First joint search of burst gravitational waves by the AURIGA-EXPLORER-NAUTILUS-VIRGO collaboration

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for the VIRGO+bars Collaboration

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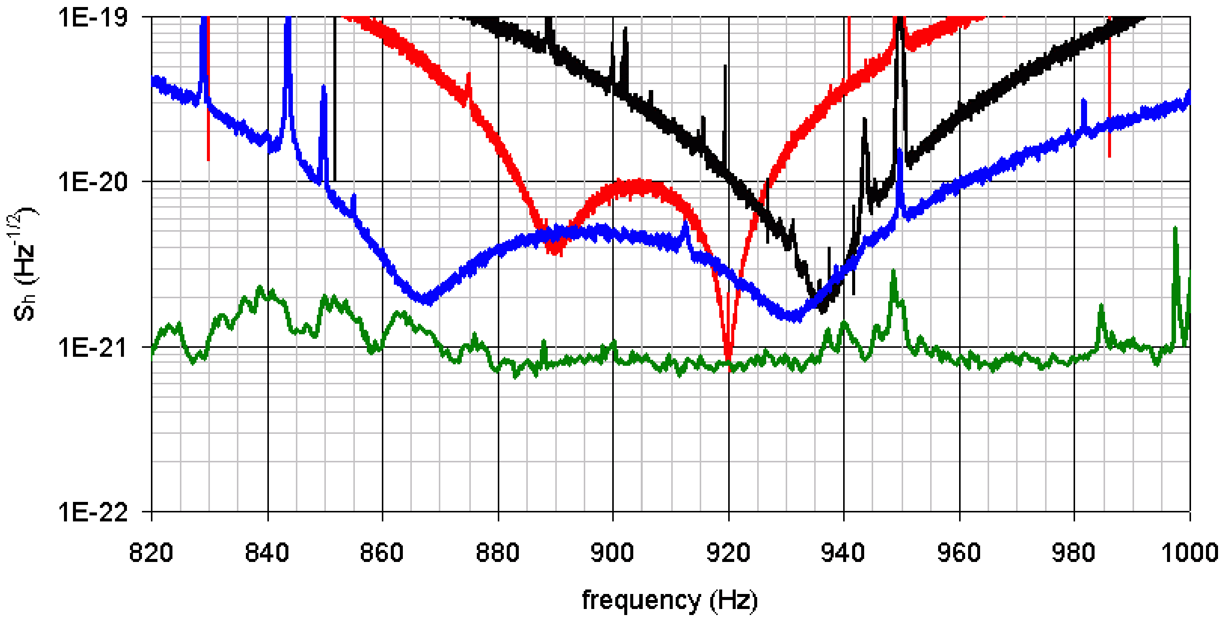
Outline

- **VIRGO+bars Network:** AURIGA, EXPLORER, NAUTILUS and VIRGO
- **Main methodology**: **coincidence search** on trigger lists provided by each detector, with expected accidental coincidences computed by time shifts.
- **Goal**: assess **interpreted** confidence intervals on the flux of gravitational waves signals coming from the galactic center (GC) and taken from the template class of damped sinusoids (DS):

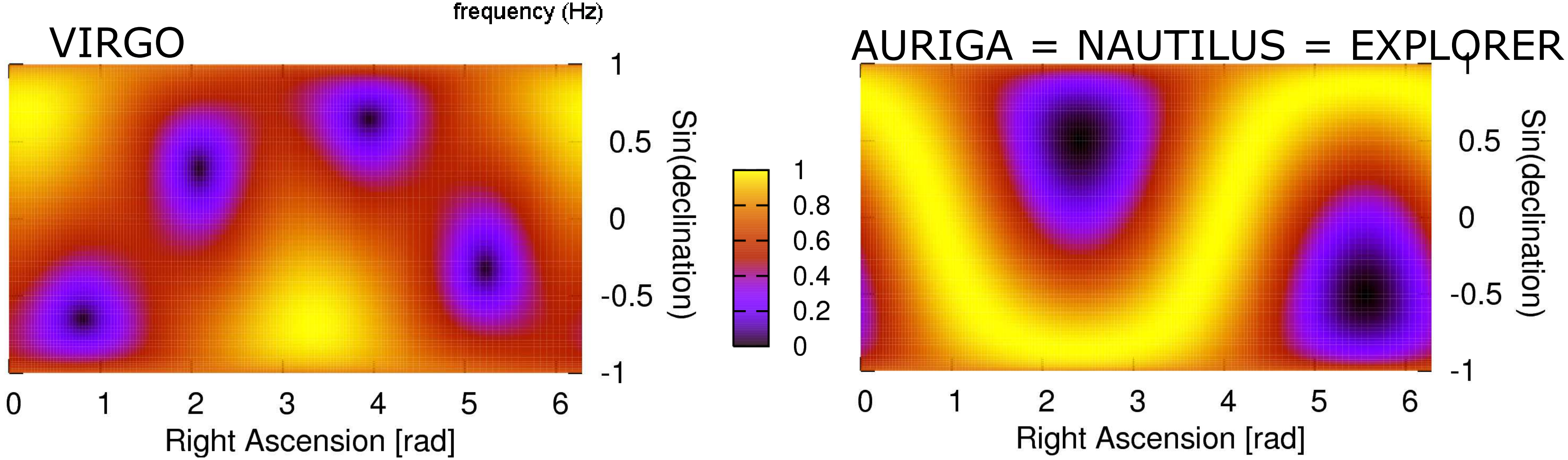
$$h(t) \propto e^{-t/\tau} \cos(2\pi f_0 t + \varphi_0)$$

- Efficiency of detection comes from **software injections** (MDC). The injected **population** has amplitudes derived from the assumption of elliptical polarization from randomly oriented rotation axis of the source.
- **Optimization of thresholds**: for each template and each given target amplitude, the best compromise between efficiency and FAR is searched, using variable threshold for each detector with ½ hour bins.
- **Blind analysis**: in order not to bias results by feedbacks on methods from looking at results, a "secret" time offset has been added to detector times.

The VIRGO-bars network



24 hours of data taking during C7, starting from GPS time 810774700 (UTC 14 Sep 2005 - 23:11 27s)



Software injections details

Damped Sinusoids: $$h(t) \propto e^{-t/\tau} \cos(2\pi f_0 t + \varphi_0)$$

• 11 **waveforms** to investigate several damping times and central frequencies:

τ (ms)	f_0 (Hz)
1	914
3	882 946
10	866 898 930
30	866 874 906 930 938

• For each template, we generated N=8640 signals (one each 10s), with uniformly random time jitter of +/- 0.5s.

• **Polarization** is **elliptic**, distributed as for signals generated by rotating systems at GC: random polarization angle ψ in [0, 2π], and random inclination angle ι such that cos ι is distributed uniformly in [–1,1].

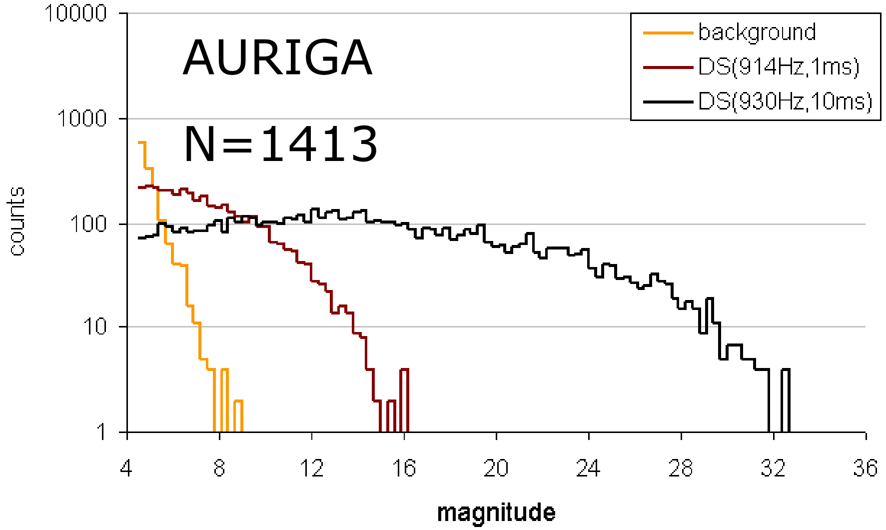
Observables provided by each detectors

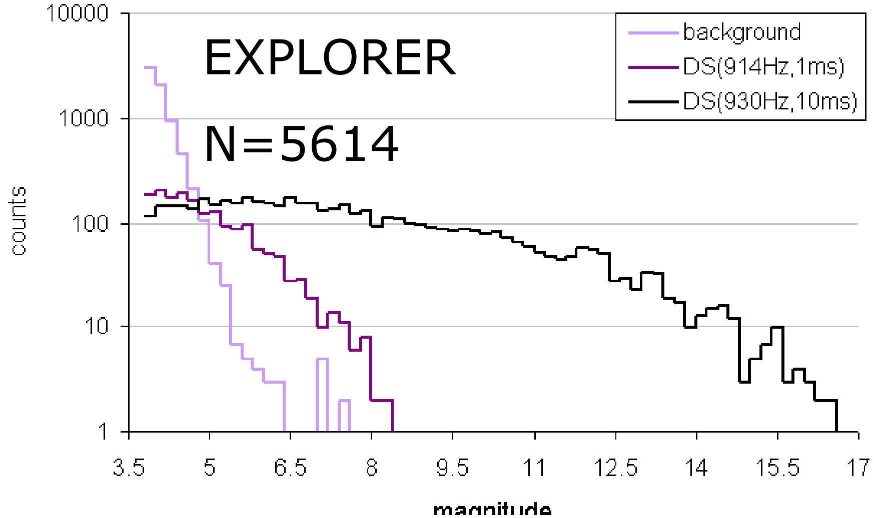
- **AURIGA: WaveBursts** (S. Klimenko *et al*, LIGO-T050222-00-Z) was succesfully adapted to AURIGA data. The cluster **S/N** (close to the optimal) was used as an indicator of the signal magnitude.

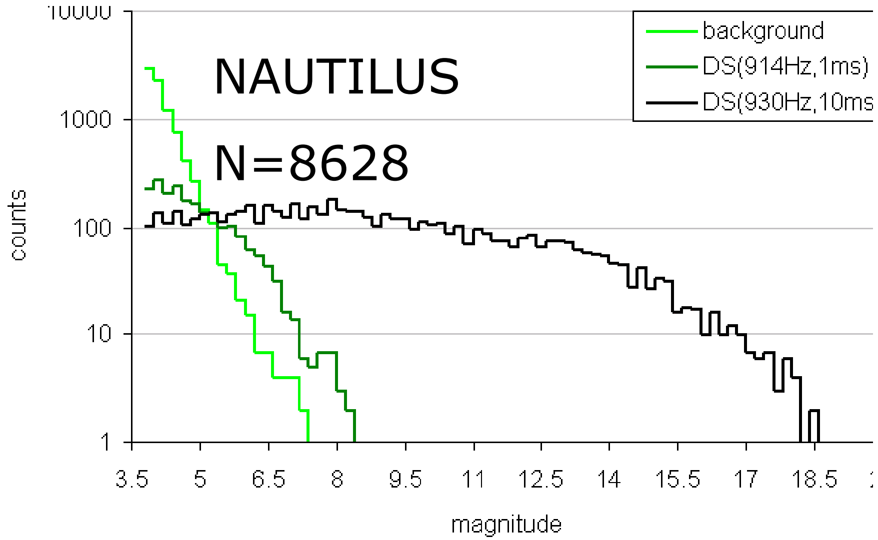
- **NAUTILUS** and **EXPLORER:** a single **linear Wiener-Kolmogorov filter matched to the impulse** response is applied to the output data. The **impulse S/N** was used as an indicator of the signal magnitude.

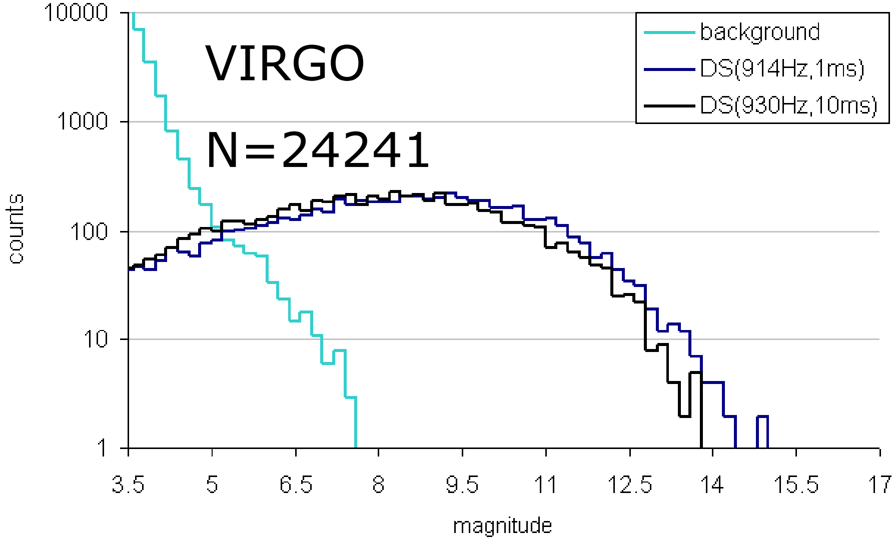
- **VIRGO: PowerFilter** is the chosen trigger generator. The **normalized logarithmic power** was used as an indicator of the signal magnitude.

Exchanged data: triggers+MDC @ 10^{-19} $Hz^{-1/2}$



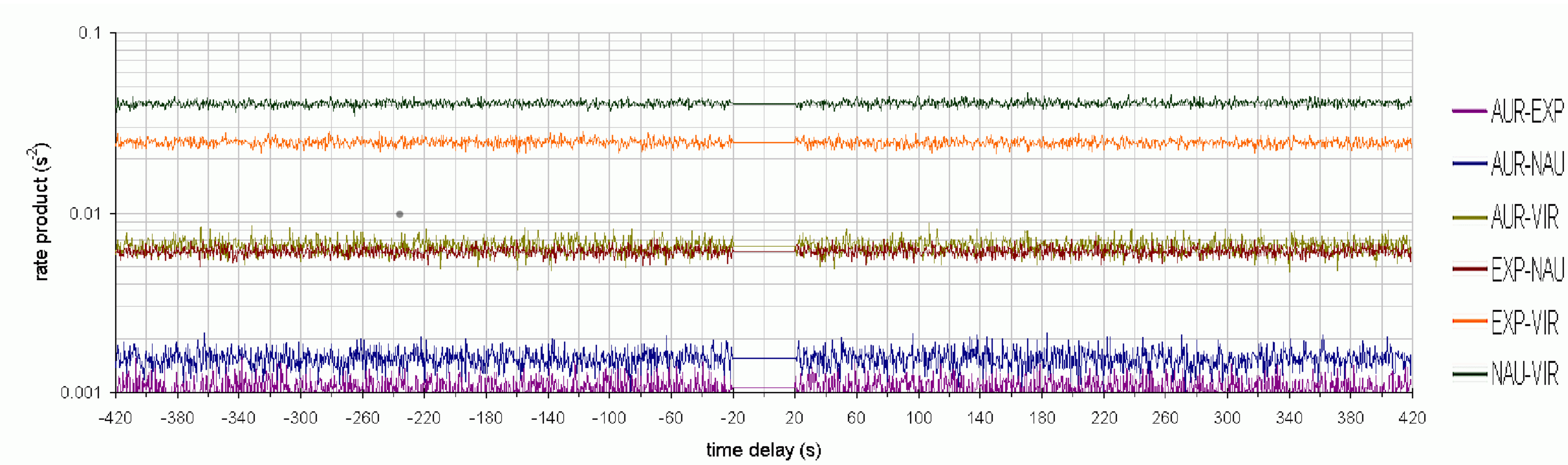




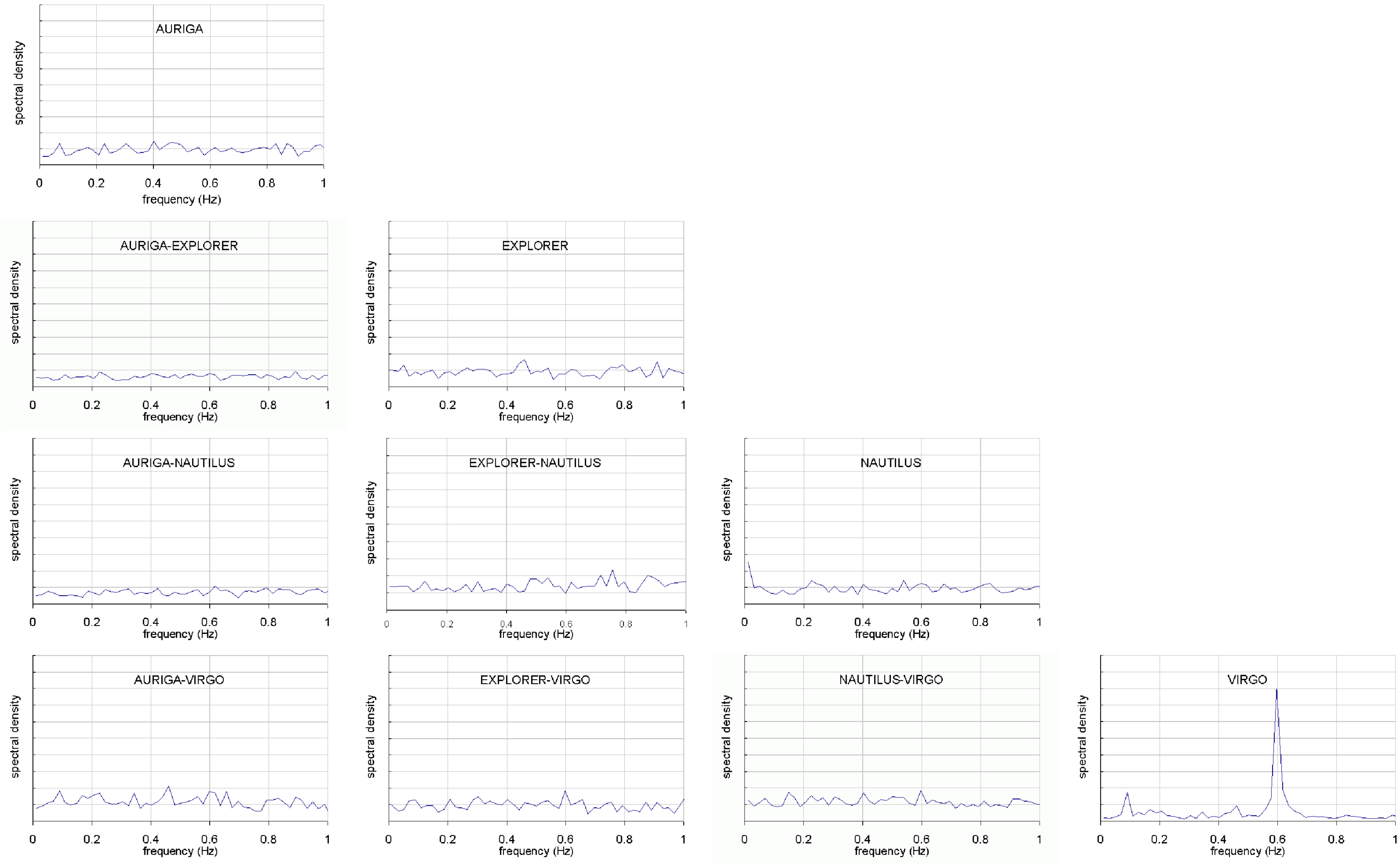


Assessing the background of accidentals

- To assess the significance of rates, we need an estimate of the rate of accidentals.
- Ideally one would like to have events at each detector distributed as independent Poisson processes. The auto-correlogram of the events at each detector should be flat.
- Instead, because of non-gaussianity, oscillations occur, for instance in Virgo which is under commissioning.
- However, the cross-correlogram is flat! So the coincidences can be regarded as a Poisson process.



A better view in the frequency domain



Optimization strategies

The real job on false alarm rate reduction is performed during network analysis.

The reduction is provided by requiring the event magnitude to exceed a higher threshold than the exchanged minimum. The efficiency of detection will be also affected. The trade-off between background and efficiency depends on our goal:

A) Detect a single GW event with high confidence, or low false alarm probability:

$$\textit{expected background counts} \ll 1$$

In this case we shall measure the efficiency (which may turn out very low) which is determined by the chosen confidence.

B) Define the best exclusion region (upper limit on rate vs amplitude):

the ratio $\textit{efficiency} / \textit{background fluctuations}$ is maximized

It is understood that we are able to estimate the mean background counts, and subtract them to the total. That is why we are limited only by the **background fluctuations** – i.e. ~sqrt(*background*).

Optimization in practice (1)

The time axis is subdivided in ½ hour long bins to account for variable efficiency (and possibly variable background rate).

The optimization proceeds by incremental steps, each time affecting the threshold on the event magnitude in one of the two detectors at one particular time bin.

How better will be the ***total background*** *with the new threshold? How worse the* ***total efficiency***? We need a benchmark in order to rank the optimization steps and to decide which is the next better move.

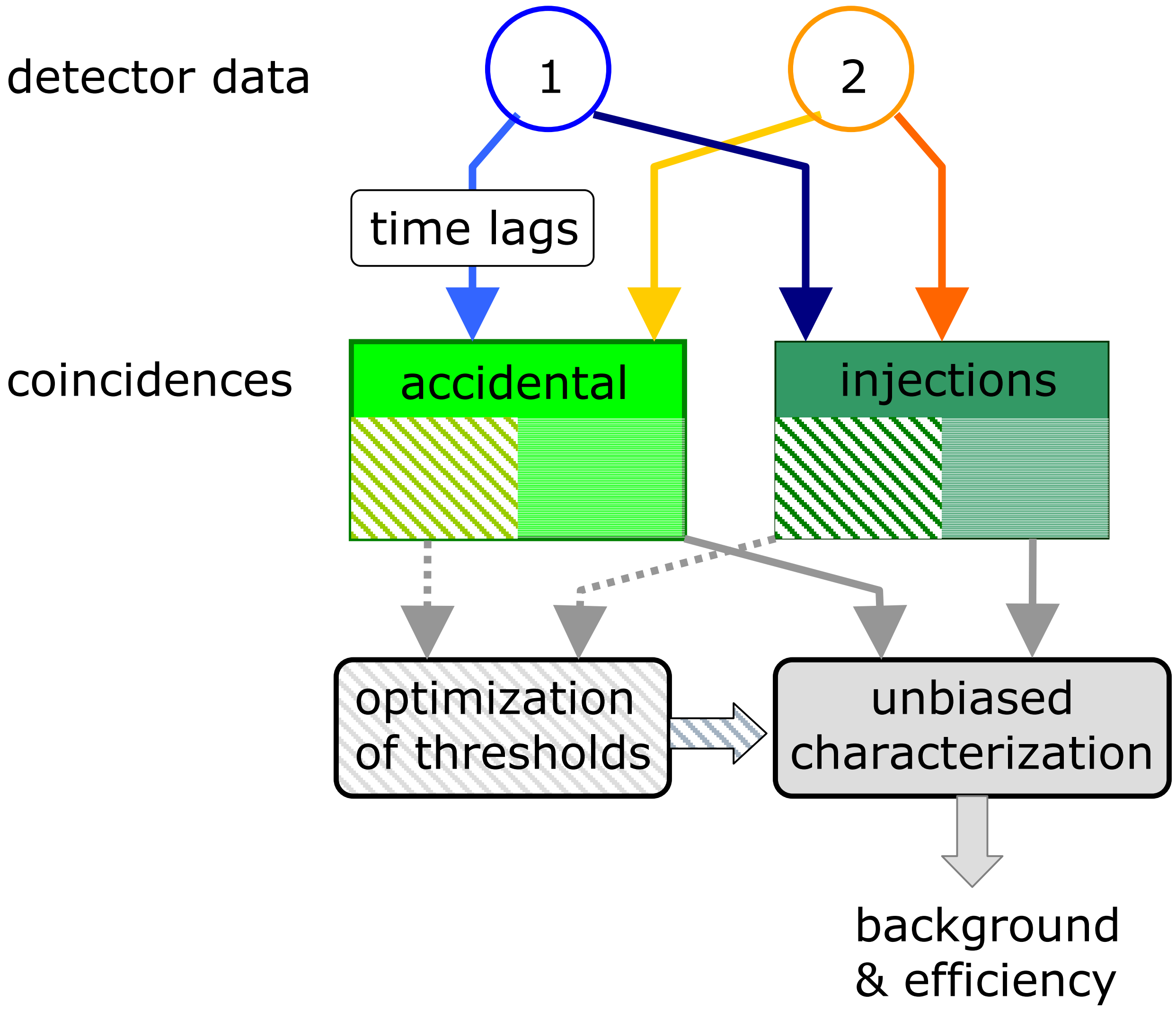
The benchmark is defined as the ratio

(*total efficiency*)/sqrt(*total background*)

A) If the target is low accidental coincidence probability, we stop the process only when the expected background has reached the desired level.

B) If the target is to have better exclusion regions, we stop when the ratio efficiency/sqrt(background) starts to decrease

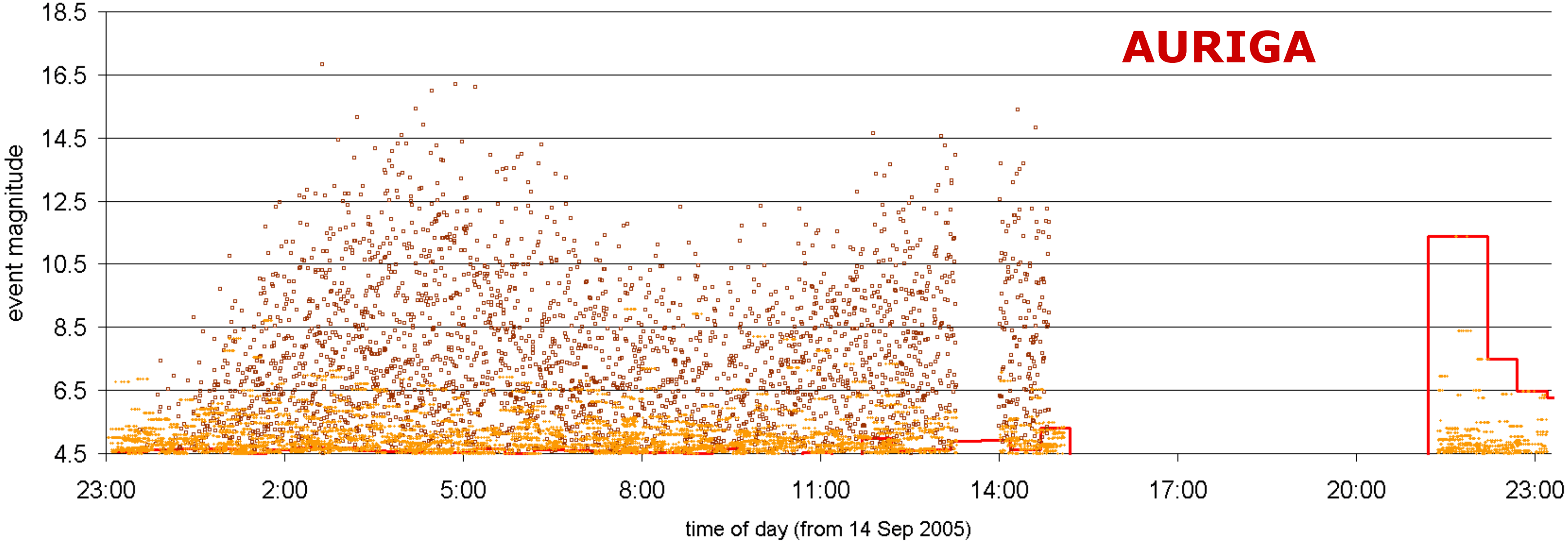
Optimization in practice (2)

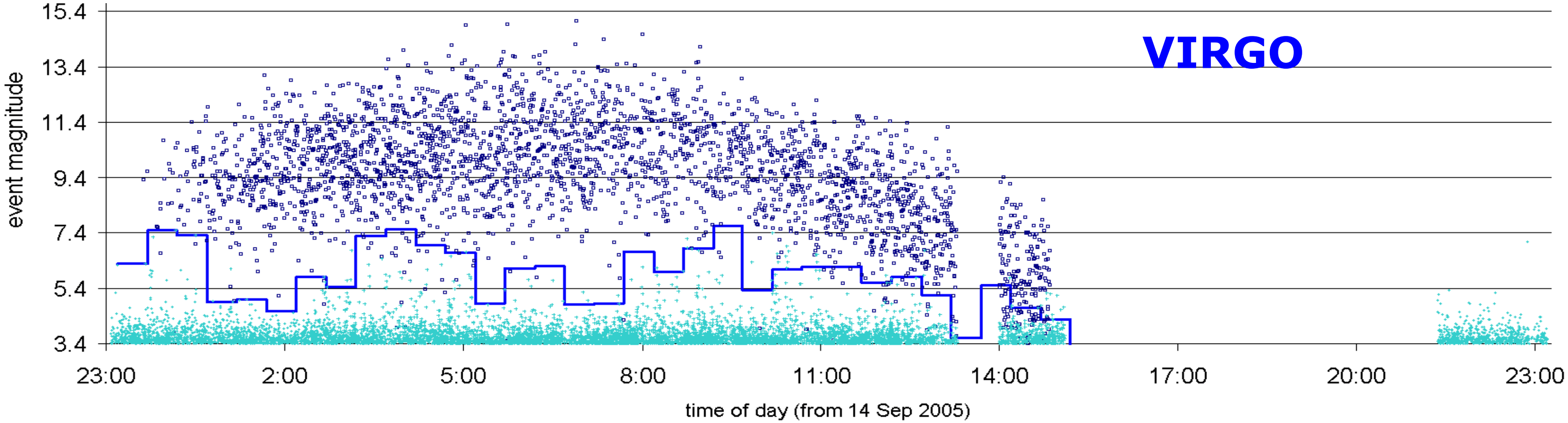


Only half of the time-delayed accidental coincidences and half of the injected signals are used to rank the bins and the thresholds. In fact, due to limited statistics, the thresholds “overfit” the input data fluctuations.

The other halves of the data are then used to give an unbiased estimate of background and efficiency to use for confidence interval calculation.

Example: DS(914 Hz, 1ms, 10^{-19} $Hz^{-1/2}$)





Statistical Analysis (1)

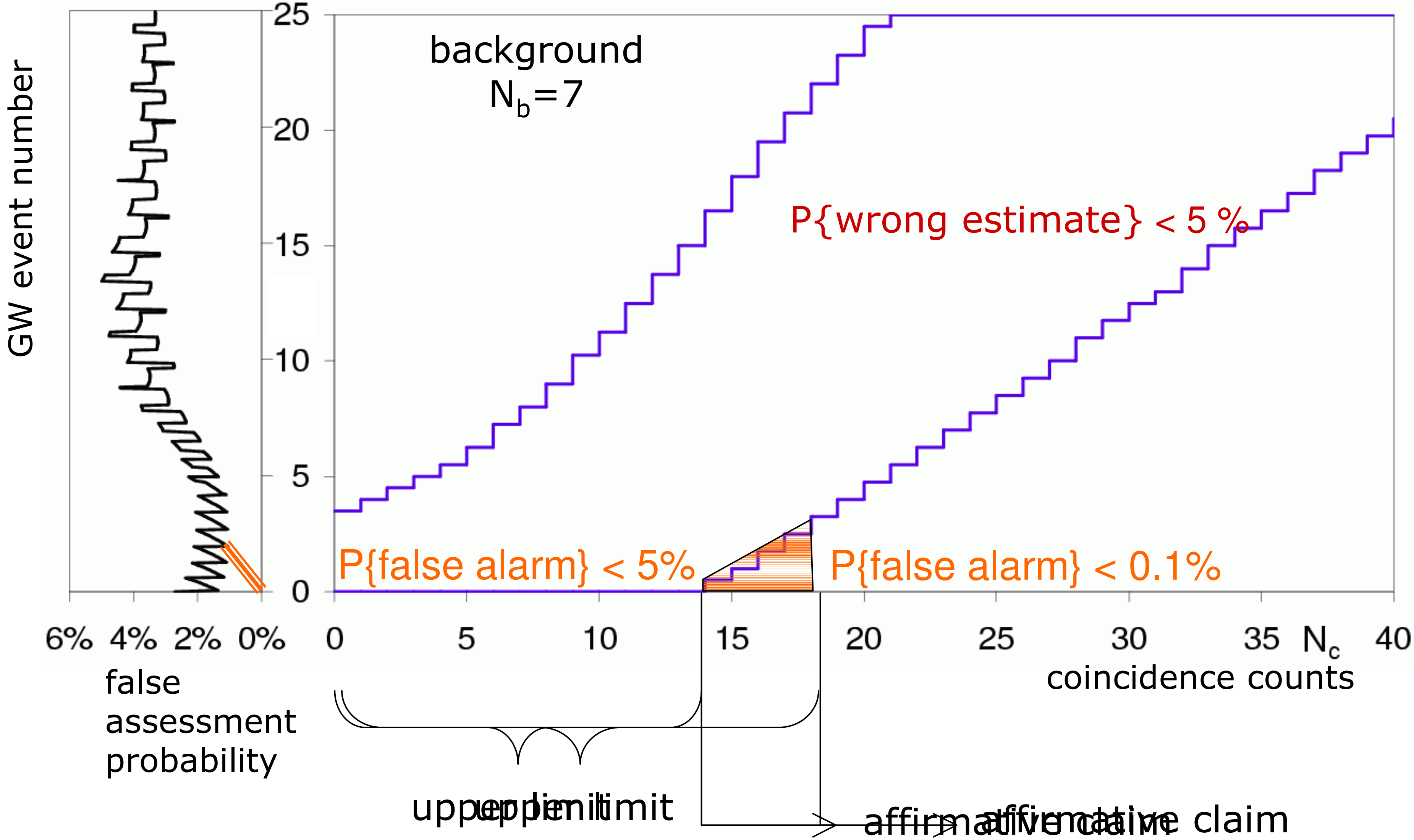
The **confidence intervals** were set according to the confidence belt already used by IGEC1 (see *L. Baggio and G.A. Prodi,* "Setting confidence intervals incoincidence search analysis" *in "Statistical problems in particle physics, astrophysics and cosmology", R.Mount, L.Lyonsand and R.Reitmeyer editors, Stanford (2003) 238*):
The resulting confidence intervals are the supports which maximize the likelyhood integral, and they are chosen in order to give (conservately) a minimum frequentist converage for all possible values of the source parameter.

but

here we made an important modification: an additional null hypothesis test modifies the coverage at low signal rates (or no signal at all).

We may loosely say that the confidence intervals are "more confident" when including the null hypothesis than when bounding the expected value of GW number.

Modifying confidence belts



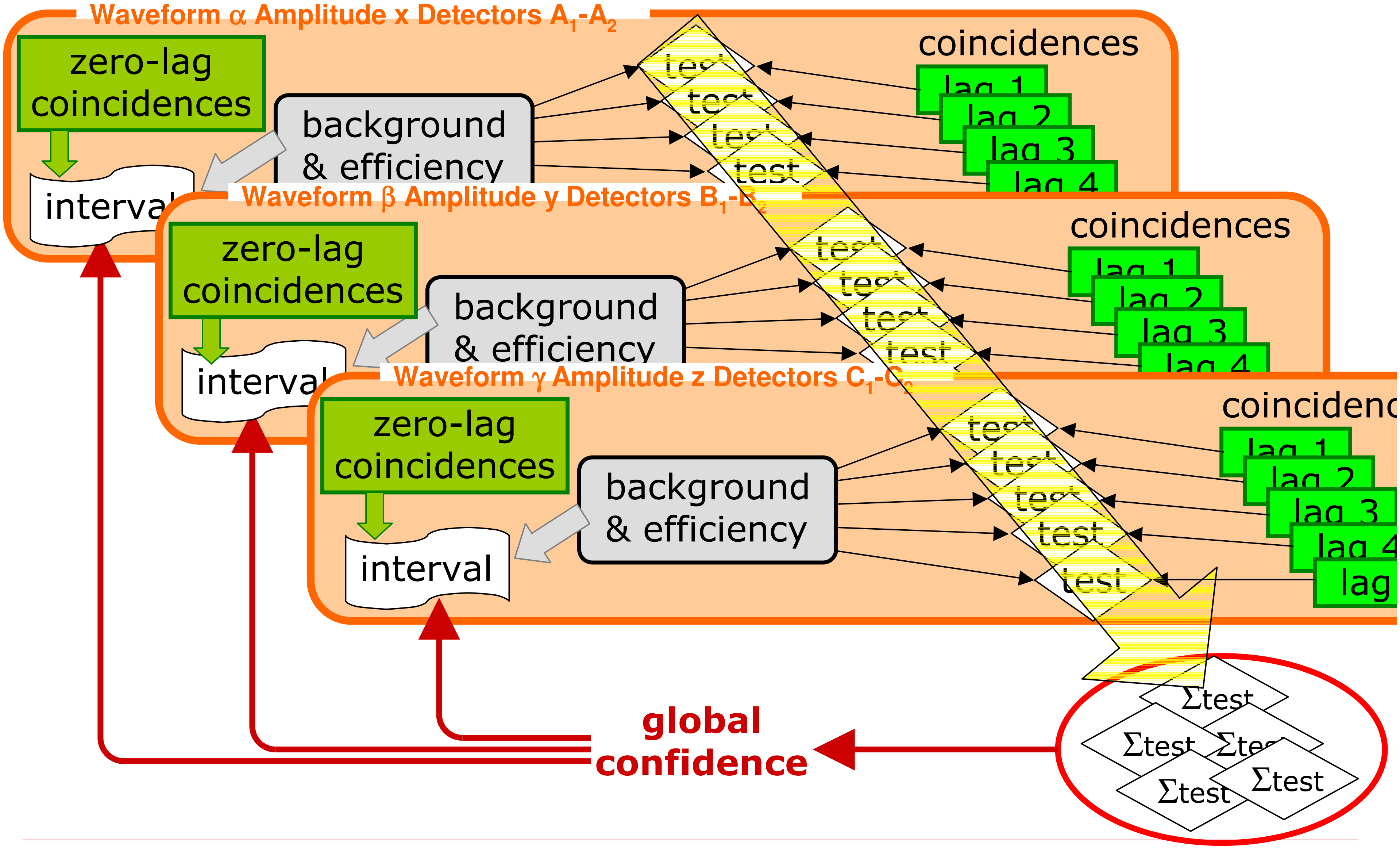
Statistical Analysis (2)

- The coincidence search and optimization procedure were performed for **different populations** (f0, τ , h_{rss}) and **many couples of detectors**, which accounts for multiple tests performed (~100). Eventually this large **trial factor** increases the false claim probability

- The effective **overall confidence** is defined as the probability of not having a single false claim in **any** of the performed tests. It is clearly linked to the confidence of the single trial. Knowing this relation we can compensate with a higher confidence on the single trial and to achieve the desired global confidence.

- This relation may be **empirically** estimated by measuring the frequency of false claims in the time-delayed configurations. In other words, for each time lag we simulate the confidence interval obtained across all optimized configurations, and we check for false rejection of the null hypothesis.

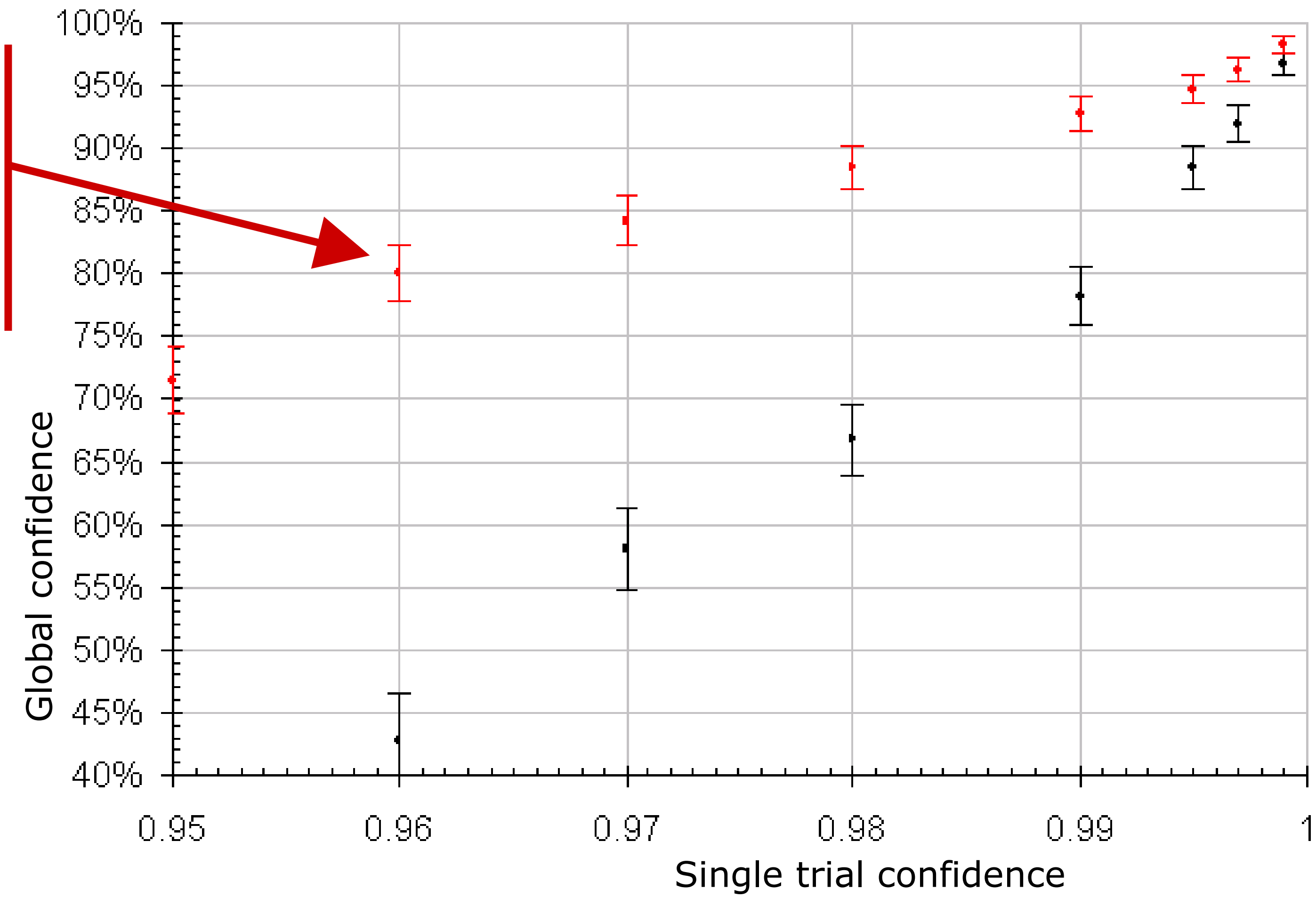
Trial factor in practice



Trial factor in 2-fold search

In two-fold coincidence search, it was possible to assess an empirical confidence of 98-99% on the results using 400 time delayed configurations

- A lower trial factor comes by analyzing only on the **best couples of detectors** for each template/amplitude.



Statistical Analysis (4)

Disclaimer: rejecting the null hypothesis implies to claim excess correlation in the observatory. This can be due to:

- GW signals.
- cross-correlated noise (not taken into account in the background measuring procedure with time lags);
- bad chance (statistically improbable but not impossible)

Excluding cross-correlations is not an easy task: when assessing the results this duality in the physical interpretation should always be kept in the mind of the readers.

The probability of accidental claim depends in the first place on the chosen threshold of acceptable p-level of the statistic test. The p-levels themselves are affected by measurement errors (background coincidence counts) and systematics (edge effects, ergodic approximation) but normally we can properly account for them.

The bottom line: *if you find coincidences in excess, what are you going to blaim first: glichiness of data and poor sensitivity, or rather that risky 90% confidence level threshold?*

Results for the 2-fold coincidence searches (1)

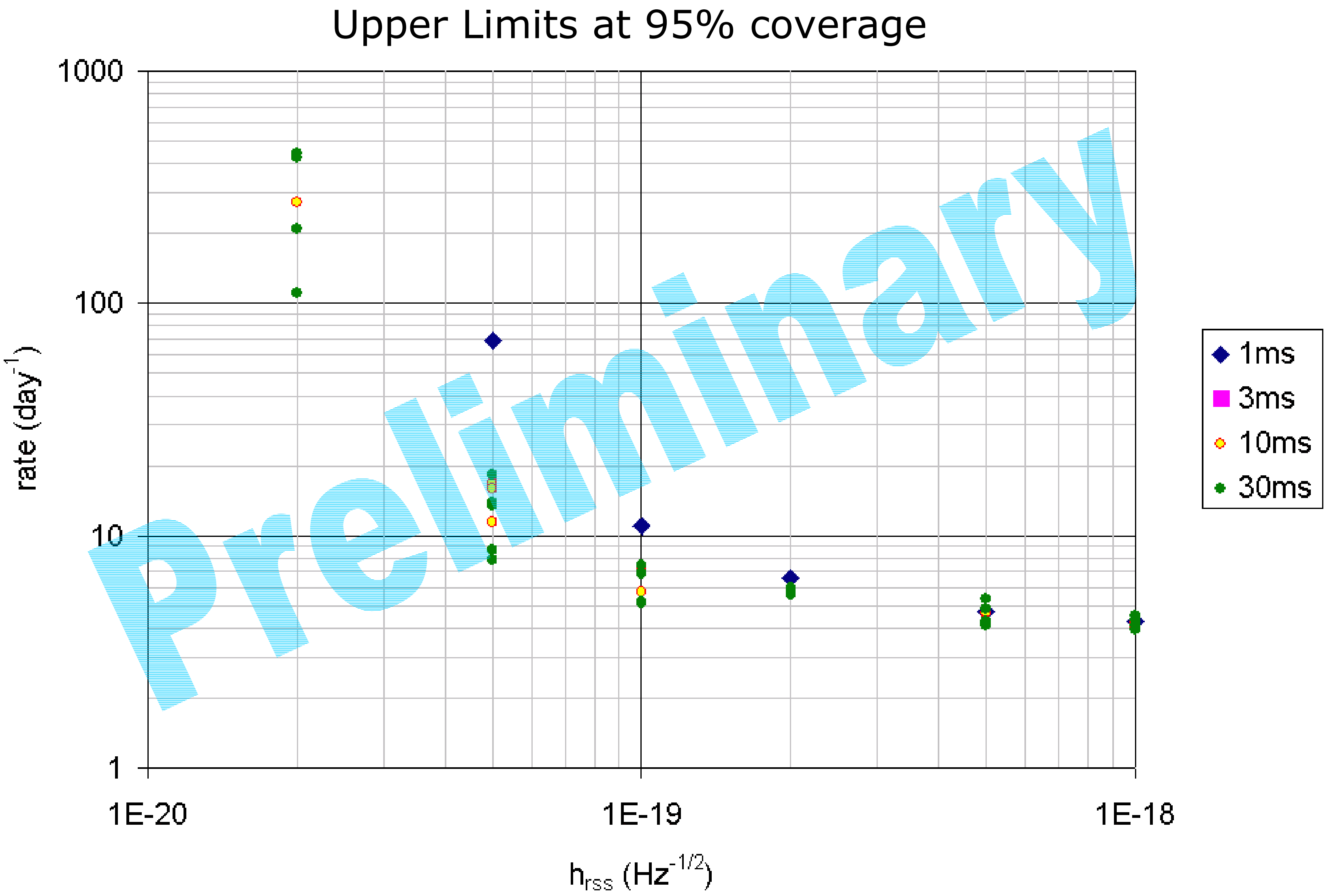
- **Goal**: to obtain the better exclusion regions.

- The level of residual accidental background being relatively high (~0.1/day), the detection of a single coincidence does not lead to claim of excess correlation.

- It was possible to assess an empirical confidence of 98-99% on the results using 400 time delayed configurations

No excess of coincidences was found. The null hypothesis is confirmed at 99%.

Results for the 2-fold coincidence searches (2)



$h_{rss}=10^{-20}$ Hz$^{-1/2}$ would correspond to ~ 10^{-3} M_o radiated at 10kpc

3-fold coincidence searches

Goal: to be able to issue a claim at 99.5% confidence on a single observed triple.

• The backgound for some configurations is low enough to reach this confidence. 400x400 time lags allow to estimate such a low false alarm probability.

• In order to limit the **trial factor**, for each waveform only a small subset of MDC amplitudes (e.g. 10^{-19}, 5 10^{-18} and 10^{-18} $Hz^{-1/2}$) will be tried. The zero-lag will be then analyzed with the optimization for the lower signal amplitude which still allows at least a level of efficiency of 40%. Configurations of detectors/template which do not reach such minimal level for any of the chosen amplitudes will be discarded.

• The analysis and checks are in progress, results to appear soon.

Summary and final remarks (1)

In order to extract the maximum of information from the collected data, we defined **optimized thresholds** which took into account the characteristics of the tested population (direction, amplitudes, polarization...) via the efficiency of detection.

The injection of many waveforms and amplitudes multiplies the computation time by order of magnitudes! However, this is not intrinsic of the method, which only requires an hint on the efficiency variability (it could be provided by an empirical formula using the noise characterization and modelization of injected signals).

While only the magnitude at the output of the event search algorithm was used, in principle any test statistic provided with or derived from the coincidences as a function of time may be included in the optimization process.

No attempt was done to regularize the final output of the threshold optimization. The implemented optimization algorithm is very primitive and the correspondence between microscopic states (threshold time series) and macroscopic observables (efficiency, background) has not been systematically investigated.

Summary and final remarks (2)

The issue which prevents the systematic use of the *ad hoc* optimization is the trial factor. The overall false claim probability can be controlled, but at the price of reduced sensitivity. Eventually, the affordable number of independent optimizations has to be limited to the most promising cases, based on a preliminary survey of the expected backgrounds and efficiency.

Gabriele Vedovato (AURIGA) is implementing a different analysis scheme based on WaveBurst in association with cross-correlation tests. This **semi-coherent all-sky network analysis** is being preliminary tested on AURIGA-VIRGO data and is giving promising results.

A Virgo-note was produced to discuss the methodology:

VIR-NOT-FIR-1390-328

EXTRA SLIDES