Joint LIGO-Virgo studies for burst events

The LIGO-Virgo Joint Working Group
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Search for Bursts

- Sources emitting short transients of gravitational radiation
  - » Supernovae core-collapse, black holes mergers, ring-downs, neutron star instabilities, cosmic string cusps …
- What we know about them …
  - » Catastrophic astrophysical events observed in the particle and/or electromagnetic sector will plausibly be accompanied by short signals in the gravitational wave sector ➡ *plausible suspects*
  - » Exact waveforms are not or poorly modeled
  - » Durations from few millisecond to x100 millisecond durations with enough power in the instruments sensitive band (100-few KHz)
  - » Searches tailored to the *plausible suspects* or aimed to the all-sky, all-times blind search for the unknown using minimal assumption on the source and waveform morphology
- Multi-detector analyses are of paramount importance

Goals of the LIGO-Virgo working group for bursts

- Materialize the benefits of a gravitational wave detector network
  - » Detection confidence
  - » Reduce false alarm rates
  - » Improve parameter estimation (source sky position, time-frequency volume, amplitude)
  - » Increased sky coverage
  - » Increased observation time
- Address challenges of a network analysis
  - » Different detectors and analysis algorithms
  - » Different sampling rates, data types, definitions and overall nomenclature
  - » Quantify the advantages and potential detriments of a network
  - » Devise an analysis strategy
- A multi-stage collaborative work underway

LIGO-Virgo Mock Data Challenge

- *The first joint project*
- Two sets of data for each of the instruments were given to analyzers:
  - » 3 hours of simulated noise data according to design sensitivity curves with narrow band lines added
  - » 1000+ software injections of various morphologies added in a separate stage
- Pose the questions:
  - » Can we read each other data ?
  - » Can we cross-analyze our data ?
  - » Establish false alarm rates as a function of signal strength using as many of the search methods envisioned to be invoked as possible
  - » Establish the sensitivity of these methods to the assumed candidate morphologies
  - » Are we agreeable to a given set of parameters for describing the signal (and noise)?
  - » Do the various search methods pick up the same/different noise characteristics, how do they compare on the assumed signal morphologies?
  - » How does their signal parameter estimation compare?

Simulated Burst signals

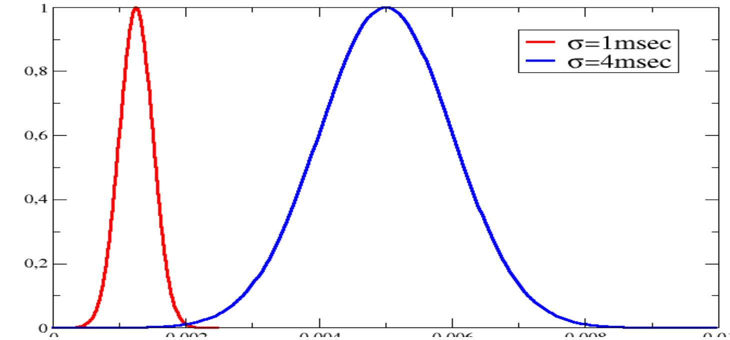
- Optimal orientation and polarization for each of the detectors
- 60 second separation
- Multiple waveform families
  - » Gaussians of 1 and 4 millisecond duration

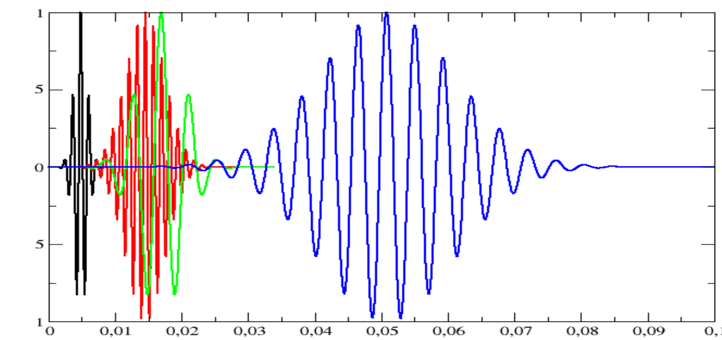
$$h(t) = \|h\| \left(\frac{1}{\sqrt{\pi}} \frac{1}{\sigma} \right)^{1/2} \exp\left[-\frac{(t - t_0)^2}{2\sigma^2} \right]$$

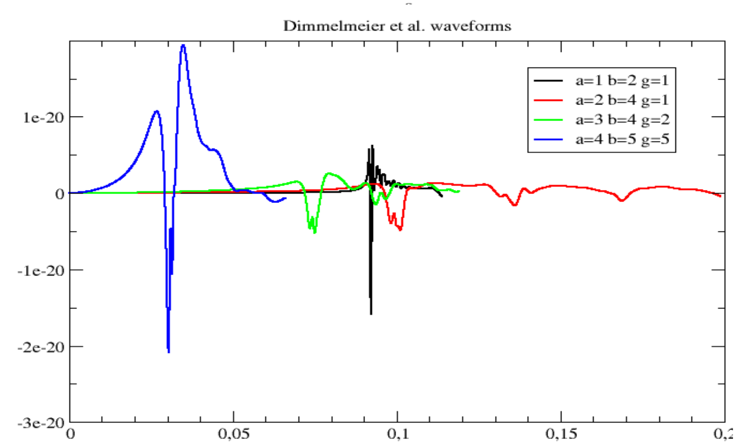
  - » Sine gaussians with central frequencies of 235, 820 Hz and Q's of 5 and 15

$$h(t) = \|h\| \left(\frac{4\sqrt{\pi} f}{Q} \right)^{1/2} \exp\left[-\frac{2(t - t_0)^2 \pi^2 f^2}{Q^2} \right] \cos\left[2\pi f (t - t_0)\right]$$

  - » Supernovae core collapse waveforms (Dimmelmeier, Font, Muller) with parameters (a=1, b=2, g=1) and (a=2, b=4, g=1)







Data analysis pipelines

- Each detector data (single interferometer) are processed separately and independently from the rest of the methods/instruments)
- Seven such method pipelines were applied relying on time-domain as well as time-frequency analysis of the raw interferometric data (more analysis methods will be incorporated in the near future)
- Receiver operating characteristics have been computed on the 3 hours of simulated data for false rates from 0.1 to 0.0001 Hz.
- Trigger lists (containing rough time-frequency characteristic) and sets of figures of merit have been generated
- A method independent parameterisation of the triggers is adopted. A post processing stand alone parameter estimation module that uses Maximum Likelihood Estimators and assumes coloured Gaussian noise (Zanolin, Sylvestre) is being introduced

Search methods

- **Q-pipeline** (Chatterji): multi-resolution time frequency search for excess power applied on data that are first whitened using zero phase linear prediction. Equivalent to optimal matched filter for minimum uncertainty waveforms of unknown phase in the whitened data
- **Kleine Welle** (Blackburn): search for statistically significant clusters of wavelet coefficients in the dyadic Haar wavelet decomposition
- **S-transform** (Clapson): search for statistically significant clusters of coefficients in the time frequency map generated using a kernel composed of complex exponentials shaped by Gaussian profiles with width inversely proportional to frequency. High pass and line removal applied on Virgo data
- **Power Filter** (Guidi): search for excess power over different time intervals and sets of frequencies
- **Peak Correlator** (Hello): Search for peaks of Wiener filtered data with Gaussian templates. For Virgo data a high pass filter and a line removal filter are applied to remove the resonance at 0.6 Hz
- **Mean Filter** (Bizouard): Search for excess in moving averages of whitened data over intervals containing from 10 to 200 samples
- **ALF** (Bizouard): Search for change in slope over moving windows of whitened data over intervals containing from 10 to 300 samples

Event parametrization

- amplitude is described in terms of h_{rss} and S/N (tested between 2 to10)

$$||h||^2 = \int_{-\infty}^{+\infty} |h(t)|^2 \, dt \qquad \rho^2 = \int_0^{\infty} \frac{4|\tilde{h}(f)|^2}{S_h(f)} \, df$$

- central frequency

$$f_c \equiv \frac{\int_0^\infty df\, f\, |\tilde{h}(f)|^2}{\int_0^\infty df\, |\tilde{h}(f)|^2}$$

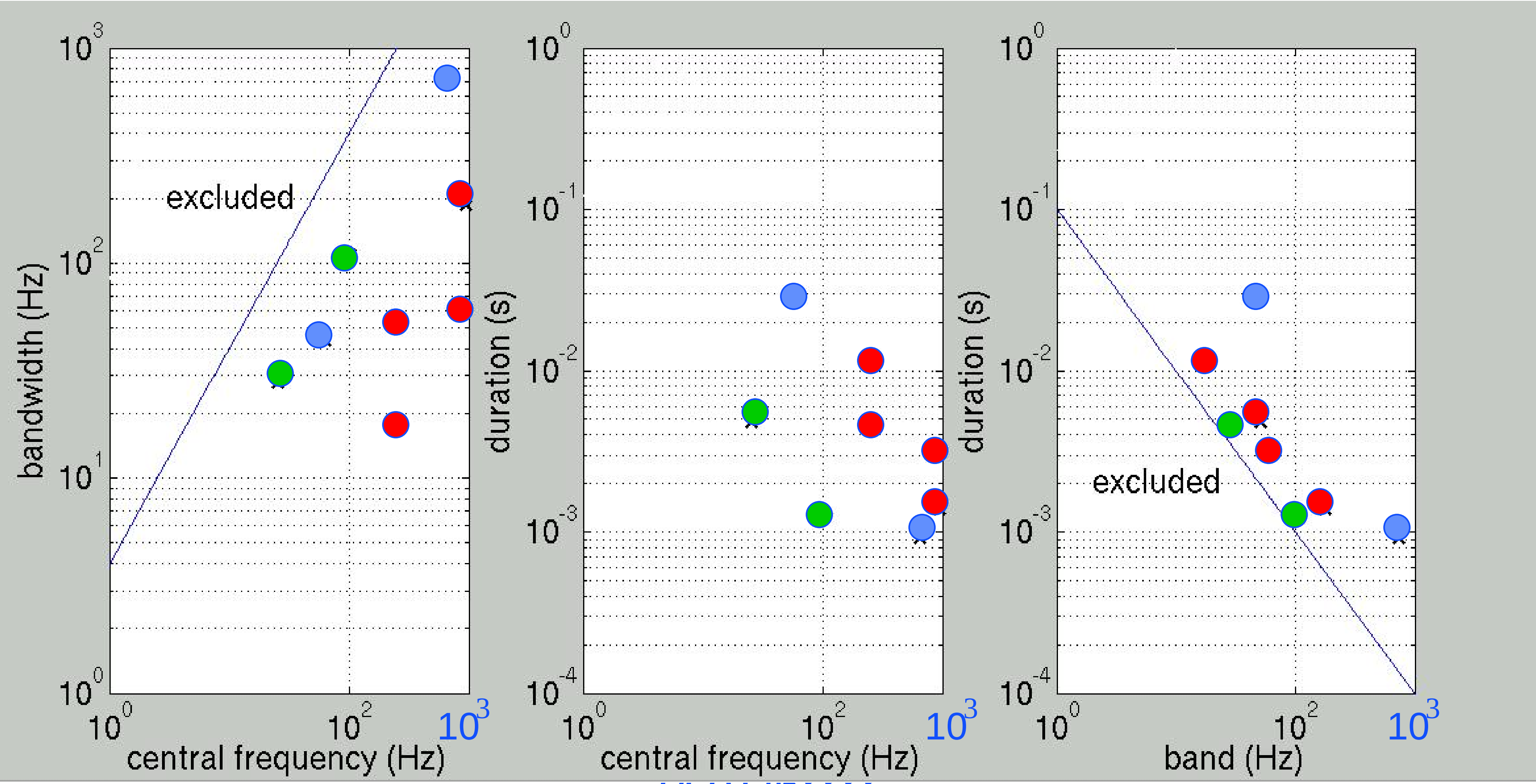
- bandwidth $\Delta f \equiv f_{75} - f_{25}$ where $0.25 \equiv \frac{\int_0^{f_{25}} df |\tilde{h}(f)|^2}{\int_0^\infty df |\tilde{h}(f)|^2}$ $\quad 0.75 \equiv \frac{\int_0^{f_{75}} df |\tilde{h}(f)|^2}{\int_0^\infty df |\tilde{h}(f)|^2}$

- duration $\Delta t \equiv t_{75} - t_{25}$ where $0.25 = \frac{\int_0^{t_{25}} dt |h(t)|^2}{\int_0^\infty dt |h(t)|^2}$ $\quad 0.75 = \frac{\int_0^{t_{75}} dt |h(t)|^2}{\int_0^\infty df |h(t)|^2}$

- The stand alone parameter estimation gets the time frequency volumes from the searches and computes the burst's parameters in the presence of noise

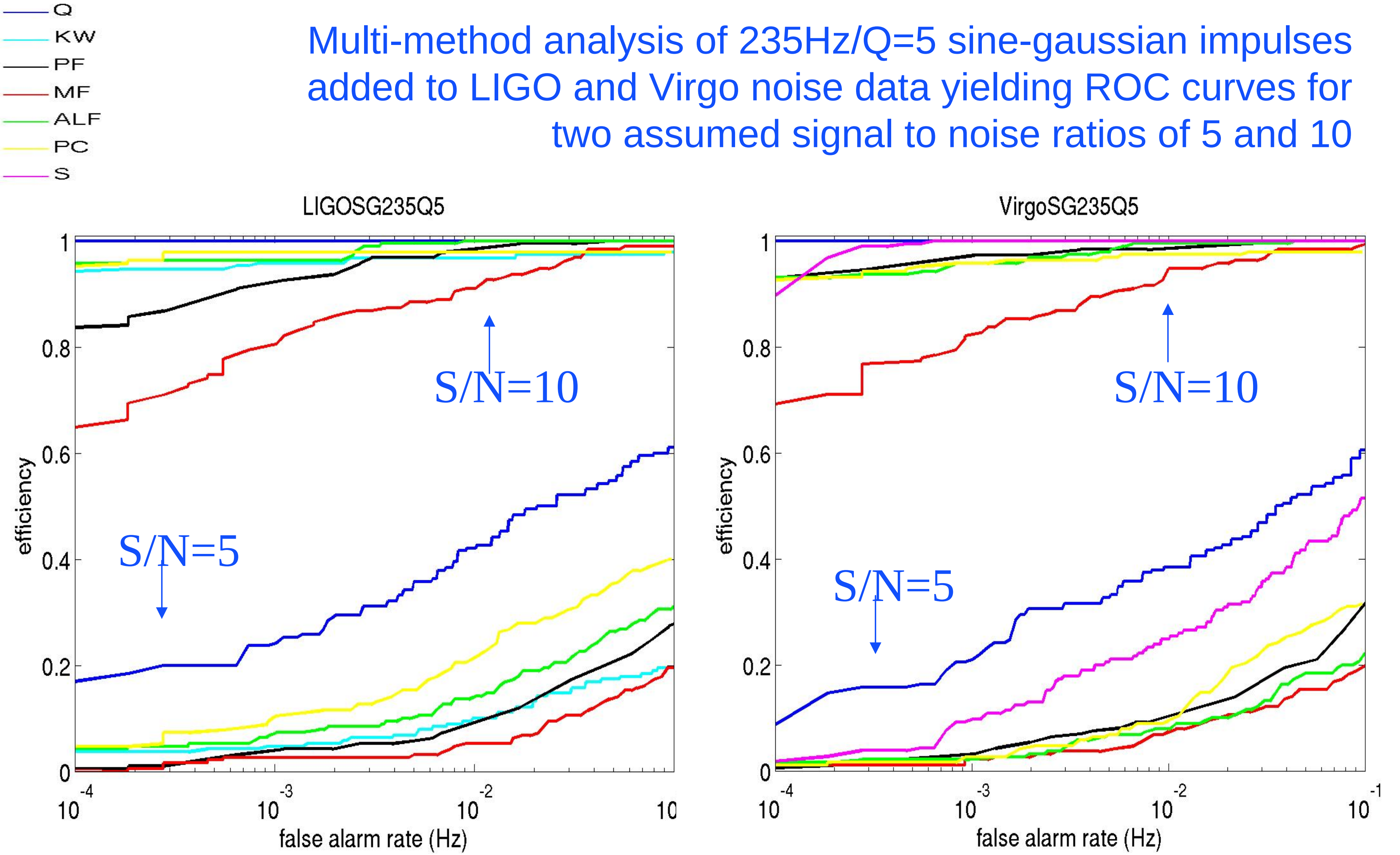
Exploring signal parameter space

● **SG** ● **GA** ● **DFM**



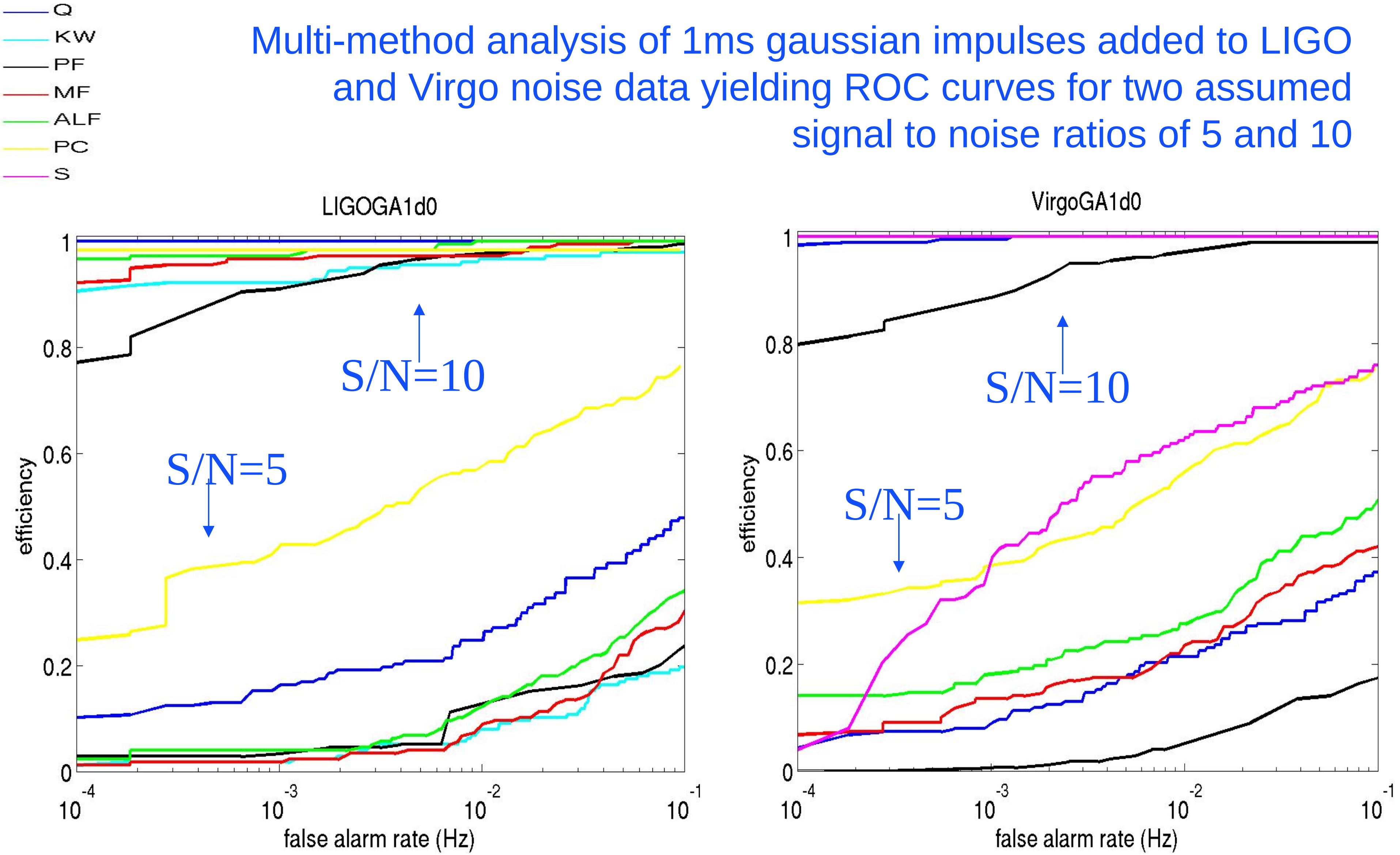
Receiver Operator Characteristics

Multi-method analysis of 235Hz/Q=5 sine-gaussian impulses added to LIGO and Virgo noise data yielding ROC curves for two assumed signal to noise ratios of 5 and 10



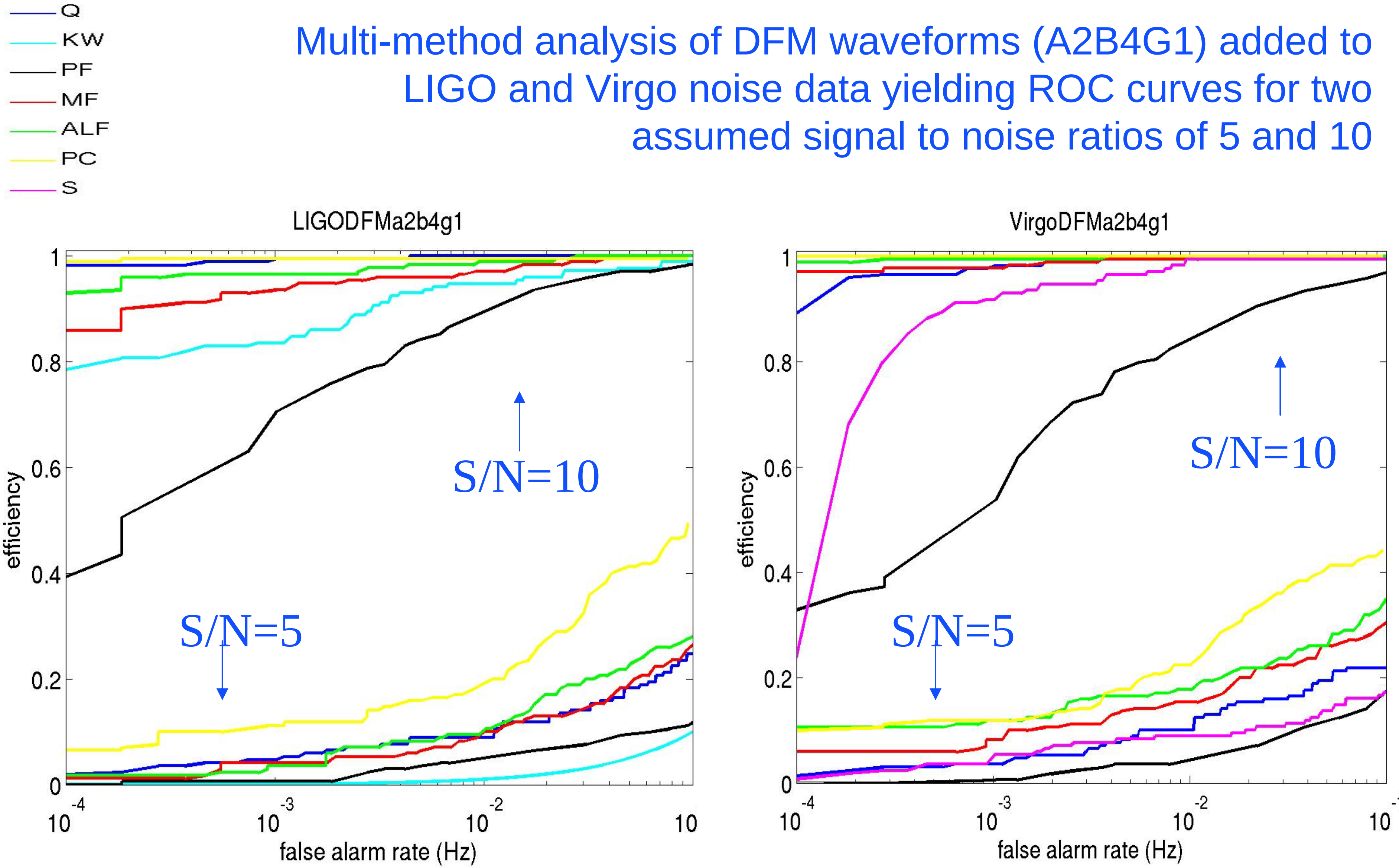
Receiver Operator Characteristics

Multi-method analysis of 1ms gaussian impulses added to LIGO and Virgo noise data yielding ROC curves for two assumed signal to noise ratios of 5 and 10



Receiver Operator Characteristics

Multi-method analysis of DFM waveforms (A2B4G1) added to LIGO and Virgo noise data yielding ROC curves for two assumed signal to noise ratios of 5 and 10



Trigger overlap studies

- Each method is tuned at a false rate = 0.1 Hz
- Preliminary, since joint false rate still to be estimated.

	LIGO			VIRGO		
	SG235Q5	**GA1**	**DFM-A2B4G1**	**SG235Q5**	**GA1**	**DFM-A2B4G1**
Best	(Q) 116	(PC) 136	(PC) 84	(Q) 115	(PC) 134	(PC) 75
.and. (SNR=5)	14	16	9	12	16	10
.or. (SNR=5)	130	144	98	121	148	93
Best	(Q,PF)190	(TD,Q) 178	(Q,PC)170	(Q,ALF)190	(TD,Q) 178	(Q,PC) 170
.and. (SNR=10)	184	174	166	174	120	164
.or. (SNR=10)	190	178	170	190	178	170
Total Injected	190	178	170	190	178	170

Lessons learnt

- Opportunity to compare search methods
- Exchange and process each other’s raw data
- Learn to speak the same language
- Build confidence in each other’s analysis
- Opportunity to compare search methods
  - » Different methods perform complement each other in covering signal parameter space
  - » They potentially trigger on different features of noise
  - » Comparative study in progress
- Estimate required resources for initial efforts

Summary and outlook

- A working group involving members of the LSC and Virgo data analysis communities has started worrying about how to approach joint search for bursts
- The benefits are significant, but they won't come without hard work from both sides
- LIGO/GEO are approaching their design sensitivities and Virgo is making drastic progress
- The first joint analysis project is only a small step toward the ultimate goal of operating the instruments as part of a global network
- Additional work gearing toward this goal is underway
  - » Continue the data exchange within the framework of simulated data but using astrophysical (coherent) waveform injections over all-sky, specific point sources or sampled from a source population
  - » Source parameter extraction via the utilization of the network
  - » Planning for the analysis of real data and injections
  - » Worrying about truly coherent searches