Search for compact binary systems in LIGO data

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Plan

1)- Overview

- **What kind of gravitational waves are we searching for ?**
- **Data description : S3 and S4 LIGO science runs.**

2)- The Search :

Expected horizon distances, detection methods, effective signal to noise ratio, coincidences between detectors, ...

3)- The S3 and S4 data results

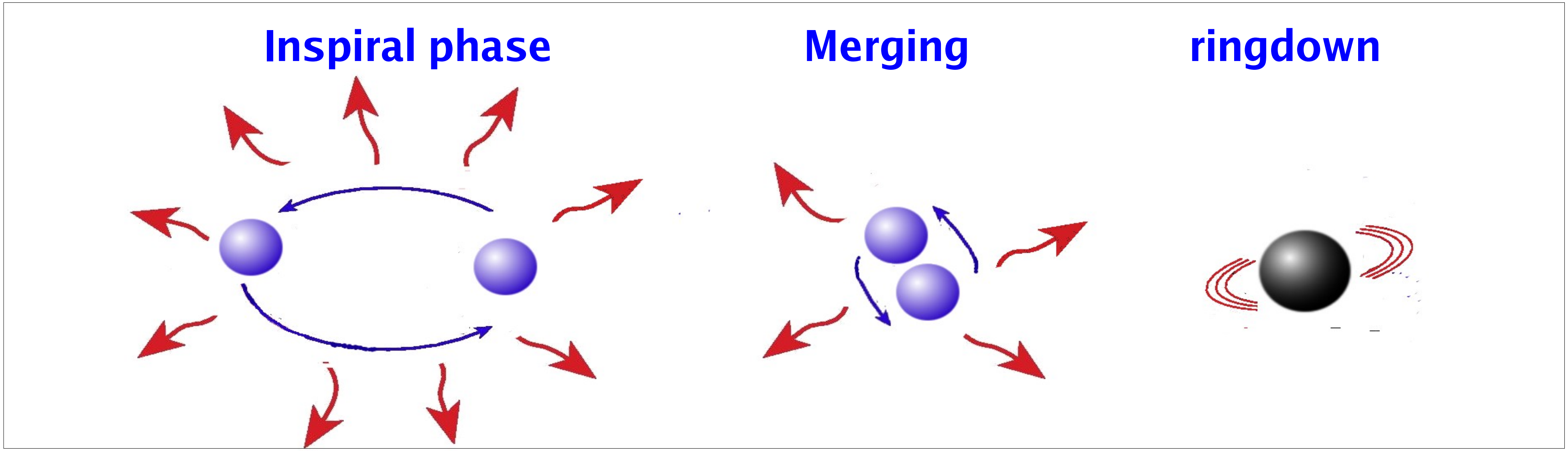
4)- Upper limits

5)- Conclusion

Overview

GW from compact binary systems

- Gravitational waves emitted from ***compact binary systems*** are known to exist :
  - PSR1913+16, first double pulsar J0737-3039 ...
- The emission of gravitational waves from compact binaries follows three main phases:



- The last cycles of the ***inspiral phase*** (and merger and ringdown) are detectable by ground based interferometers such as LIGO observatories.

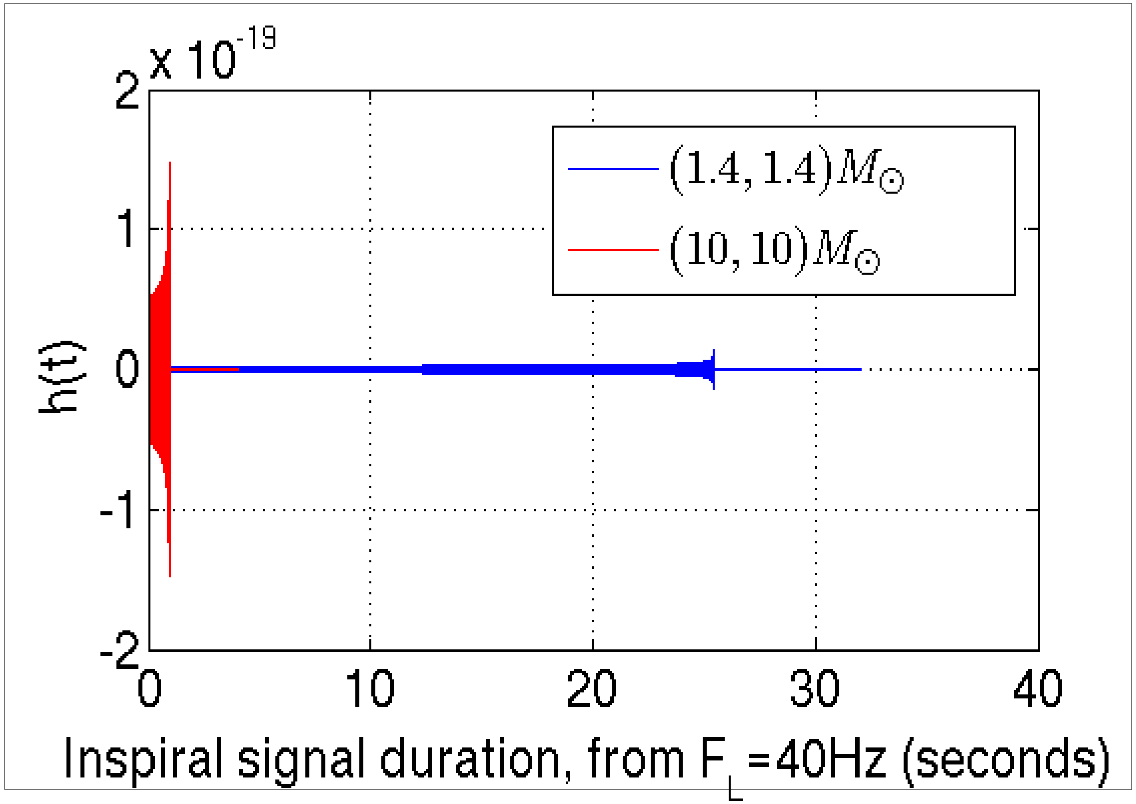
The Inspiral signals (1)

The inspiral phase can be modeled, and represented by :

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

The **amplitude** and **duration** of $h_{c,s}(t)$ depend on the masses, $\mathbf{m_1}$ and $\mathbf{m_2}$, of the binary system considered and the lower cut-off frequency F_L.

D_{eff} contains the physical distance and orientation of the binary system.

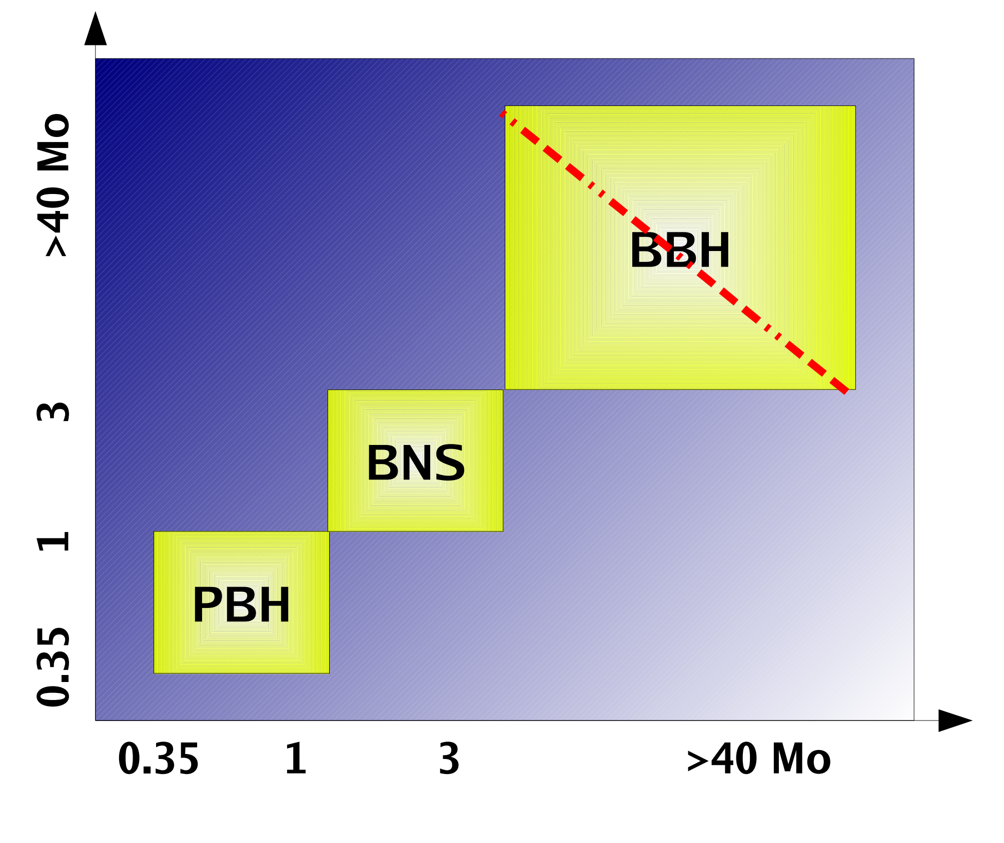


The Inspiral signals (2)

There is a wide range of compact object from sub-solar mass up to tens of solar mass; the duration varies from 25 seconds for $m_1=m_2=1.4\ M_\odot$ to less than a second for m1=m2=10 $M_\odot$.

In this study, we search for :

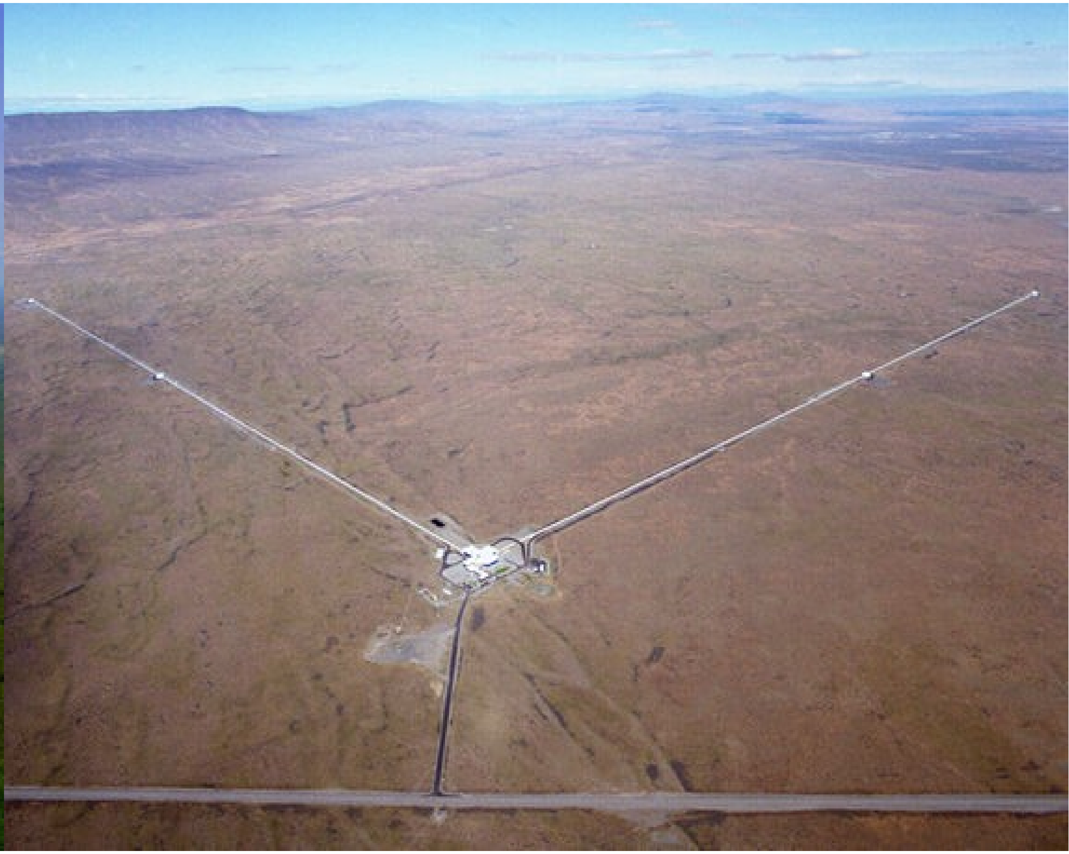
- Primordial Black Holes binaries (***PBH* binaries**) : m_1, m_2 in [0.35, 1.0] $M_\odot$
- Binary neutron stars (***BNS***): m_1, m_2 in [1.0, 3.0] $M_\odot$
- Binary Black Holes (***BBH***) : m_1, m_2 in [3.0, 80.0] $M_\odot$ with total mass less than 80 $M_\odot$.



Different waveforms led to different search parameters/filtering.

The LIGO observatories

LIGO consists of 3 detectors, 2 co-located in Hanford (WA) and 1 in Livingston (LA). We use the following abbreviations for each of them: H1 (4km long), H2 (2km long), and L1 (4km long).

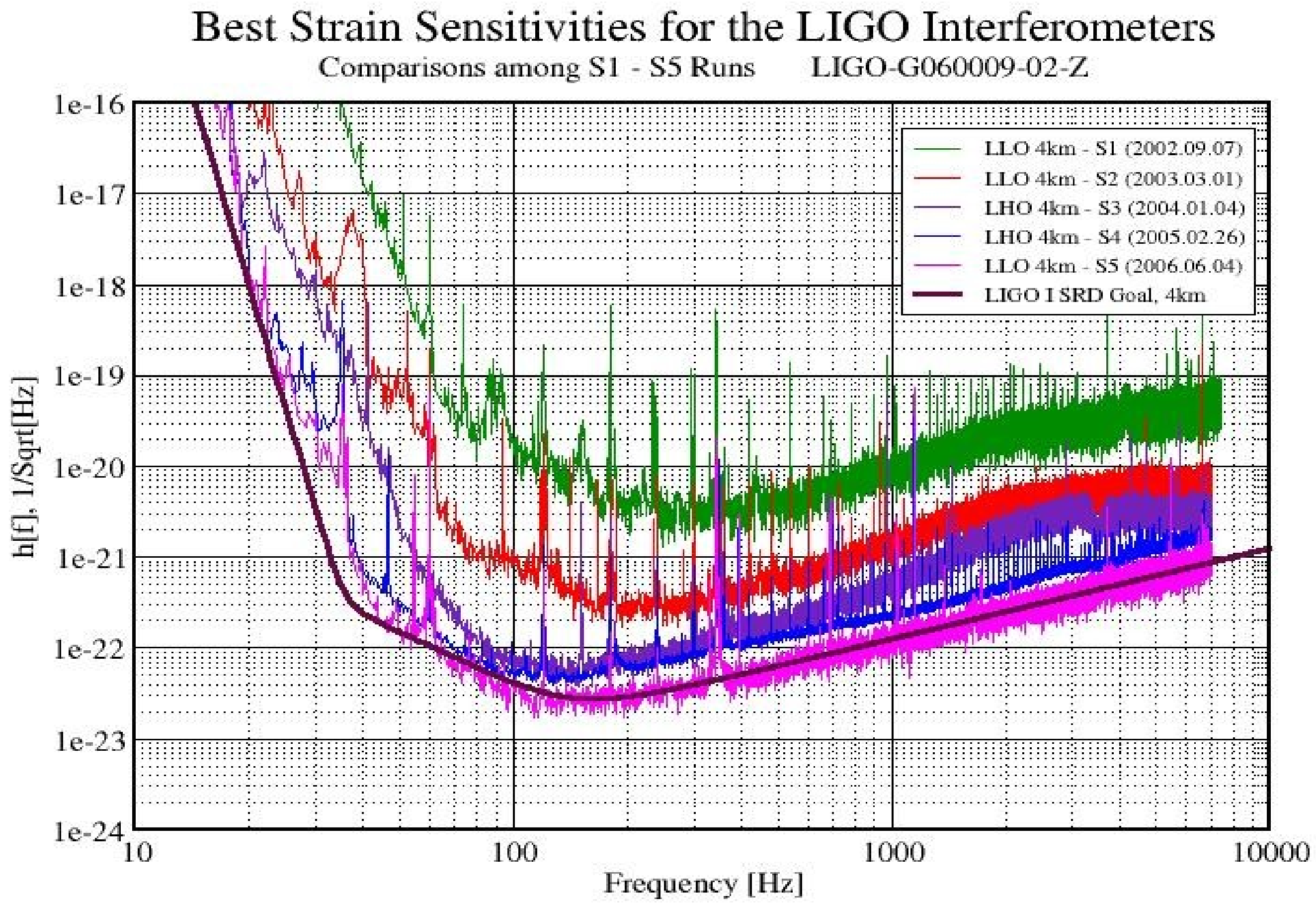


The LIGO data

We searched for gravitational waves from coalescence of compact binaries (PBH binaries, BNS, and BBH) in the S3 and S4 LIGO science runs.

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

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



The search

What is the horizon distance ?

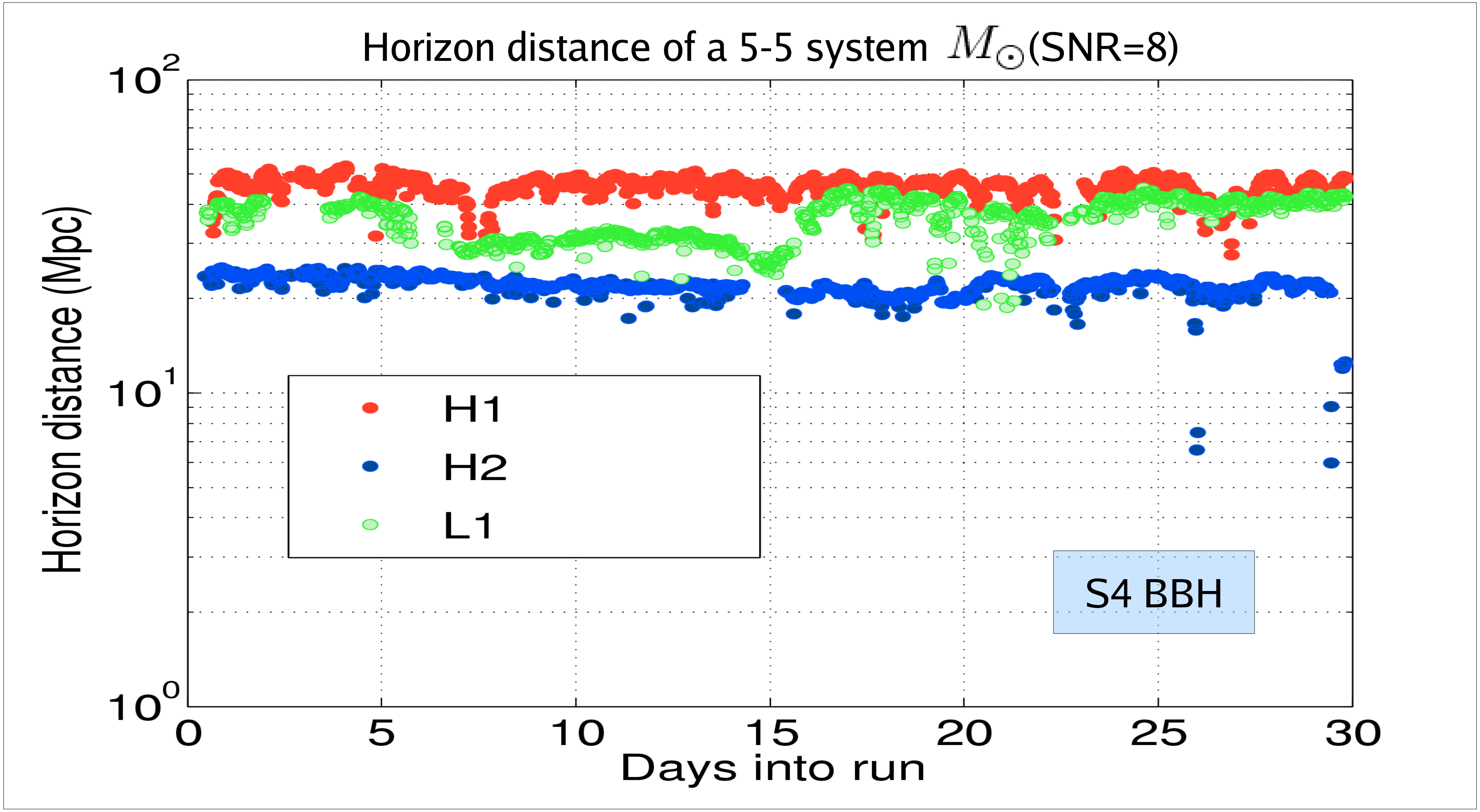
A preliminary step is the computation of ***the horizon distance,*** (i.e. the distance at which an optimally oriented and located binary system can be seen with a given signal to noise ratio):

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

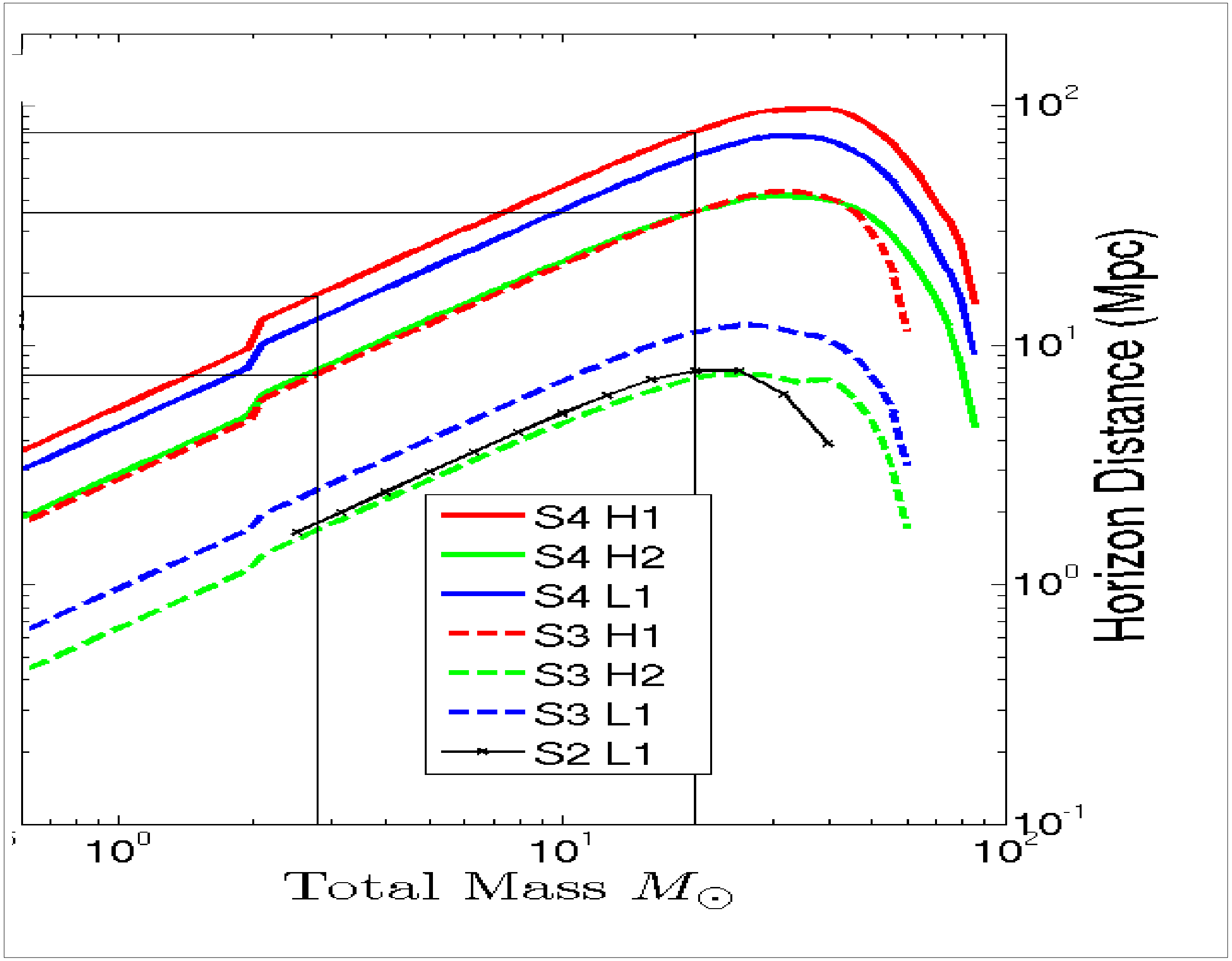
It is based on the power spectrum density of the real data and the expected waveform parameters $S_h(f)$ are generated every 2048 seconds so as to follow noise fluctuations.

Horizon distance (2)

Example : BBH horizon distance fluctuation (SNR=8) through the entire S4 runs. Similar fluctuations in BNS and PBH binary search:



Horizon distance (S3 and S4)



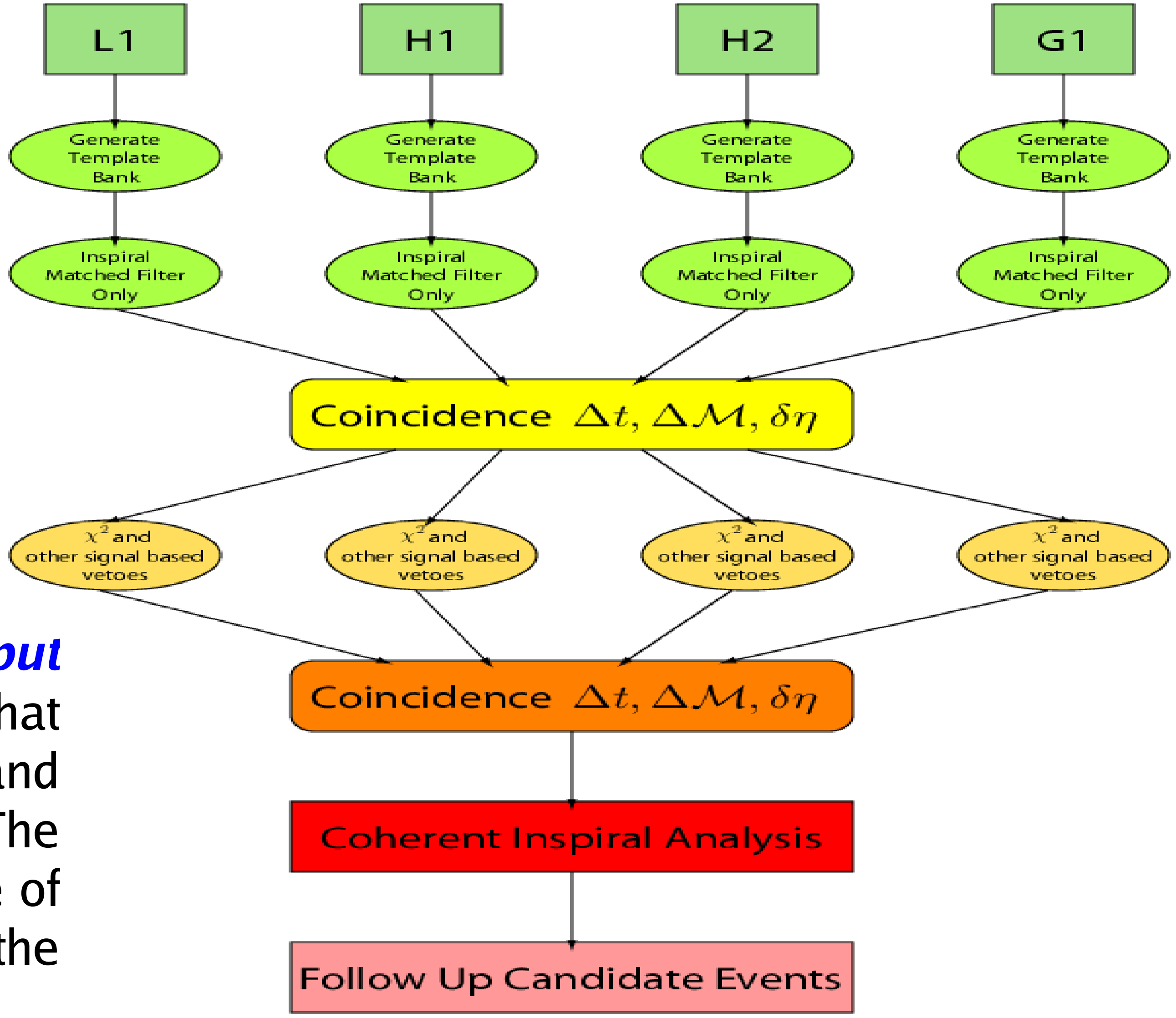
Horizon distance is useful for sanity check, quick understanding of the detector behaviour, etc. BUT this is not the search itself.

Search pipeline and Coincidence

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

	S3(hours)	S4(hours)
H1H2L1 times	184	365
H1L1 times	604	126
H1H2 times	-	46
H2L1 times	-	39

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.



Difference between PBH binary, BNS and BBH search

The BNS and PBH binary searches are very similar:

- Templates based on second order restricted to post-Newtonian waveforms, in the stationary phase approximation.
- Identical template bank placement.
- Identical filtering process
- Similar coincidence windows
- Hierarchical search
- Chi square

Final triggers associated to an effective SNR which combines the SNR and its Chi square value.

The BBH search used the same pipeline but :

- Target waveform non accurately known. We used templates based on phenomenological waveforms, which uses two phenomenological parameters. Consequences :
  1. Different template bank.
  2. Different filtering.
  3. Non physical mass parameters
- Coincidence in time, and the 2 phenomenological parameters.
- No chi square applied.

Final triggers associated to the classical SNR.

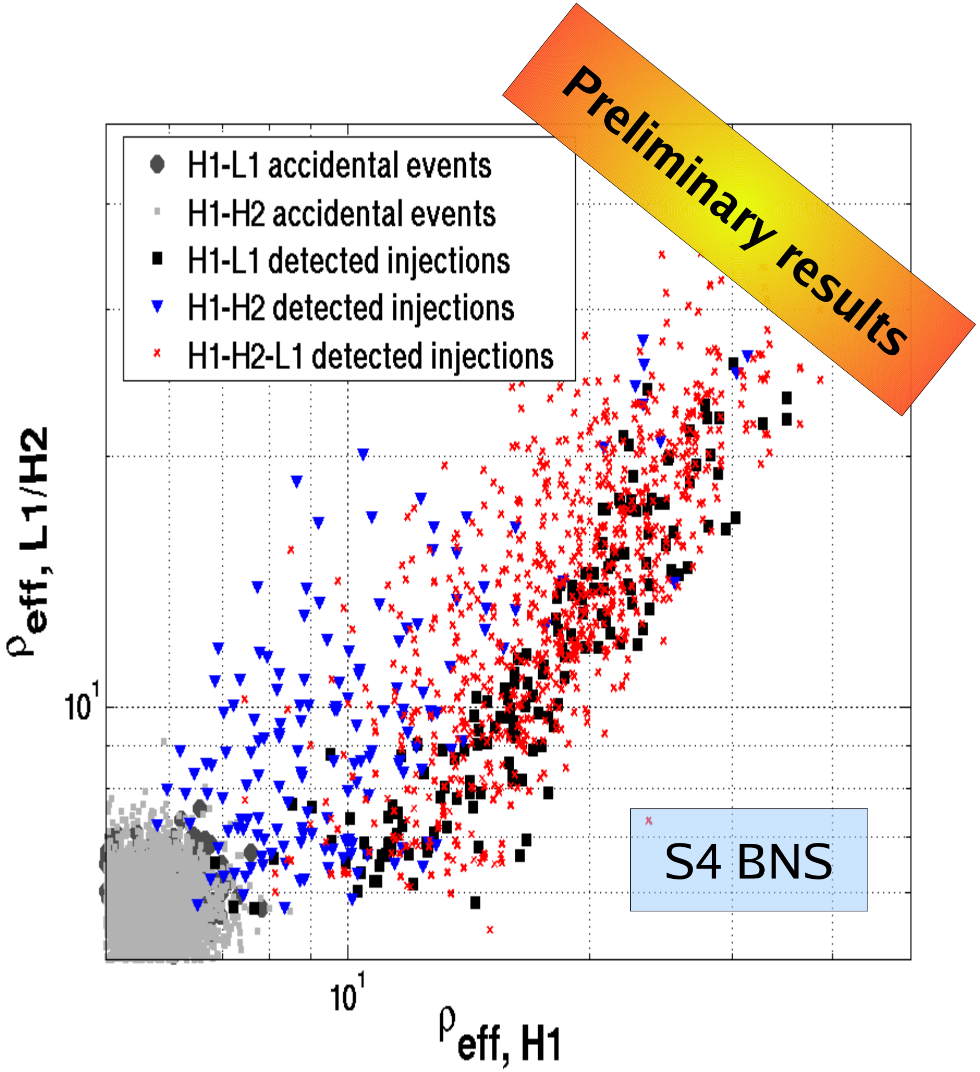
Background and simulations

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

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

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

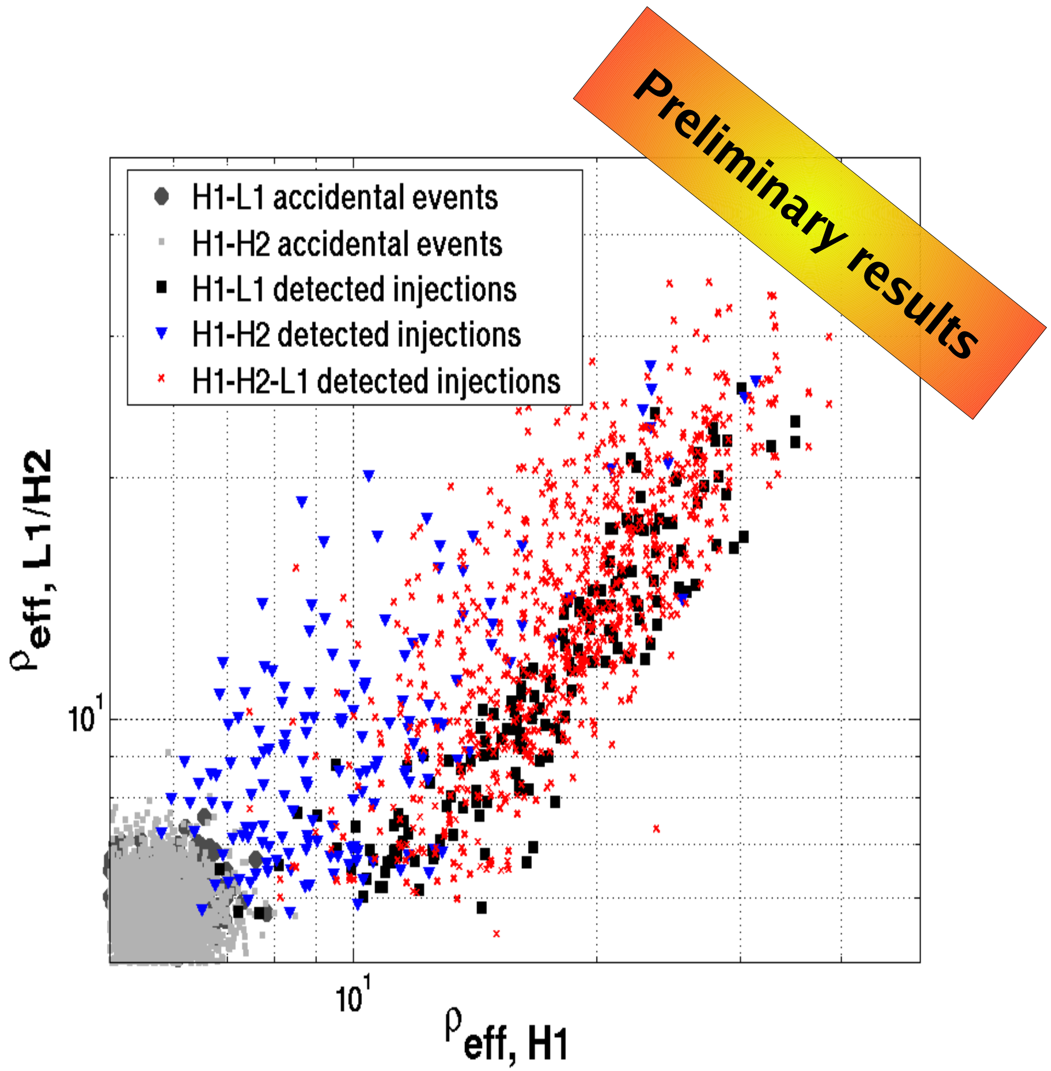
3-Results: Finally, we analyse the data (no injections, no time shifts). The resulting triggers constitutes the ***in-time coincident triggers, or candidate events.***



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

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

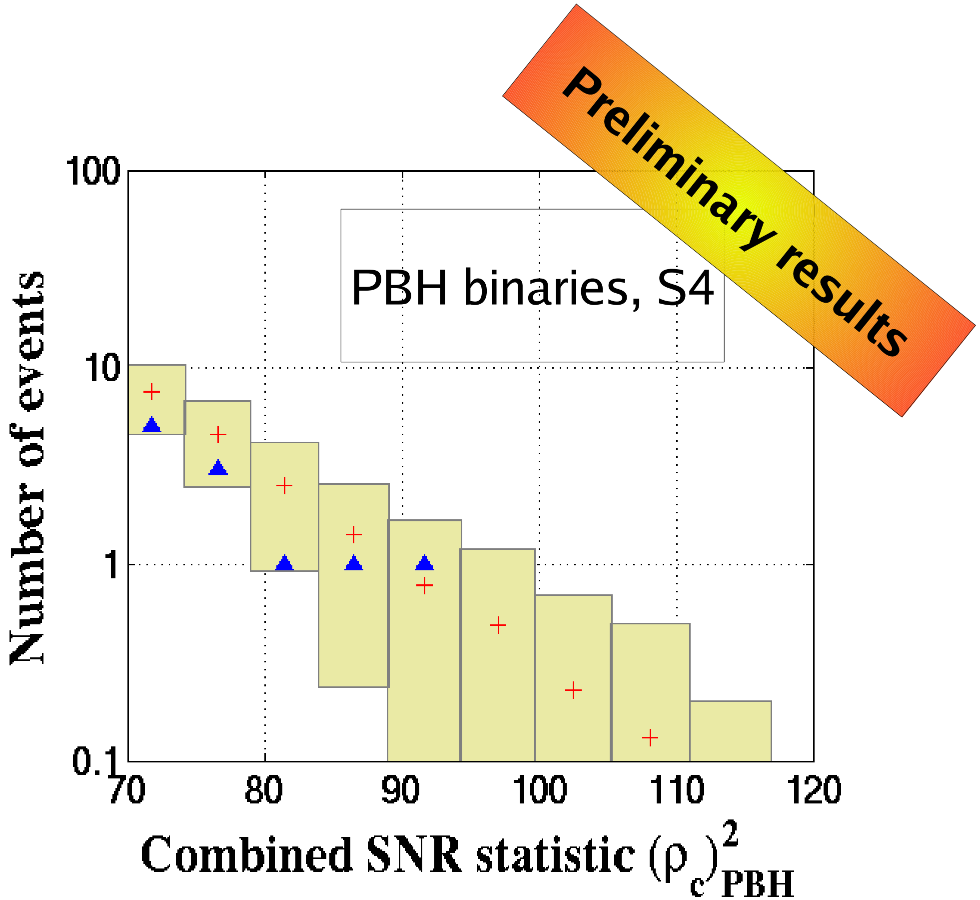


Results

Comparison between candidates and background

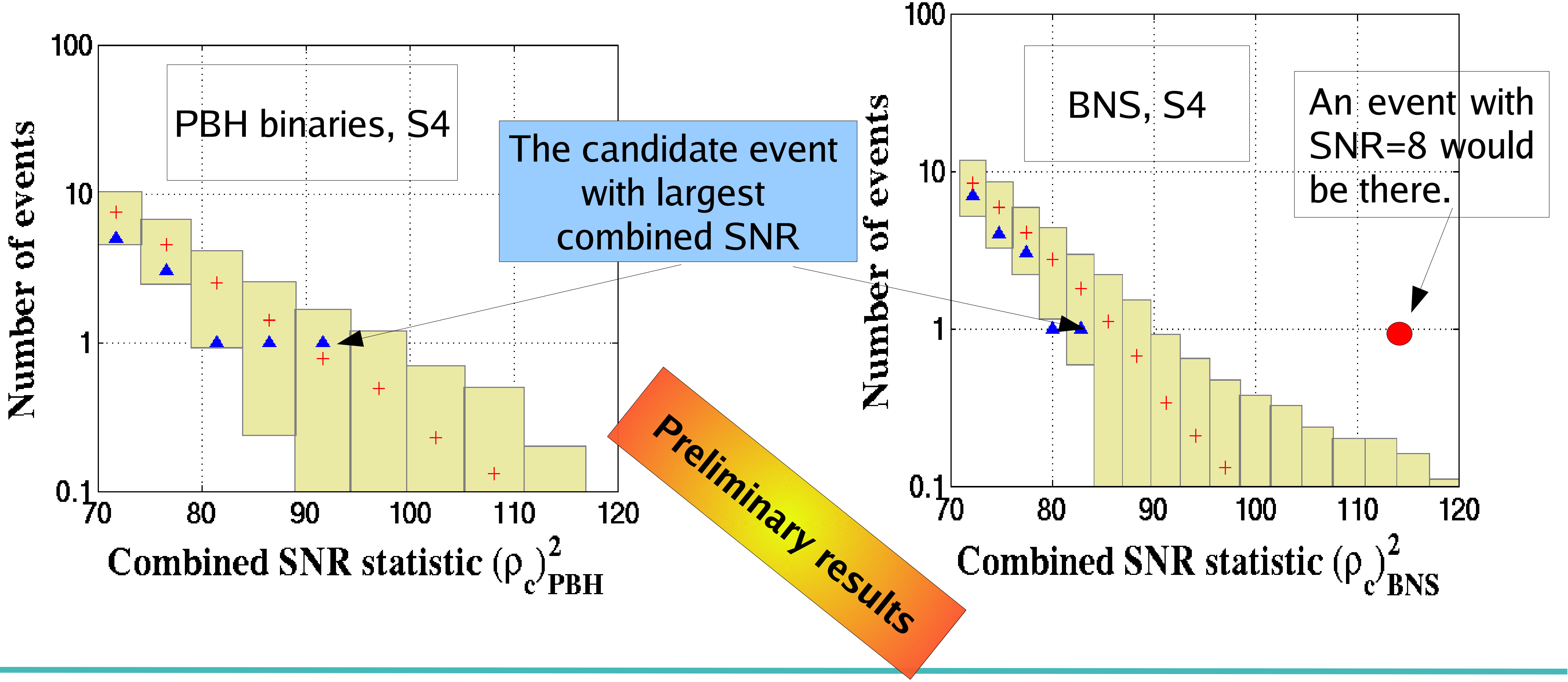
From each search (PBH, BNS and BBH), a list of in-time coincident triggers, or candidate events is provided and have to be compared with the background estimate, over 100 realisations.

The comparison is performed by using a combined statistics; we combine the individual SNR in each detector so that it represents a constant false alarm statistic. For instance, in the PBH binary and BNS searches, we use the sum of the SNR squared.



Detection above background ?

PBH, BNS and BBH, in S3 and S4 shows that distribution of candidate events is consistent with expectation, except S3 BBH (next slide).



Follow up of candidates

Irrespective of the position of the loudest candidate events with respect to the expected background, we follow up the loudest candidates in various ways:

What was the status of the instruments ?

Spectrograms of the data are used to check for obvious instrumental artefacts.

In the BBH search, further follow up using physical template families are performed.

What are the parameters of the triggers : does the effective distances are consistent ? Are the parameters (SNR, masses...) on the edge of coincidence windows....

More tests such as Null-stream analysis are used.

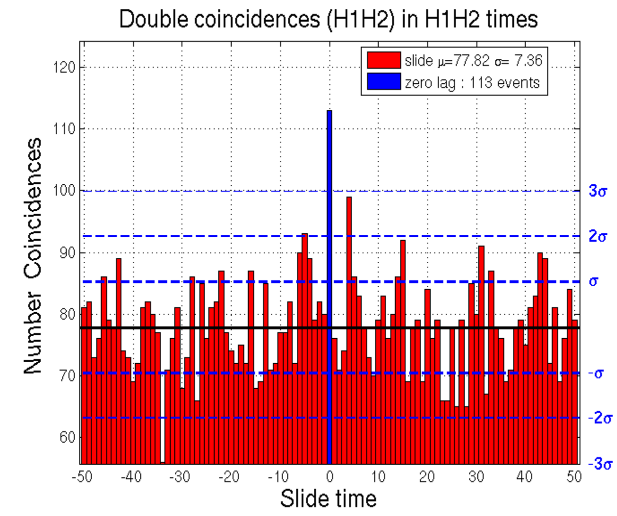
...

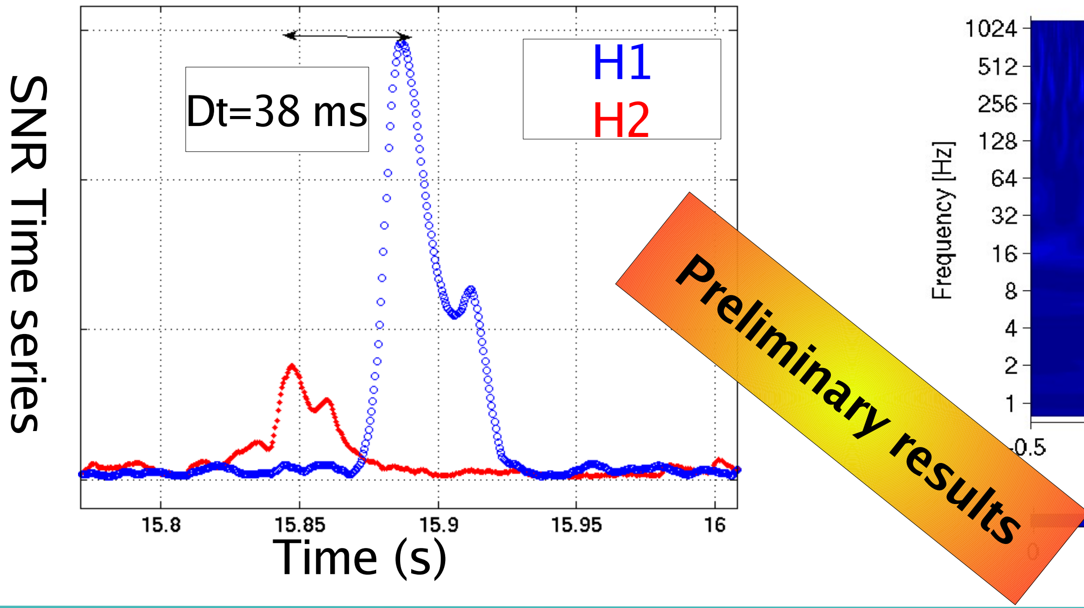
First, candidates with largest SNR are investigated.

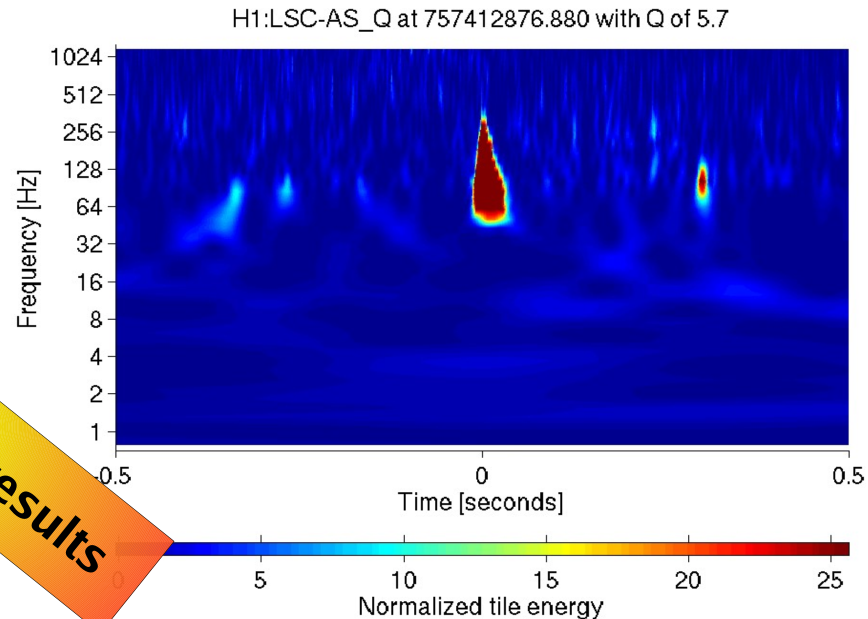
Follow up of candidates: example

In S3 BBH, one candidate was found above estimated background, in H1H2 coincidence.

- We know that in the 2 co-located H1 and H2 detectors, the background is under-estimated (right)
- We used physical template families and shows a large time delay in H1 and H2 (below).
- Null stream analysis definitely rejected this candidate from our list of plausible candidates.
- This candidate was rejected after various tests (previous slides) were applied.







any detection ?

No detection in S3 or S4, in either of the PBH binary, BNS or BBH search.

All triggers in BNS and PBH binary search are consistent with background estimates.

One candidate in S3 BBH with large SNR (H1/H2 coincidence but not found in L1), which was rejected by various methods.

Loudest candidates in each search were further investigated but none was identified as plausible GW.

So, we looked at the upper limits.

Upper limits

S4 Upper limit results

- No detection made, so we derived the upper limits in each search.
- We used only results from the best sensitive run, namely S4

Expected merger rates (***V.Kalogera et al., ApL 614, R. O'Shaughnessy et al. ApJ.633, Alcock et al. ApJ,512***)

BNS : $[2-120]\,10^{-6}\,yr^{-1}\,L_{10}^{-1}$

BBH : $[0.4]\,10^{-6}\,yr^{-1}\,L_{10}^{-1}$

PBH $10^{-2}\,yr^{-1}\,L_{10}^{-1}$

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

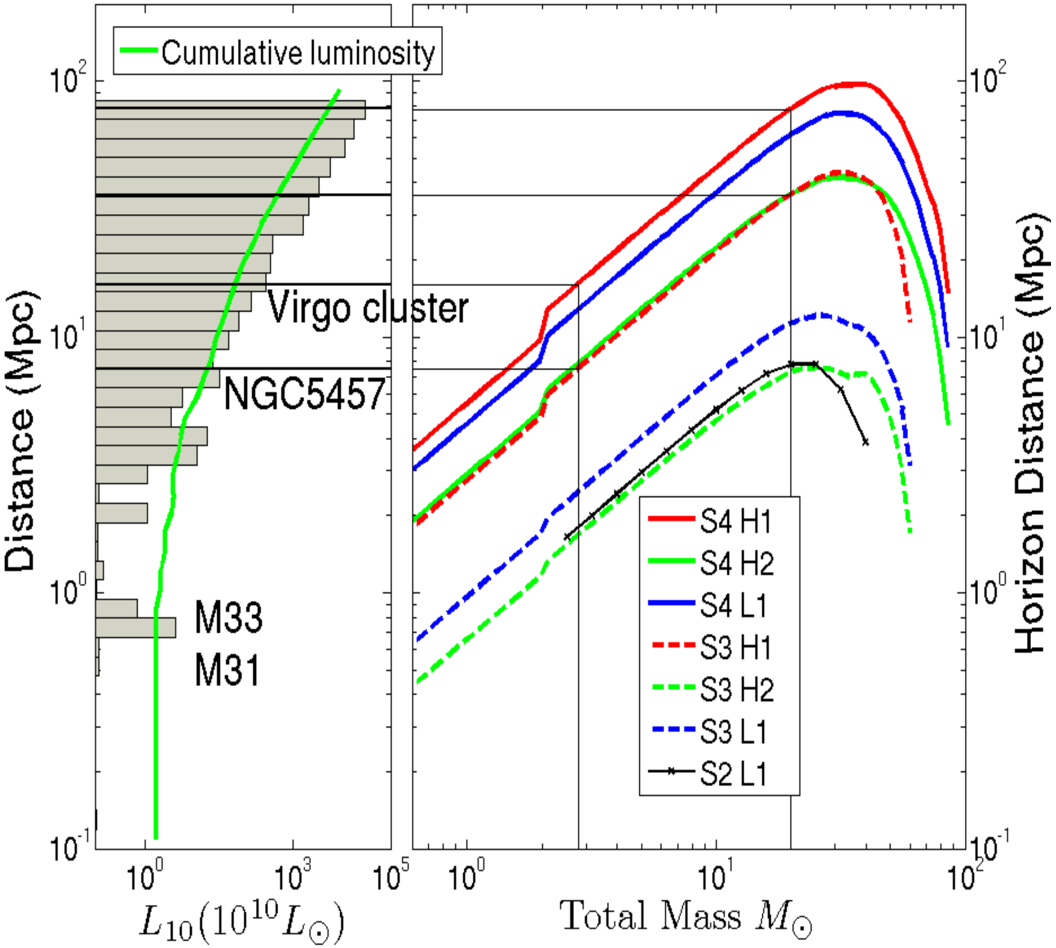
= 0.6 Milky Way Equivalent Galaxy.

S4 Upper limit results

The Bayesian upper limit calculation is based on the loudest event statistic (***P.Brady et al., CGQ 21***) which uses

- The detection efficiency at the loudest event (how many injections found with combined SNR above the largest candidate event.
- The background triggers.
- Galaxy Population
- Time analysed (about 520 hours in S4)

- systematics errors such as Monte-Carlo errors, waveform inaccuracy, calibration errors...



S4 Upper limit results (1)

1- Gaussian distribution

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

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

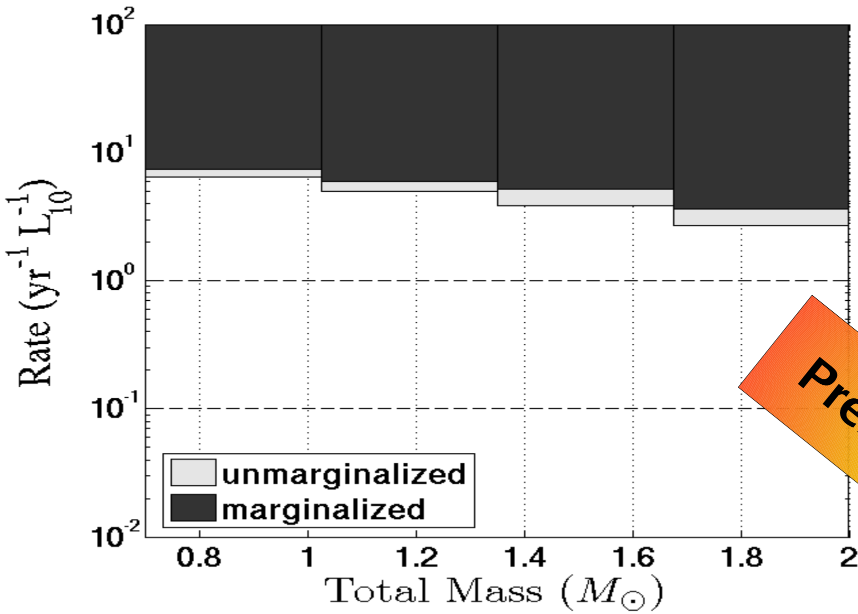
- BNS assuming gaussian distribution around a 1.4-1.4 solar mass system:

$$1.5\ yr^{-1} L_{10}^{-1}$$

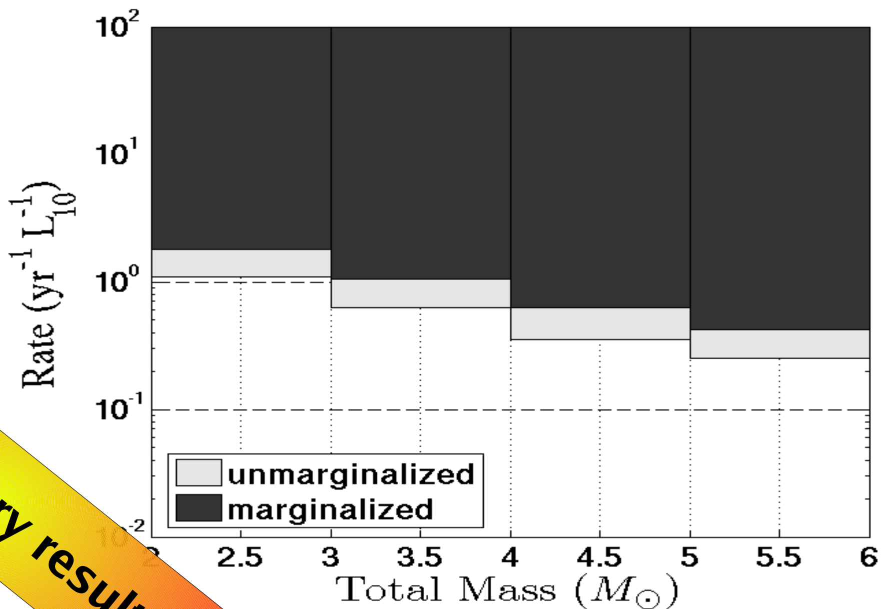
BBH : to be released soon (review not fully completed)

2- Uniform distribution

PBH binaries, S4



BNS, S4



Preliminary results

Conclusion

No detection of GW signal from coalescing compact binaries nor in S3 neither in S4

New upper limits on merger rates :

$4.9\ yr^{-1} L_{10}^{-1}$	for PBH binaries
$1.5\ yr^{-1} L_{10}^{-1}$	for BNS
to be released soon	for BBH

Status of the analysis :

We have a mature BNS and PBH search pipeline. What we can achieved right now is to clearly identify simulated events at a SNR = 8 .

Although BBH search is also mature (same pipeline), we will use PN template Families in the future BBH search so as to reduce the background rate.

Present and Future :

Apply the tools developed on S5 and future science runs.

Extra : effective distance

This figure, based on the S4 BNS search, shows a scatter plot with effective distance corresponding to background coincident triggers AND coincident triggers associated to simulated injections.

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

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