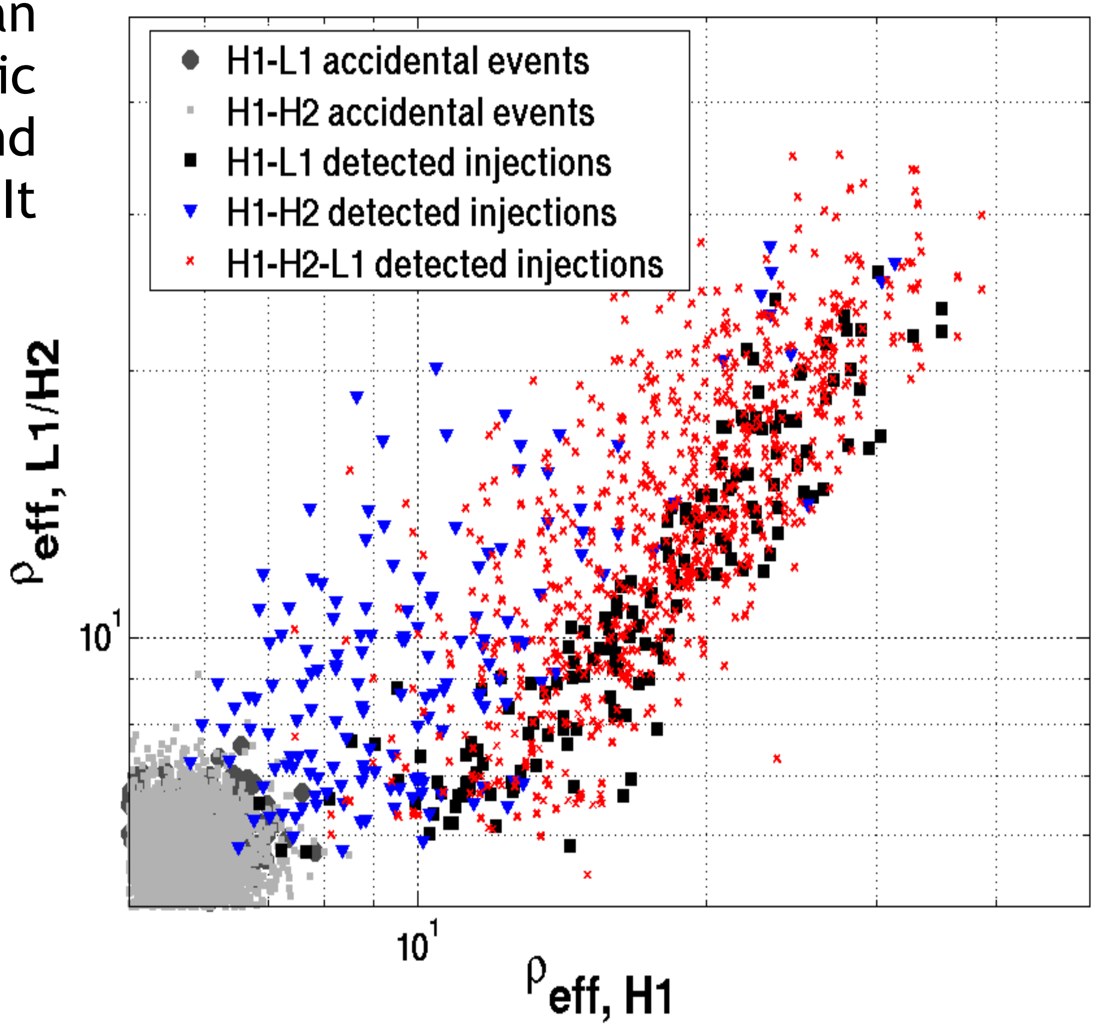
- Templates based on second order restricted to post-Newtonian waveforms, in the stationary phase approximation (SPA), for the PBH and BNS searches, and phenomenological templates for BBH search.

- Chi-squared used in the BNS and PBH searches ***only*** :
  - reduces background significantly.
  - Allows to use an effective SNR that well separates background and simulated events.

# Effective SNR (BNS and PBH)

In PBH and BNS search, we use an effective SNR, that is a statistic which well separates the background triggers from simulated injections. It is defined by

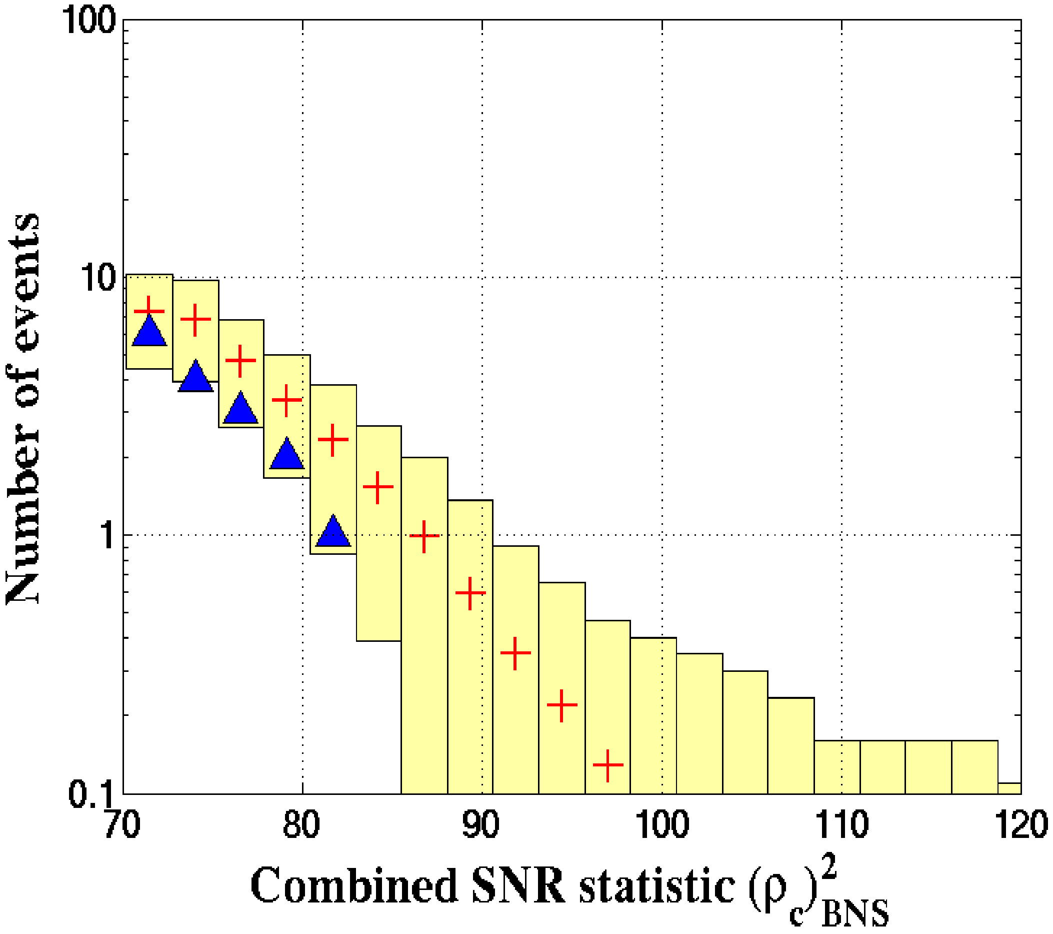
$$\rho_{\text{eff}}^2 = \frac{\rho^2}{\sqrt{\left(\frac{\chi^2}{\text{DoF}}\right)\left(1+\frac{\rho^2}{250}\right)}}$$



# *In-time and time-shifted coincident triggers*

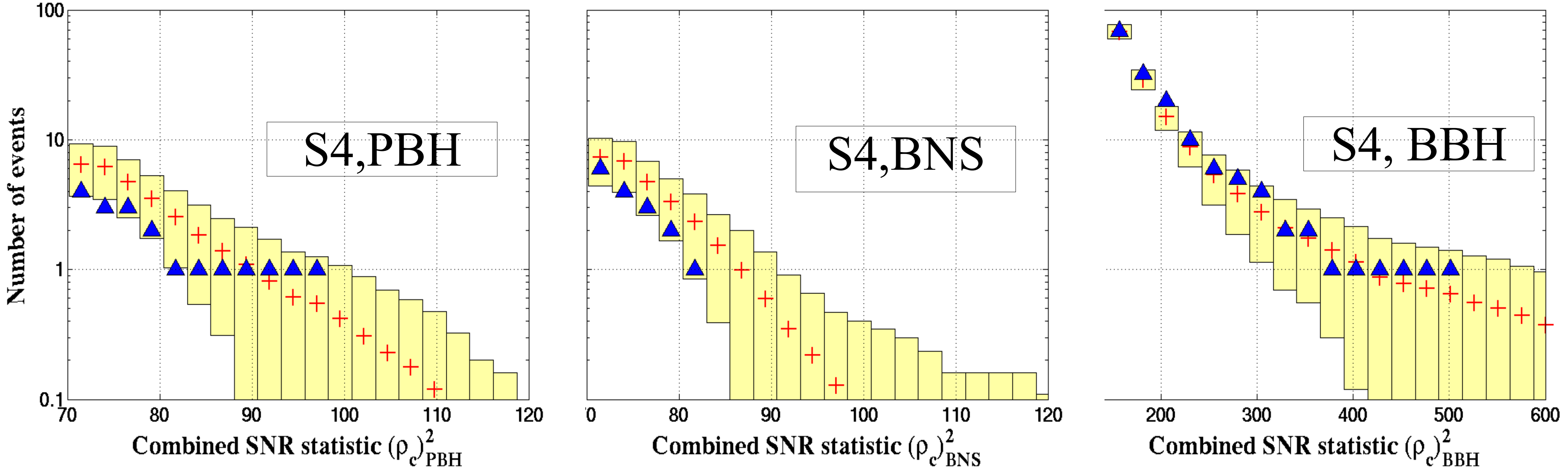
From each search (PBH, BNS and BBH), a list of in-time coincident triggers is available. These triggers need to be compared with the background estimate, which is made over 100 realisations (time-shifted).

If an in-time coincidence trigger is above the estimated background, then it is a candidate event, and needs follow-ups



# Candidate events

PBH, BNS and BBH, in S3 and S4 show that distribution of in-time coincidence triggers is consistent with expectation, except for the S3 BBH.



Follow ups are needed for candidate events, if any. Irrespective of the list of possible candidates, we follow up the loudest coincidence triggers.

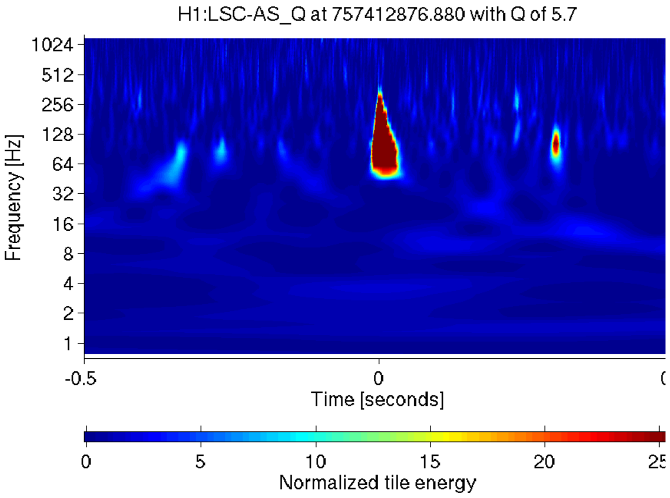
# *S3 BBH loudest candidate events*

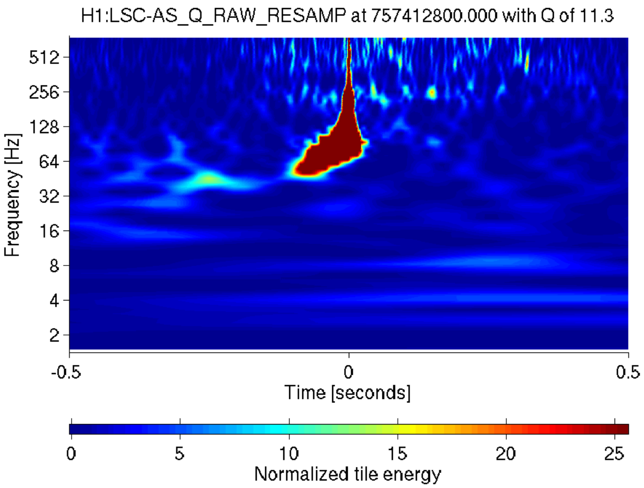
In S3 BBH search, 1 coincident trigger (H1/H2) found above estimated background (5 sigmas) with large SNR (150 in H1). Consistent with injections (same SNR, similar SNR time series). Using physical template families, we estimated the chisq, which did not reject the candidate.

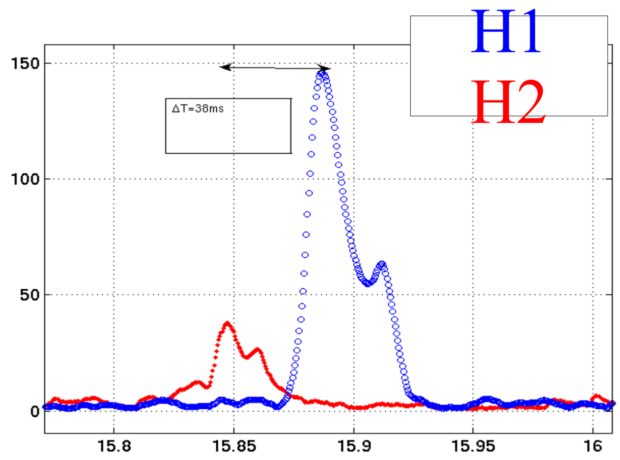
BUT (1) very high mass and therefore short time duration.

(2) No chirp-like time-frequency pattern (see 2 TF plots below).

(3) very wide time-shifts between H1 and H2 (see figure below) of 38ms whereas expectation gives a mean of zero and std of 6.5ms.







Serious candidate but not a plausible GW signal.

# *S4 Upper limit results*

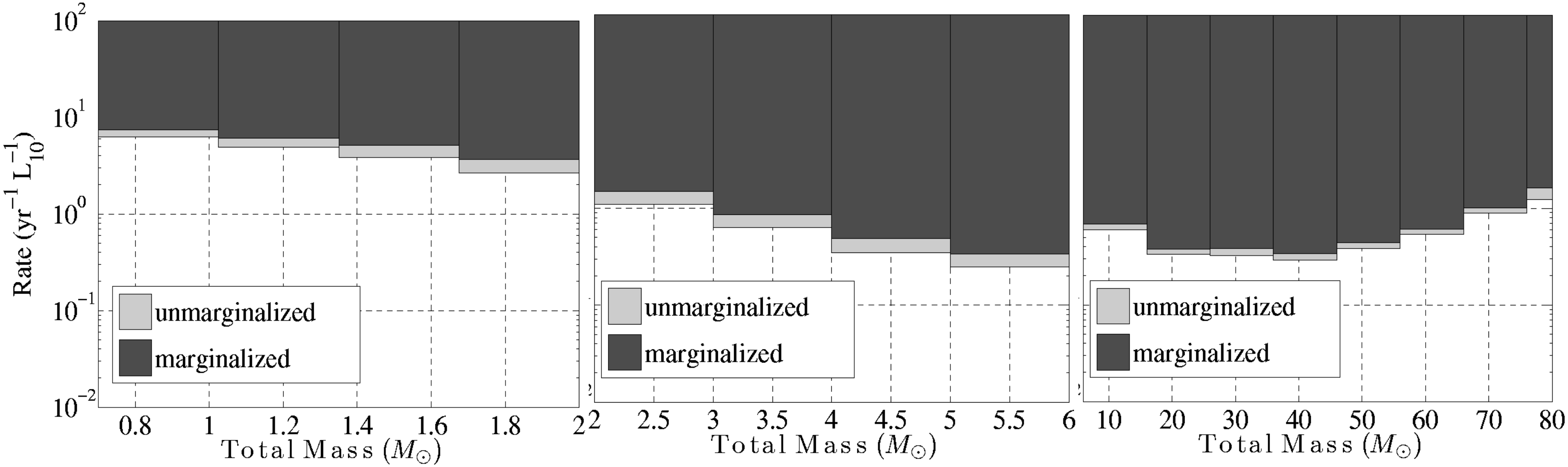
The Bayesian upper limit calculation is based on

- The detection efficiency at the loudest event (*how many injections found with combined SNR above the largest in-time coincidence triggers*).
- The estimated background.
- A galaxy population
- Time analysed (about 520 hours in S4)
- systematics errors such as Monte-Carlo errors, waveform inaccuracy, calibration errors...

We used only results from the more sensitive run, namely S4

# S4 Upper limit results (1)

## Uniform distribution



# S4 Upper limit results (2)

## Gaussian distribution

PBH binary assuming Gaussian distribution around a 0.75-0.75 solar mass system:

$$4.9\ yr^{-1} L_{10}^{-1}$$

BBH assuming a Gaussian distribution around a 5-5 solar mass system:

$$0.5\ yr^{-1} L_{10}^{-1}$$

BNS assuming Gaussian distribution around a 1.4-1.4 solar mass system.

$$1.2\ yr^{-1} L_{10}^{-1}$$

$$L_{10} = 10^{10} L_{\odot}$$

**= 0.6 Milky Way Equivalent Galaxy.**

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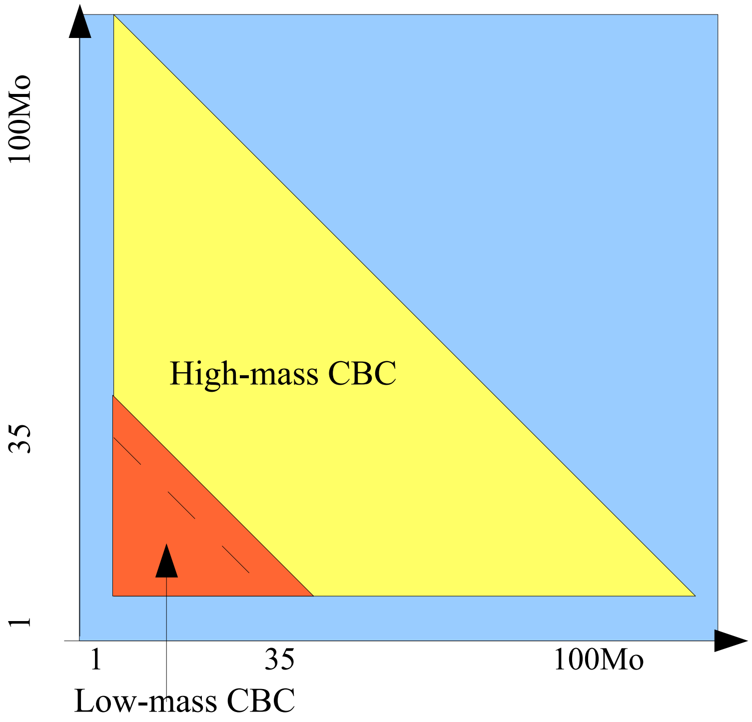
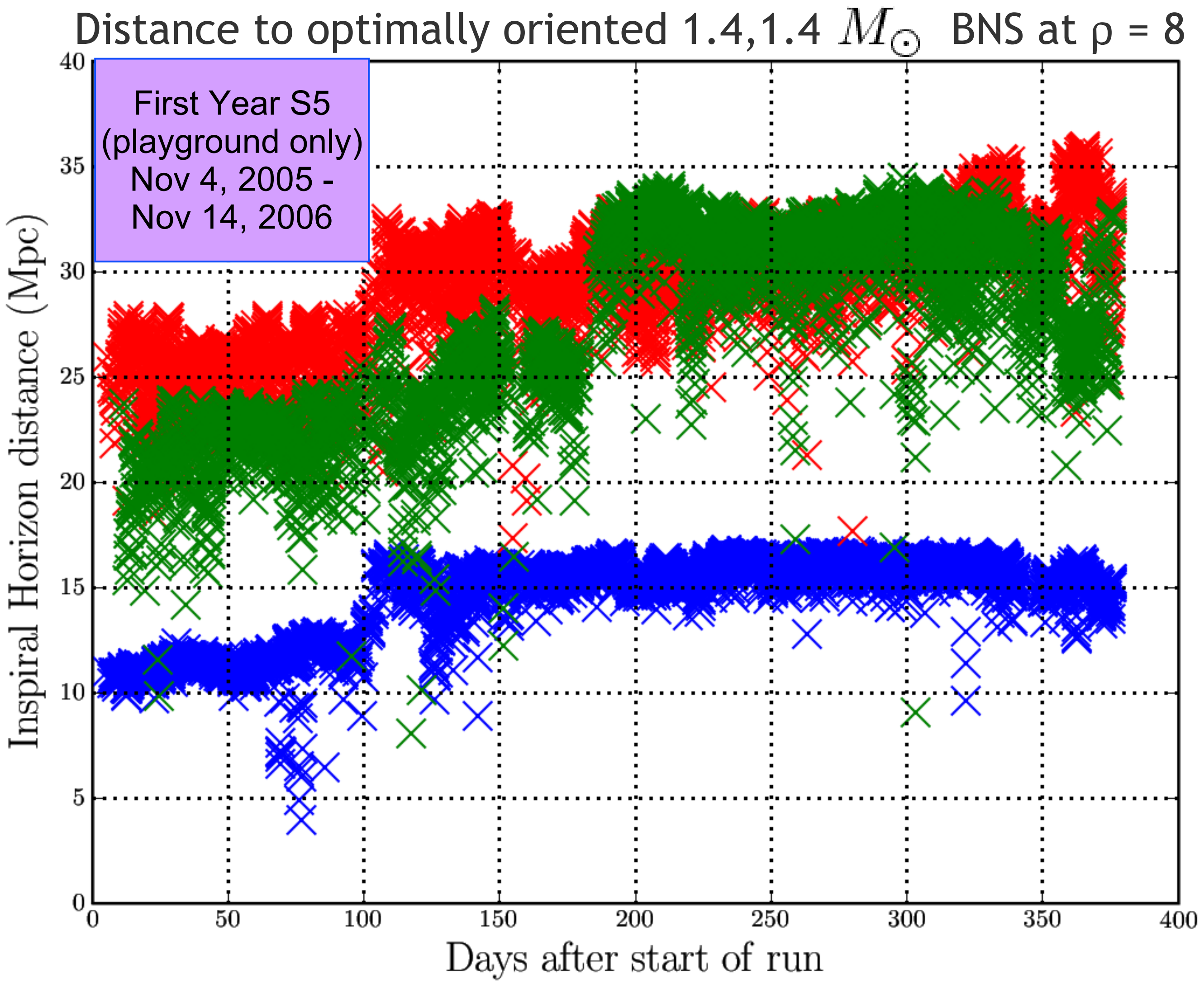
# Searches underway

- Start of run (11/4/05) to anniversary of LLO joining S5 (11/14/06)
- Low-mass CBC
  - Max total mass 35 $M_\odot$
  - Uses 2PN SPA templates
- High-mass CBC
  - Total mass range 25 - 100 $M_\odot$
  - Uses EOB templates generated in time-domain



# *First year S5 BNS horizon distance*



First Year S5
(playground only)
Nov 4, 2005 -
Nov 14, 2006

# *Improvements to pipeline*

- Physical templates now used for BBH
  - Reduces background rate
  - Allows chi-squared test to be used
- Improved method for coincidence analysis
  - Uses ellipsoidal parameter-dependent coincidence windows
  - Reduces background by up to 10x
- New clustering algorithm
- Memory management issues arising with combining a year's worth of triggers
  - RAM
  - Disk space

# Conclusions

**No detection of GW** signal from coalescing compact binaries in S3 nor in S4.

Upper limits on merger rates :

$4.9\ yr^{-1} L_{10}^{-1}$ for PBH binaries

$1.2\ yr^{-1} L_{10}^{-1}$ for BNS (expected: $[10-170]10^{-6}\ yr^{-1} L_{10}^{-1}$

$0.5\ yr^{-1} L_{10}^{-1}$ for BBH (expected: $[0.06-6]10^{-6}\ yr^{-1} L_{10}^{-1}$

Status of the analysis :

Mature BNS and PBH search pipeline. We can clearly identify simulated events at a SNR = 8 .

We will use PN template Families to cover the BBH in the future searches so as to reduce the background rate.

Present and Future :

Apply the tools developed on S5 and future science runs.