Results from LIGO's Second Search for Gravitational-Wave Bursts

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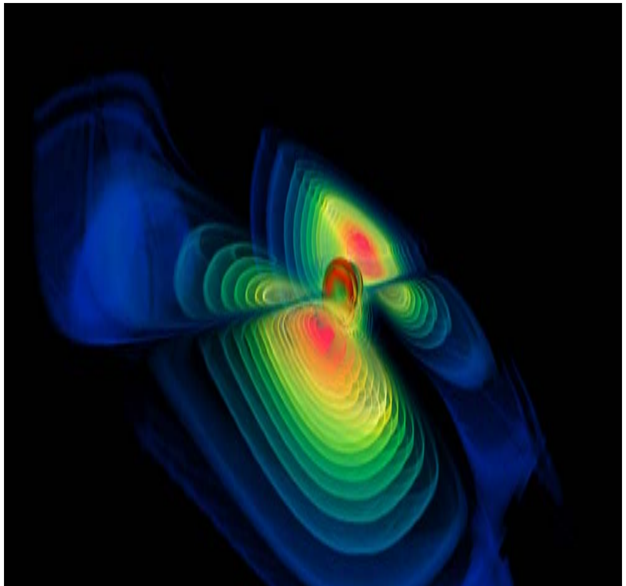
Outline

- Gravitational Wave Bursts: Goals
- Un-triggered Searches
  - » Scan entire data set looking for coincident signals in each detector
  - » Methodology, procedure
  - » Improvements since first search
- Triggered Searches
  - » Intensive examination of data around times of observed astronomical event
  - » Methodology, procedure
  - » Example: results for GRB 030329
- Summary & Outlook

Bursts Analysis: Targets

- Catastrophic events involving solar-mass compact objects can produce transient "bursts" of gravitational radiation:
  - » core-collapse supernovae
  - » merging, perturbed, or accreting black holes
  - » gamma-ray burst engines
  - » others?
- Gravitational waves could provide probe of these relativistic systems.

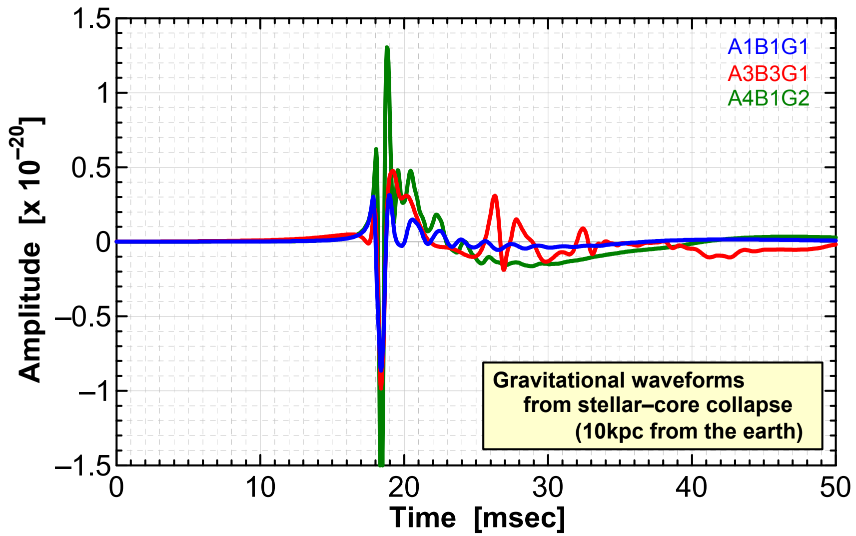


Colliding black holes (National Center for Supercomputing Applications)

Bursts Analysis: Philosophy

- Precise nature of gravitational-wave burst (GWB) signals typically unknown or poorly modeled.
  - » Make no astrophysical assumption about the nature and origin of the burst (no templates!).
  - » Search for generic GWBs of duration ~1ms-1s, frequency ~100-4000Hz.

supernova waveforms (Zwerger & Muller 1997)



Bursts Analysis: Goals

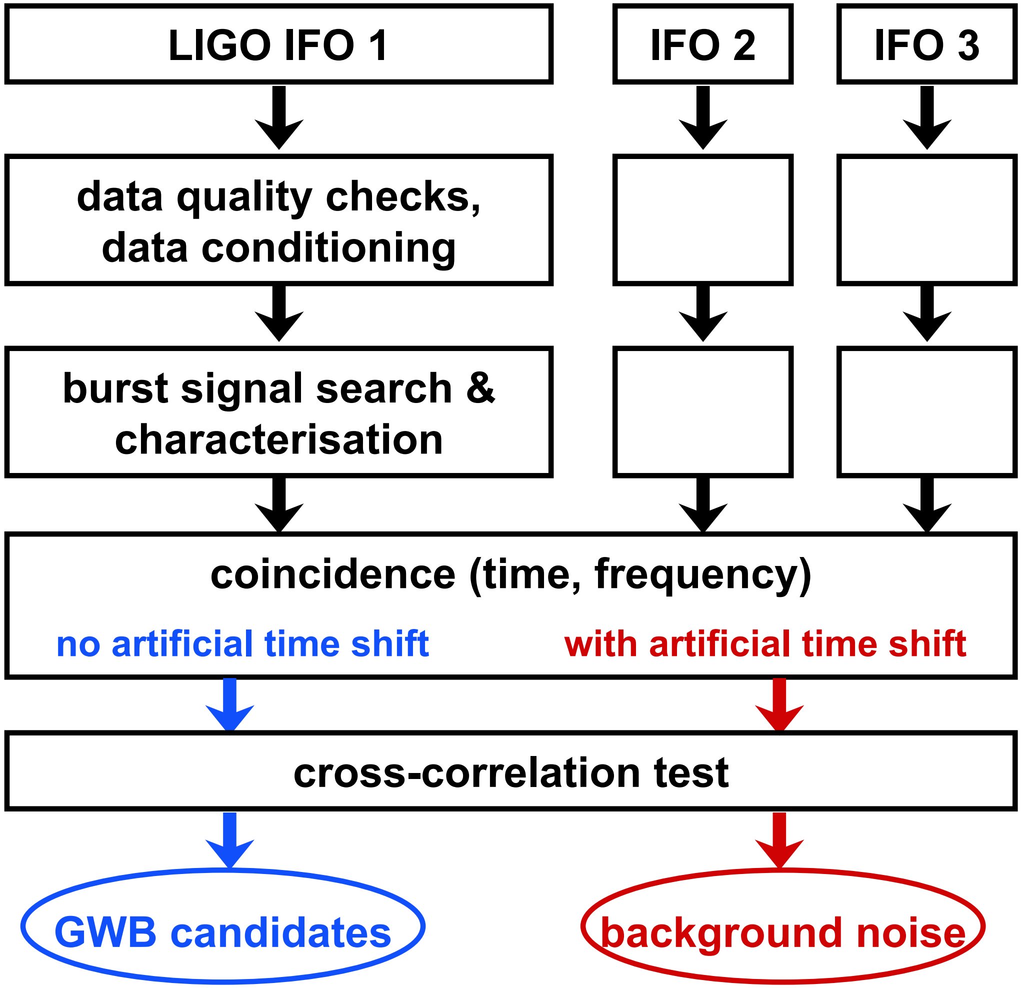
- Un-triggered Search:
  - » Scan LIGO data set looking for coincident signals in each detector.
  - » Make detections or set upper limit on rate of GWBs.
  - » Interpret limit in terms of source and population models.
- Triggered Search:
  - » Detect or set upper limit on strength of GWBs associated with astronomical events (eg, GRBs).
- Establish methodology and validate procedures.

Un-triggered searches for GWBs in the LIGO S2 data

Un-triggered Search: Methodology

- Measure number of possible GWBs in the data
  - » Require GW candidates to be coincident in all detectors
  - » Require GW candidates to be coherent in all detectors
- Estimate false alarm rate due to background noise
  - » Repeat coincidence, coherence tests with artificial time shifts
  - » Set thresholds for search such that expected $N_{\mathbf{background}} < 1$
- Possible detection if excess of coincident events compared to that expected from background.
  - » If no significant excess then set upper limit on rate of detectable GWBs.
- Estimate efficiency to real GWBs
  - » Add simulated signals to the data
- Tune pipeline using 10% subset of data: “playground”
  - » Playground data not used for final GWB search; avoids bias

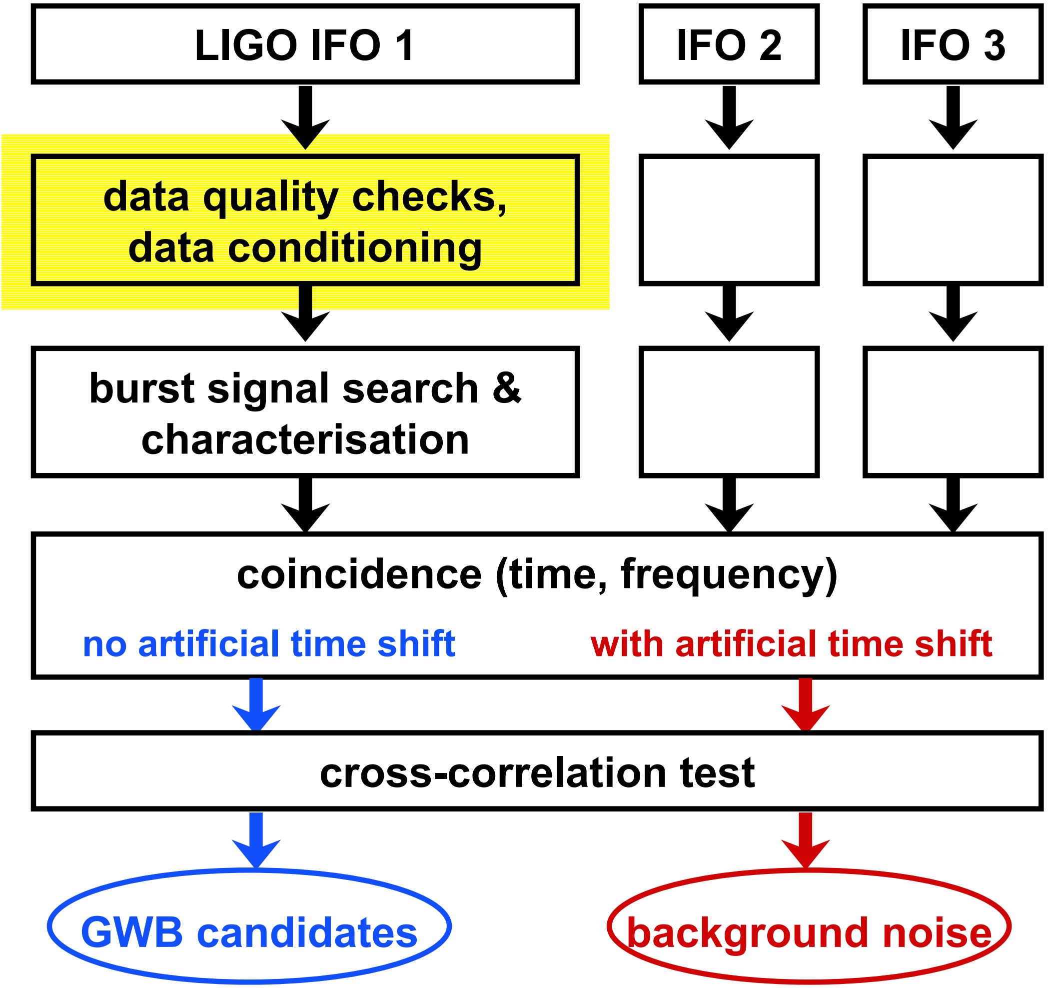
Un-triggered Analysis Procedure



Data Quality & Conditioning

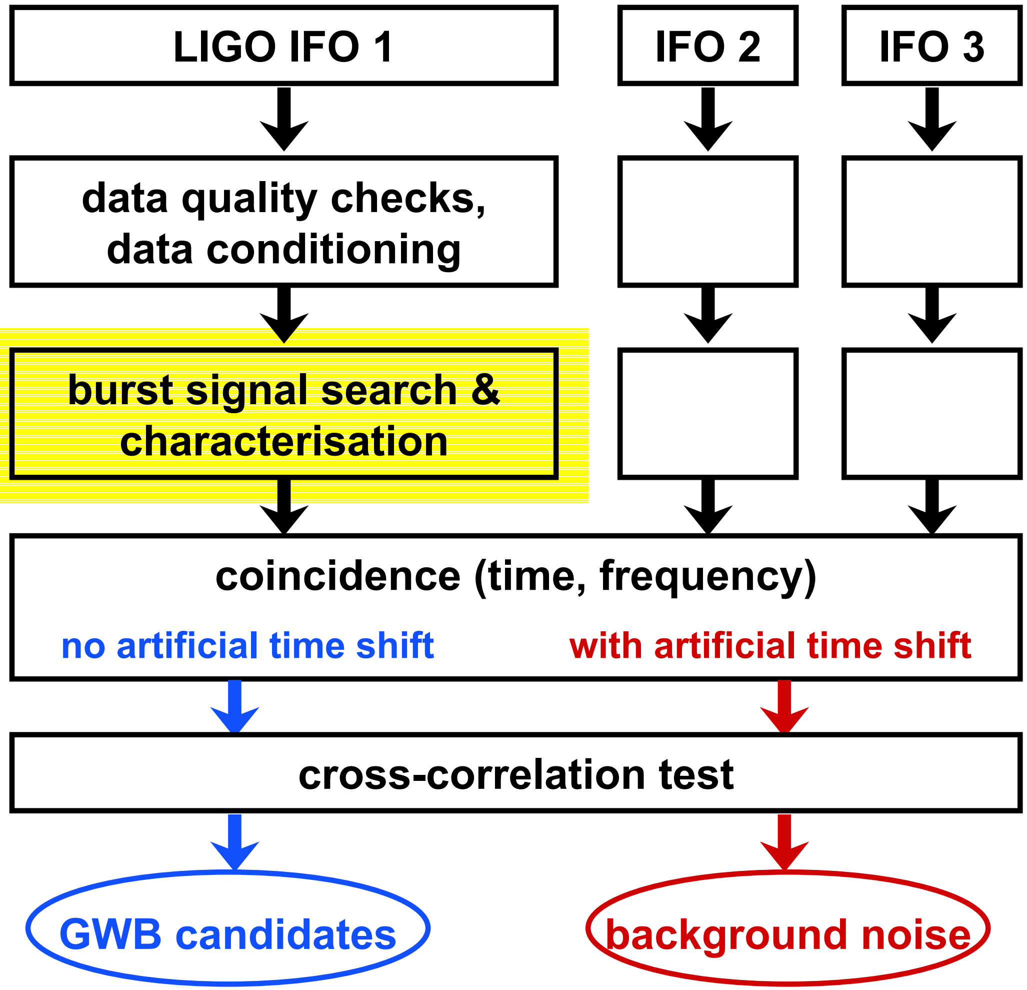
- Discard data that do not pass quality criteria (eg, noise levels) - few %
- High-pass filtering
- Base-banding
- Whitening using linear predictor filters

- S1: Lost ~2/3 of data to quality cuts; non-adaptive conditioning led to more ringing, non-white data.

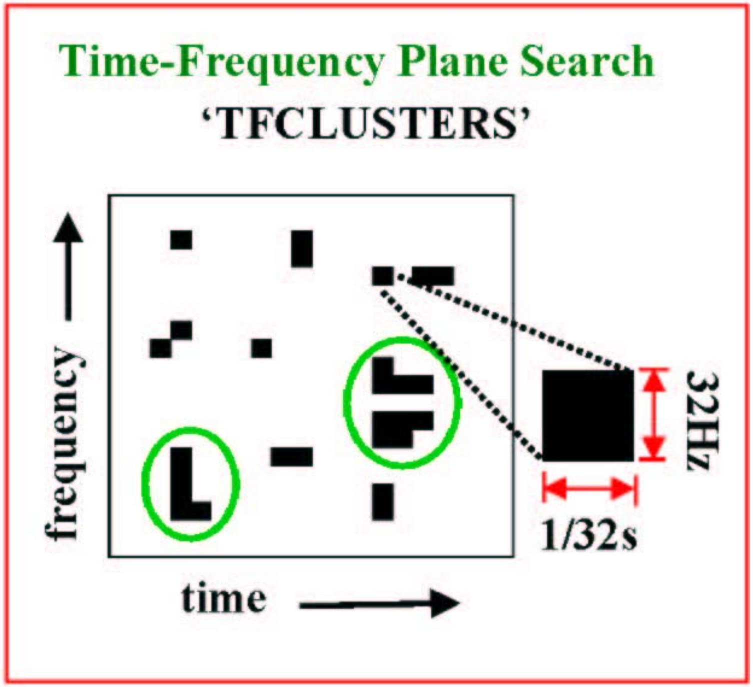


Burst Signal Identification

- » Multiple detection codes:
  - – TFClusters (freq domain)
  - – Excess Power (freq domain)
  - – WaveBurst (wavelet domain)
  - – BlockNormal (time domain)
- » Adaptive thresholding to handle non-stationary data
- » Tuned for maximum efficiency at fixed false alarm rate
- » S1: Some non-adaptive code, less tuning.



Example: TFClusters



- Threshold on power in the time-frequency plane.
- "Events" are clusters of pixels with improbably large power.

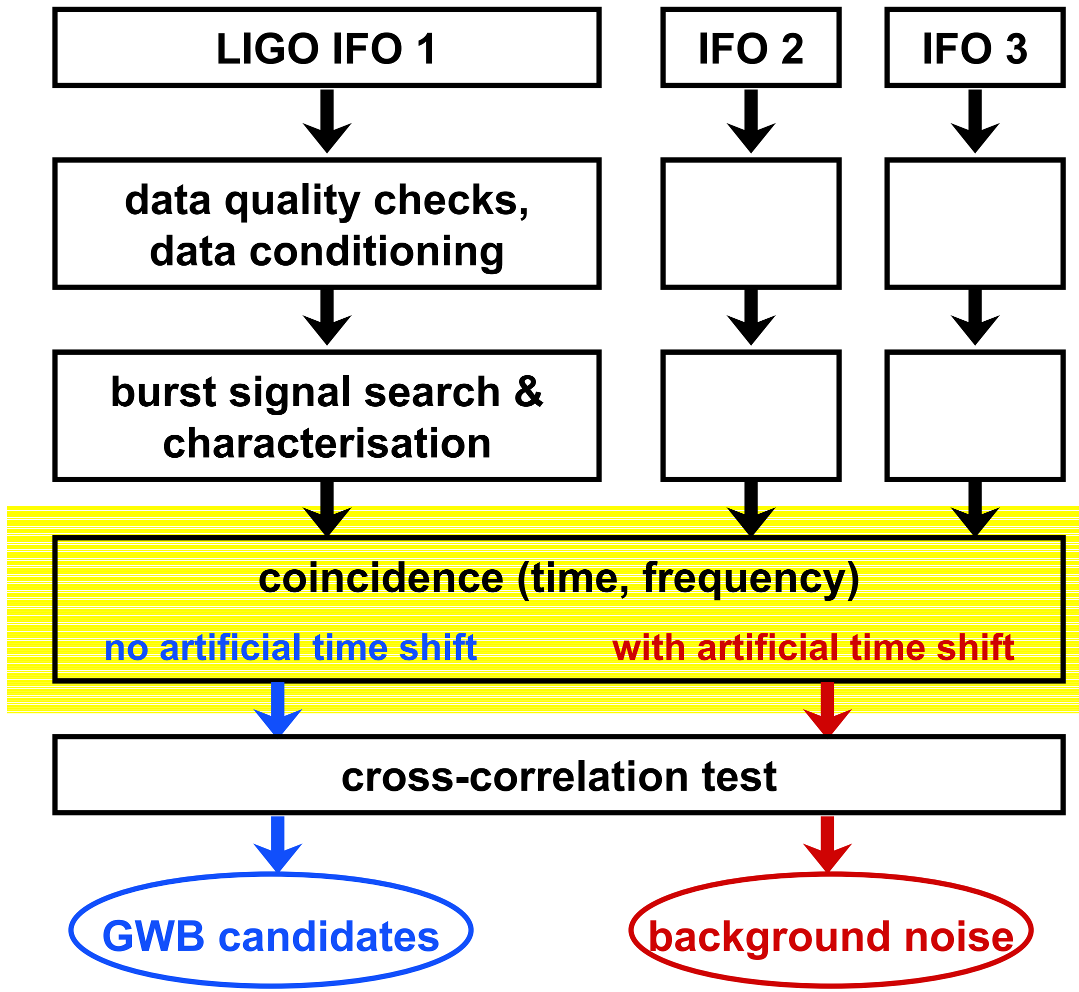
Coincidence

» Require simultaneous (within ~30ms) detection in each IFO

» Require frequency match

» Estimate rate of accidental coincidence of noise fluctuations using artificial time shifts

» S1: 500ms coincidence window (!)

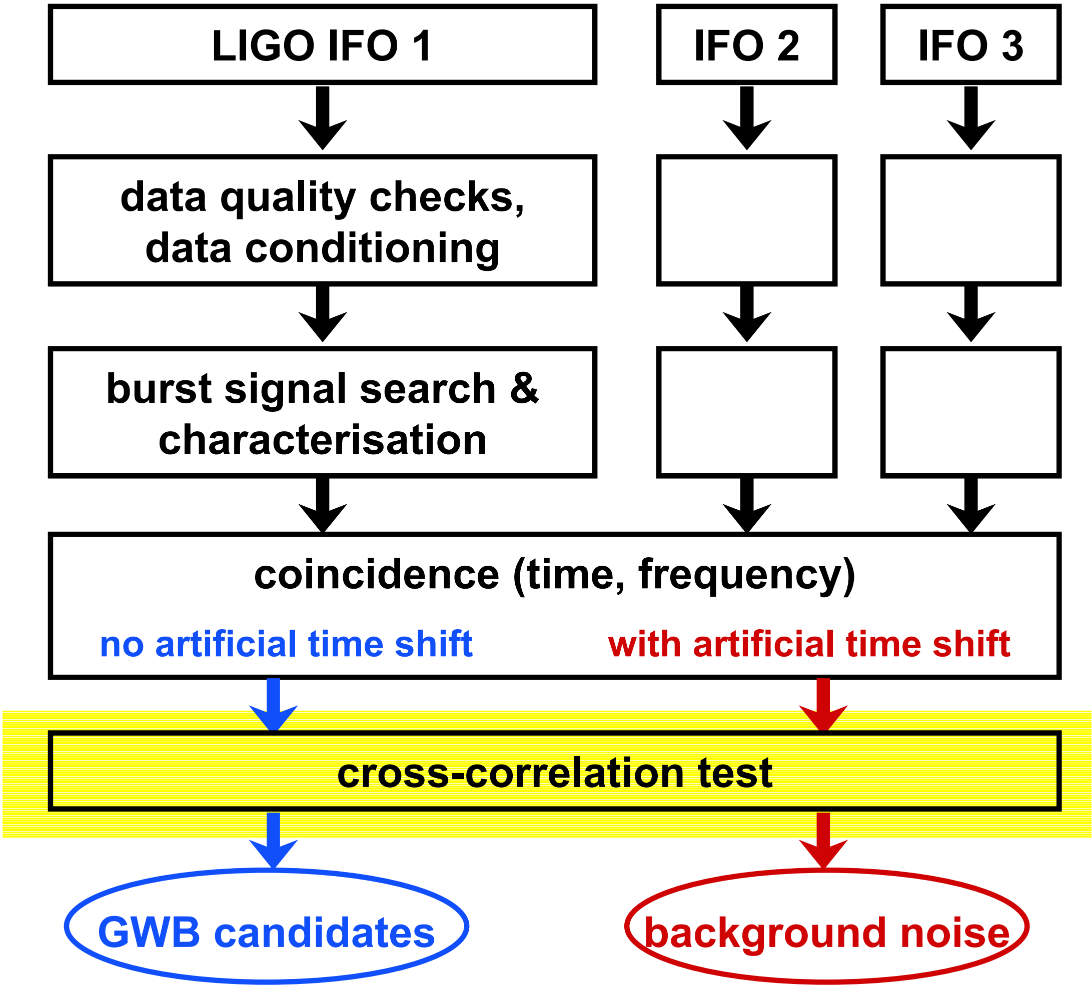


Cross-Correlation Test

- » Require cross-correlation of data from each pair of detectors exceed threshold:

$$r_k = \frac{\sum_i (x_i - \bar{x})(y_{i+k} - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_{i+k} - \bar{y})^2}}$$

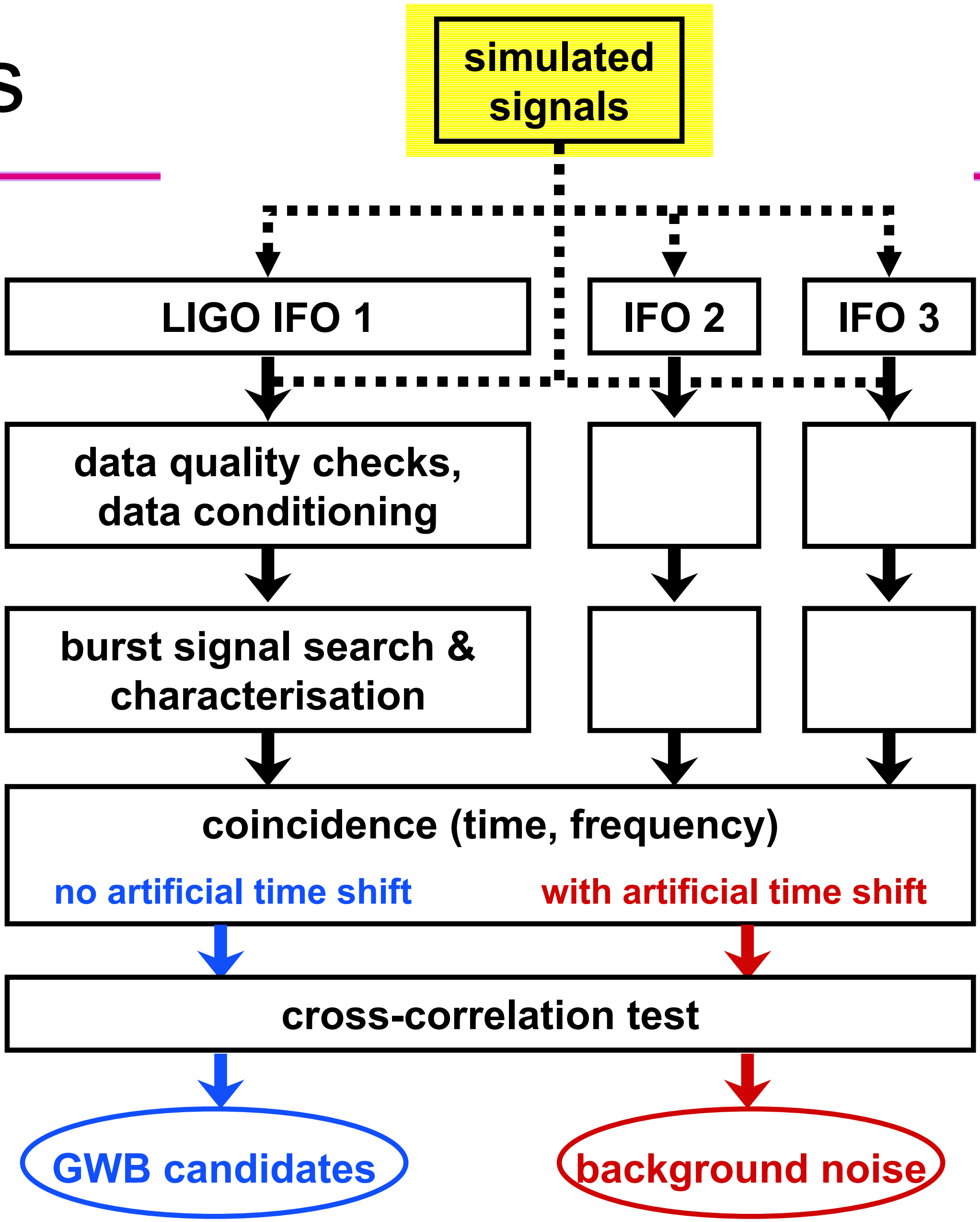
- » Strong reduction of false alarm rate (~99%) with no loss of efficiency
- » Check of waveform consistency in each detector
- » Entirely new since S1



Simulations

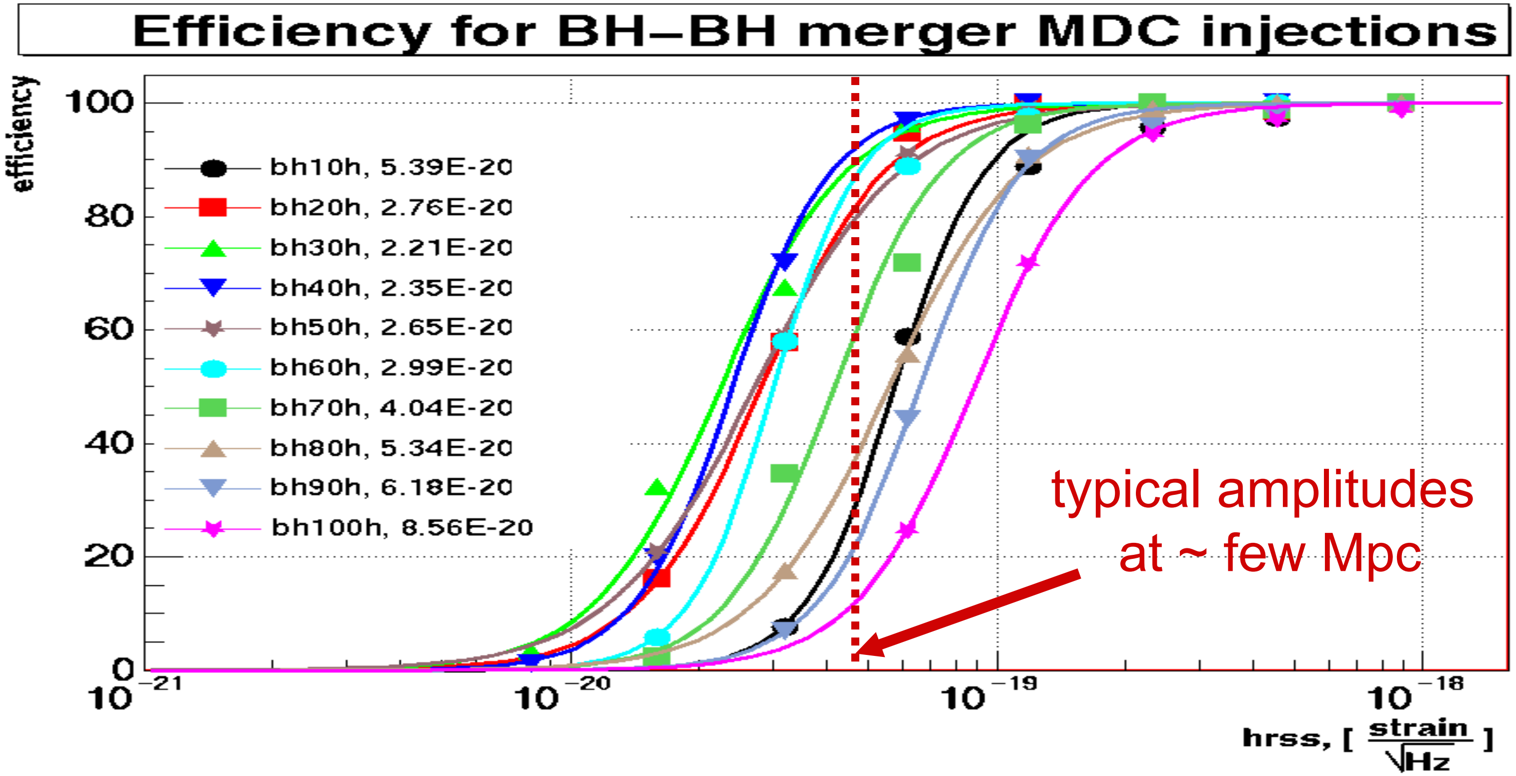
- Add simulated GWBs to IFO control signals or output data
- Used to tune analysis (eg: coincidence windows) and estimate efficiency to real GWBs.
- Include effects like sky position, signal polarization.

- New since S1: All-sky simulations of astro-physical waveforms (eg supernovae)



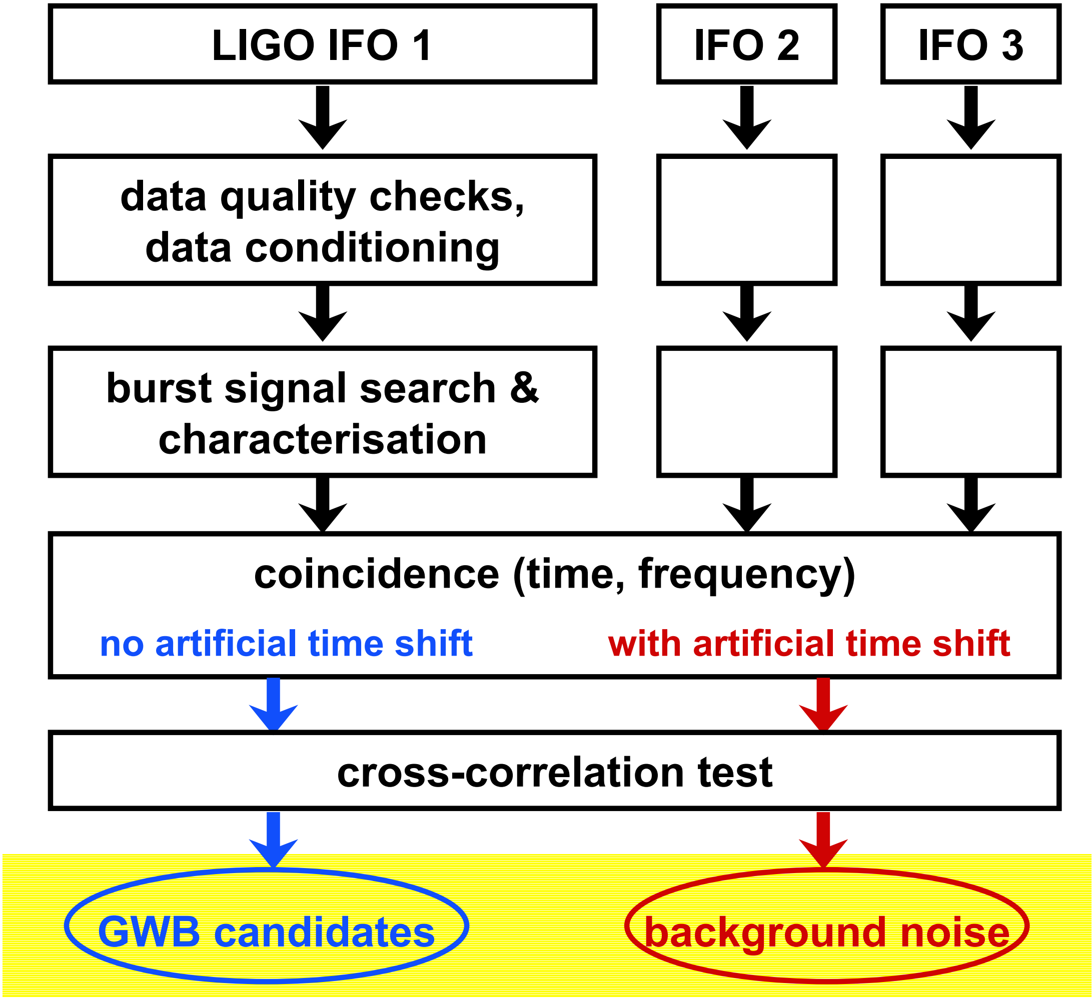
Ex: Black-Hole Mergers

- From WaveBurst search code (wavelet based).
- Can detect BH mergers to few Mpc.



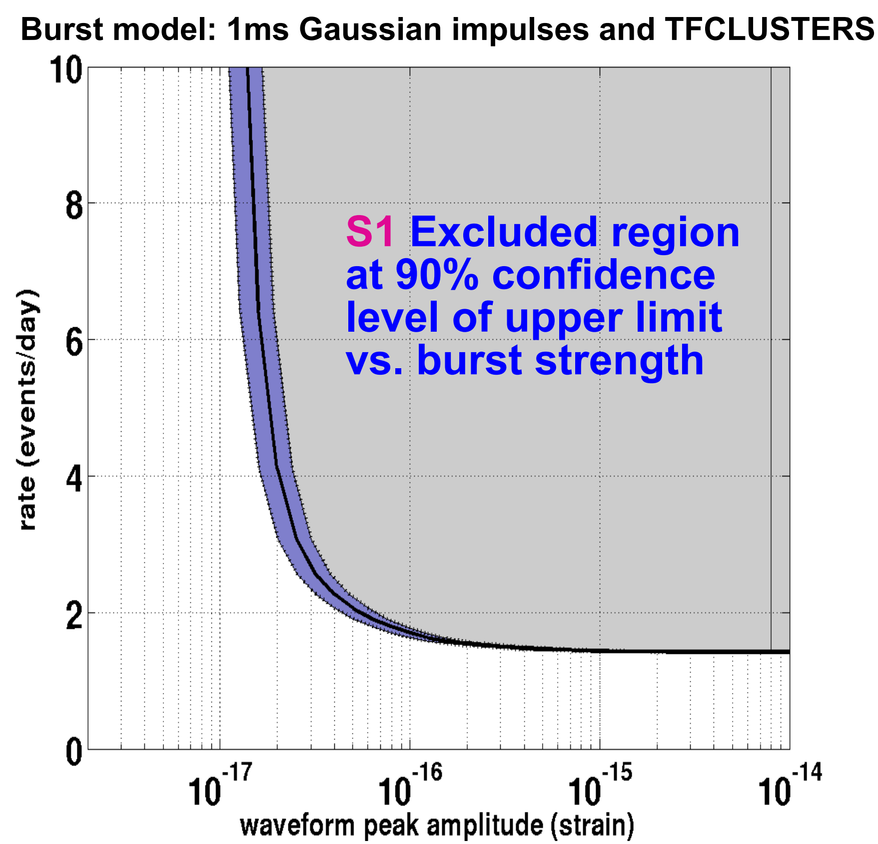
Detection / Upper Limit

- » Compare number of coincident events to that expected from background noise (eg: Feldman & Cousins 1998)
- » Significant excess is possible detection
- » No excess ⇒ upper limit

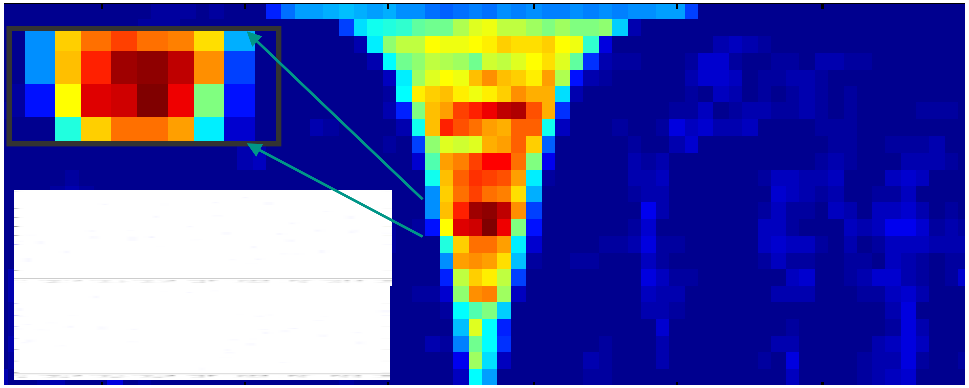


Ex: S1 Search Results

- Upper limit on rate is a function of signal strength.
- LIGO Science Run 1:
  - » gr-qc/0312056
  - » rate: R < 1.6/day
  - » sensitivity: $h_{rss} > O(10^{-18})Hz^{-1/2}$
- LIGO Science Run 2:
  - » ***Analysis in final stages.***
  - » ***Expected rate:*** R ~0.3/day
  - » ***Expected sensitivity:*** $h_{rss} > O(10^{-19})Hz^{-1/2}$



Search for the gravitational-wave signature of GRB030329/SN2003dh



Externally initiated searches for gravitational waves

- Violent cosmic events include supernovae, neutrino bursts, GRBs, etc…
  » Some of these may produce a significant flux of gravitational waves in the LIGO frequency band.
- Various trigger and data distribution networks:
  » International Supernovae Network (I.S.N.)
  » Supernovae Early Warning System (SNEWS)
  » The GRB Coordinates Network (GCN)
  » The third InterPlanetary Network (IPN3)
- Opportunity for targeted coherent search for gravitational-wave counterpart
  » Here concentrate on one search triggered by an extraordinary event: GRB030329

Gamma-Ray Bursts (GRB)

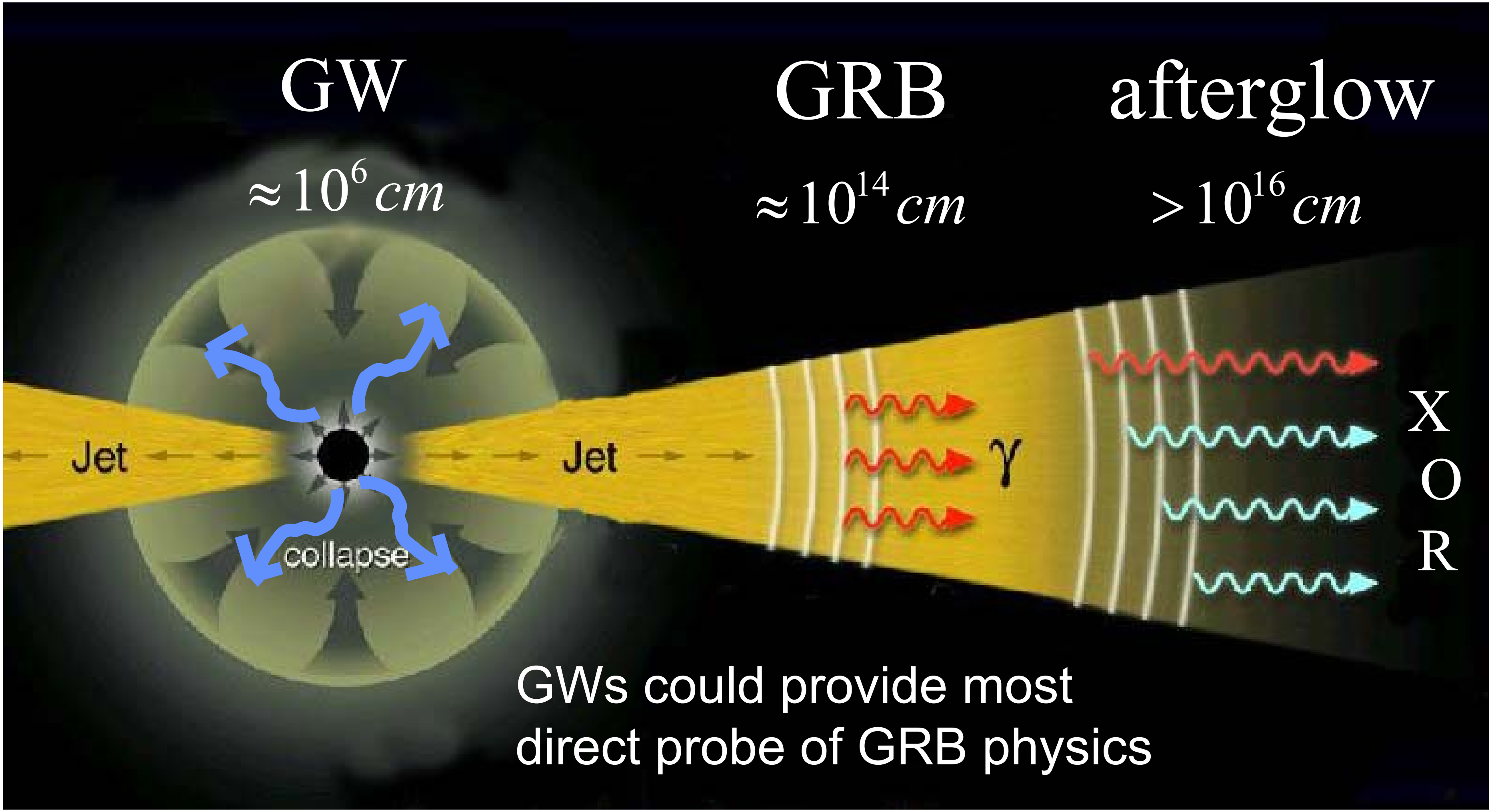
Known:

- Bright, transient bursts of gamma rays
- Observed at rate ~1/day
- Duration: 0.01s - 100s
- "Afterglow" seen in other wavelengths (long-duration GRBs)
  - cosmological distances (z~1)
  - highly energetic (10^{51}-10^{53} ergs)
  - beamed (1 GRB visible out of every ~500)

Thought:

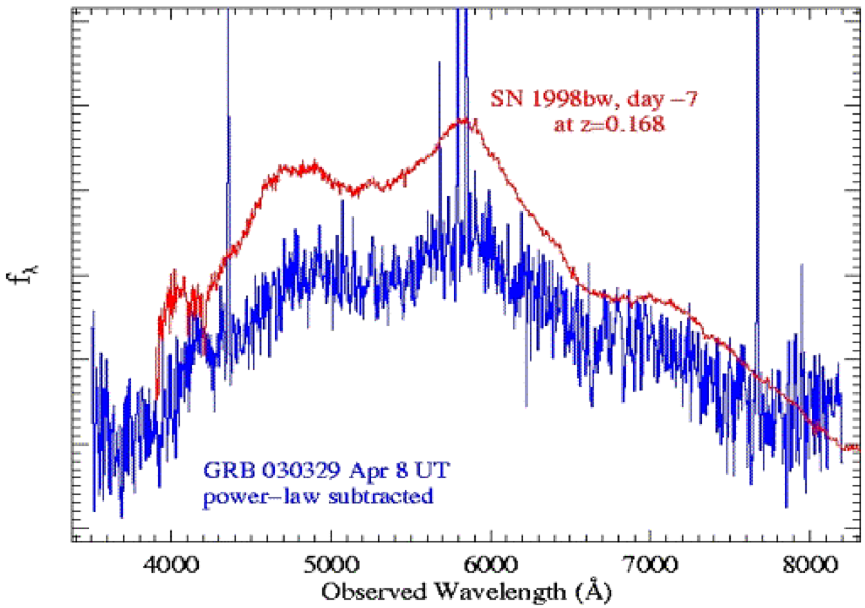
- Central engine is solar-mass accreting black hole resulting from hypernovae, compact binary inspirals, collapsars.
  - » Violent, strongly relativistic processes may dump significant fraction of a solar mass into gravitational waves in the LIGO band
- Prototype detection strategies using exceptional candidates

Fireball Model



GRB030329: “Monster GRB”

- Detected March 29 2003
- One of closest ever seen
  - » z=0.1685
  - » d=800Mpc
- Second-brightest GRB observed (intrinsic luminosity).
- Provides strong evidence for supernova origin of long GRBs.



Analysis Methodology

- Use cross-correlation of data from pairs of detectors
  - similar to cross-correlation test used in un-triggered search
- Compare cross-correlation values around time of electromagnetic trigger ("signal region") to values at other times ("background region")
  - set cross-correlation threshold for fixed false alarm rate
  - possible detection if cross-correlation around trigger time crosses threshold

Signal Region for GRB030329

-Theories prefer:

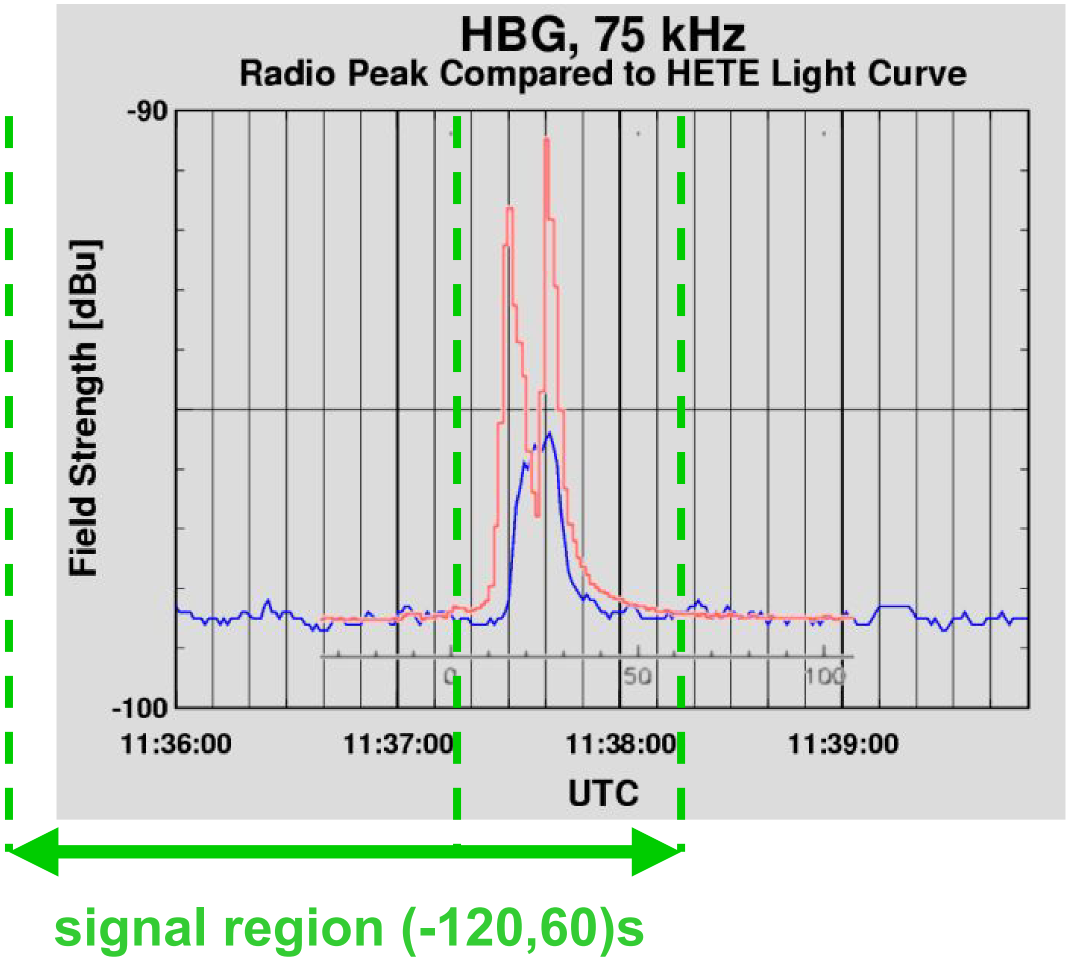
- very short ~10ms burst
- long (~1-10s) quasi-sinusoids (Araya-Góchez, M. Van Putten)

- Relative delay between the gravity wave and GRB is predicted to be small ~O(s)

- Signal region: [t_0-120s, t_0+60s] covers most predictions

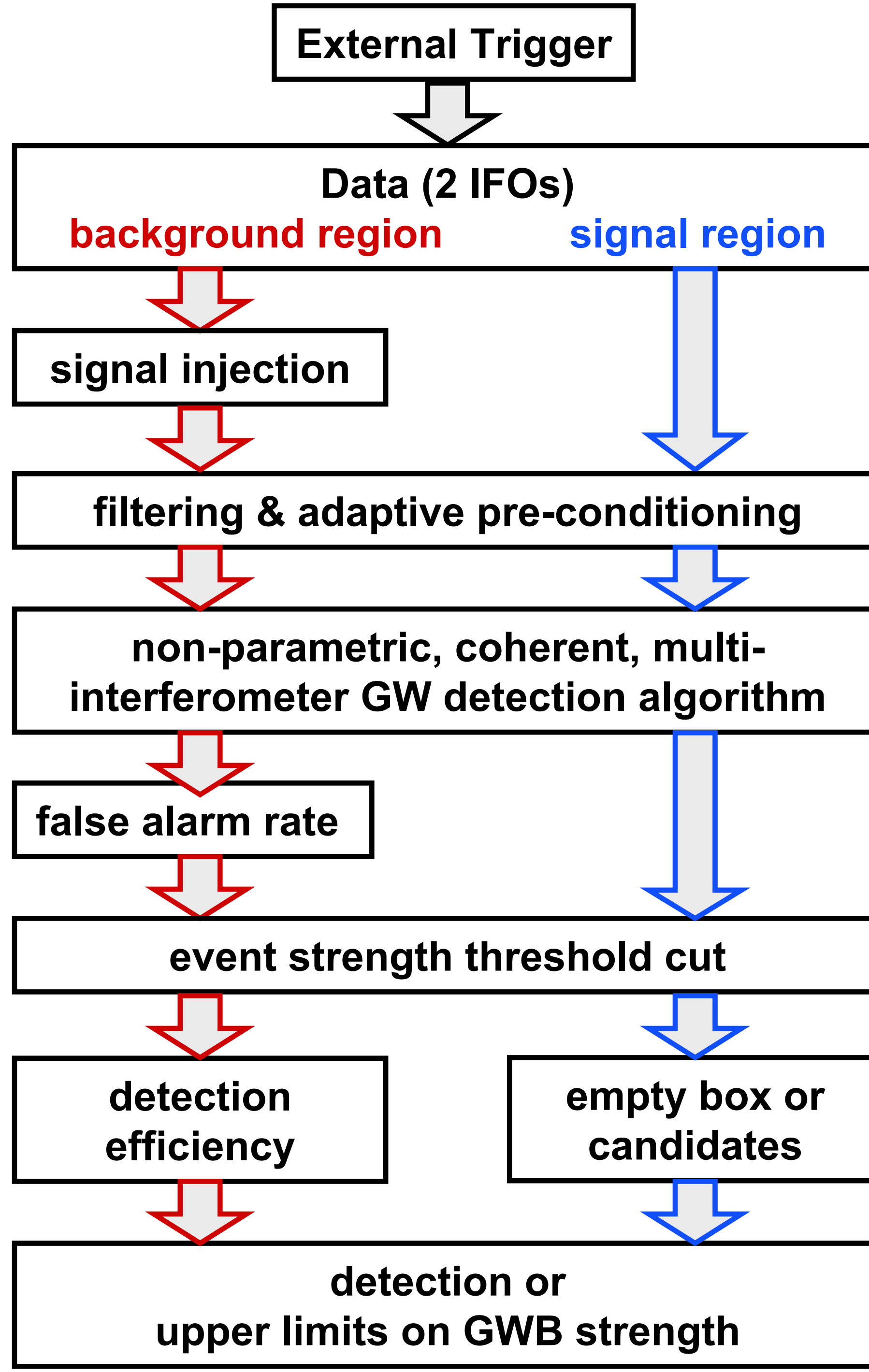
-Background region: [t_0-12000s, t_0+4000s] excluding signal region.

- Model specific ranges can also be considered



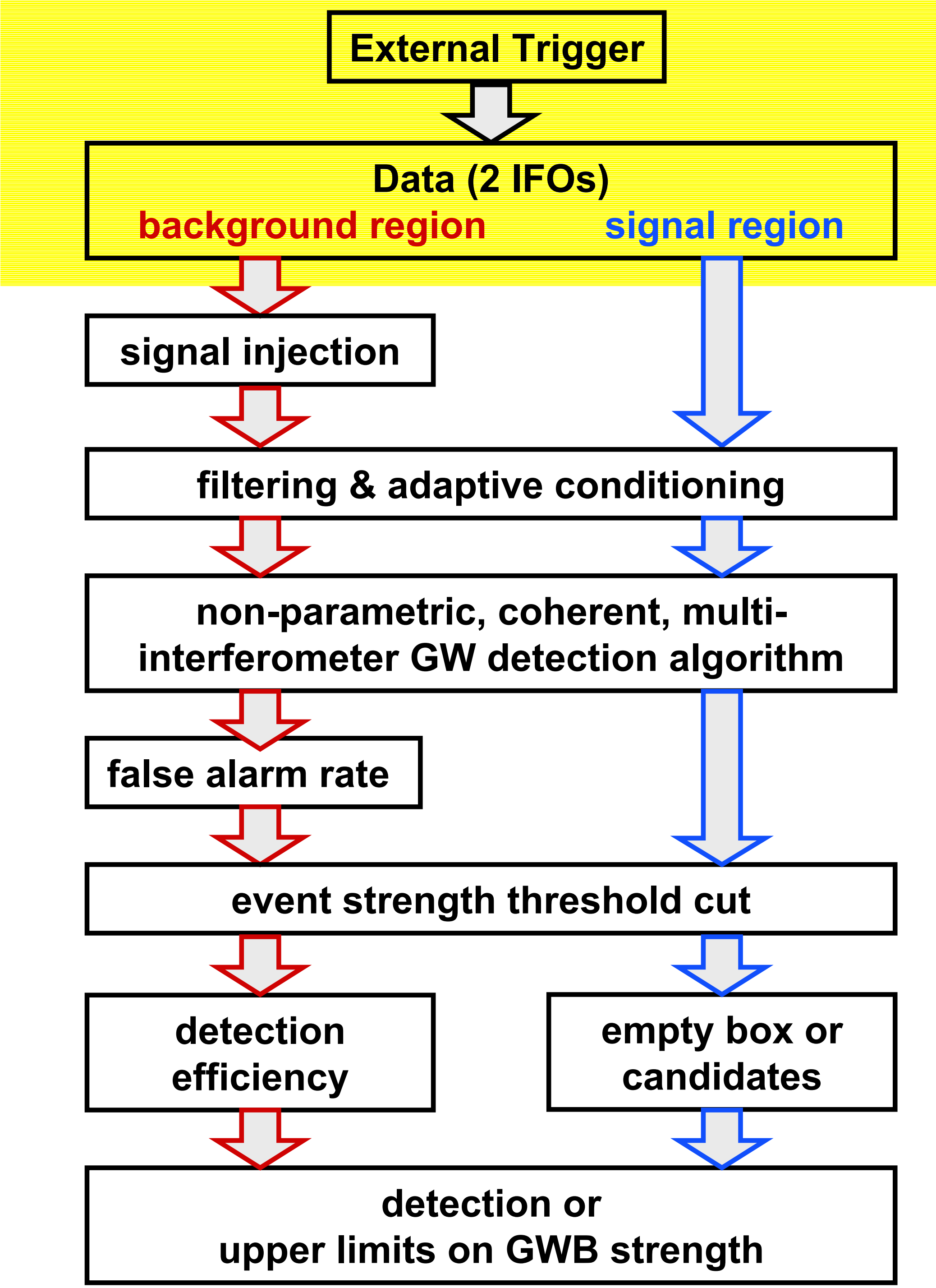
http://www.mpe.mpg.de/~jcg/grb030329.html

Externally Triggered Analysis Procedure



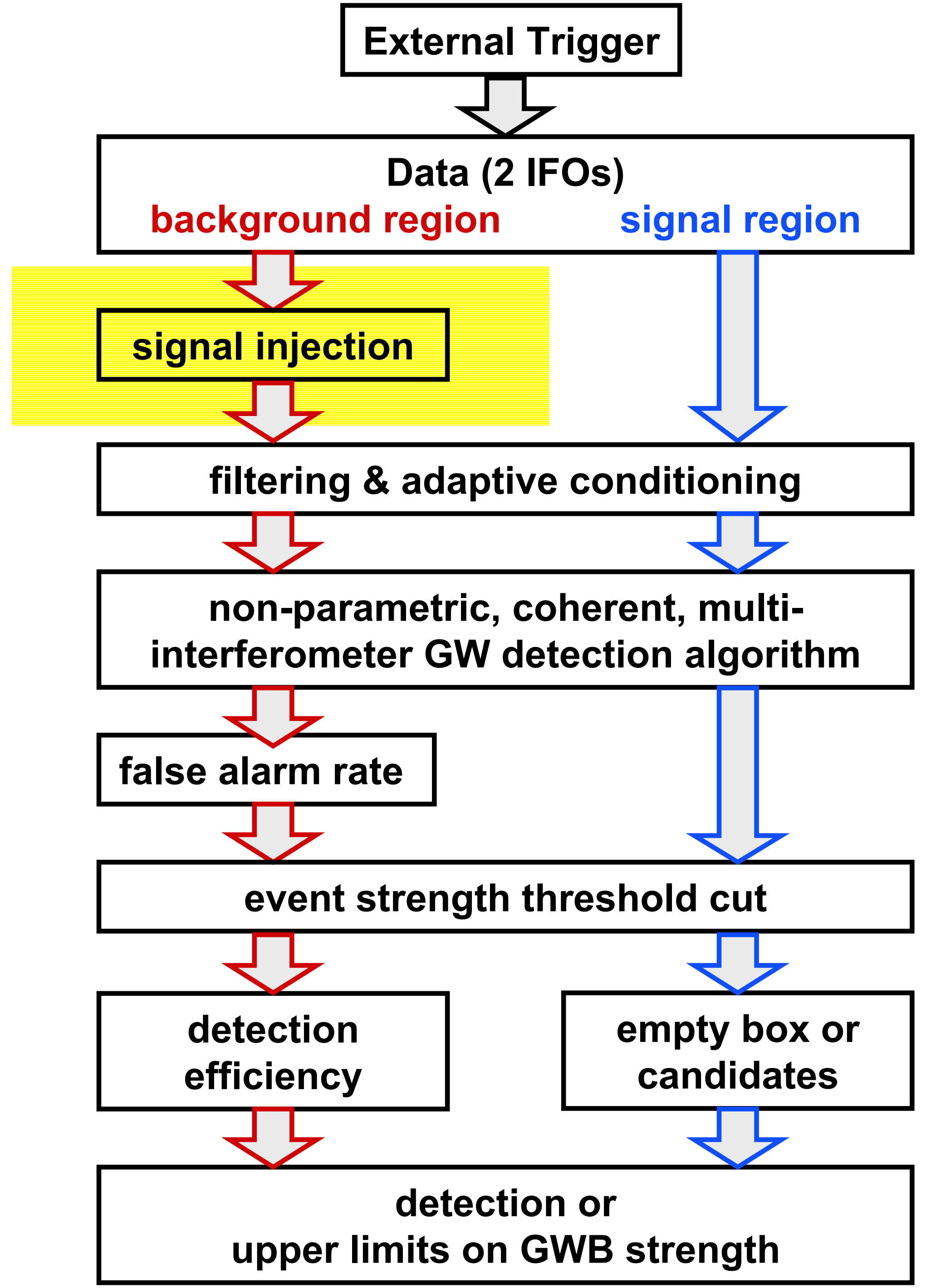
LIGO

- Data Selection:
  - » Data from signal and background region goes through same pipeline
  - » Background: used to tune pipeline, set thresholds ("playground")
  - » Signal: look for GWB



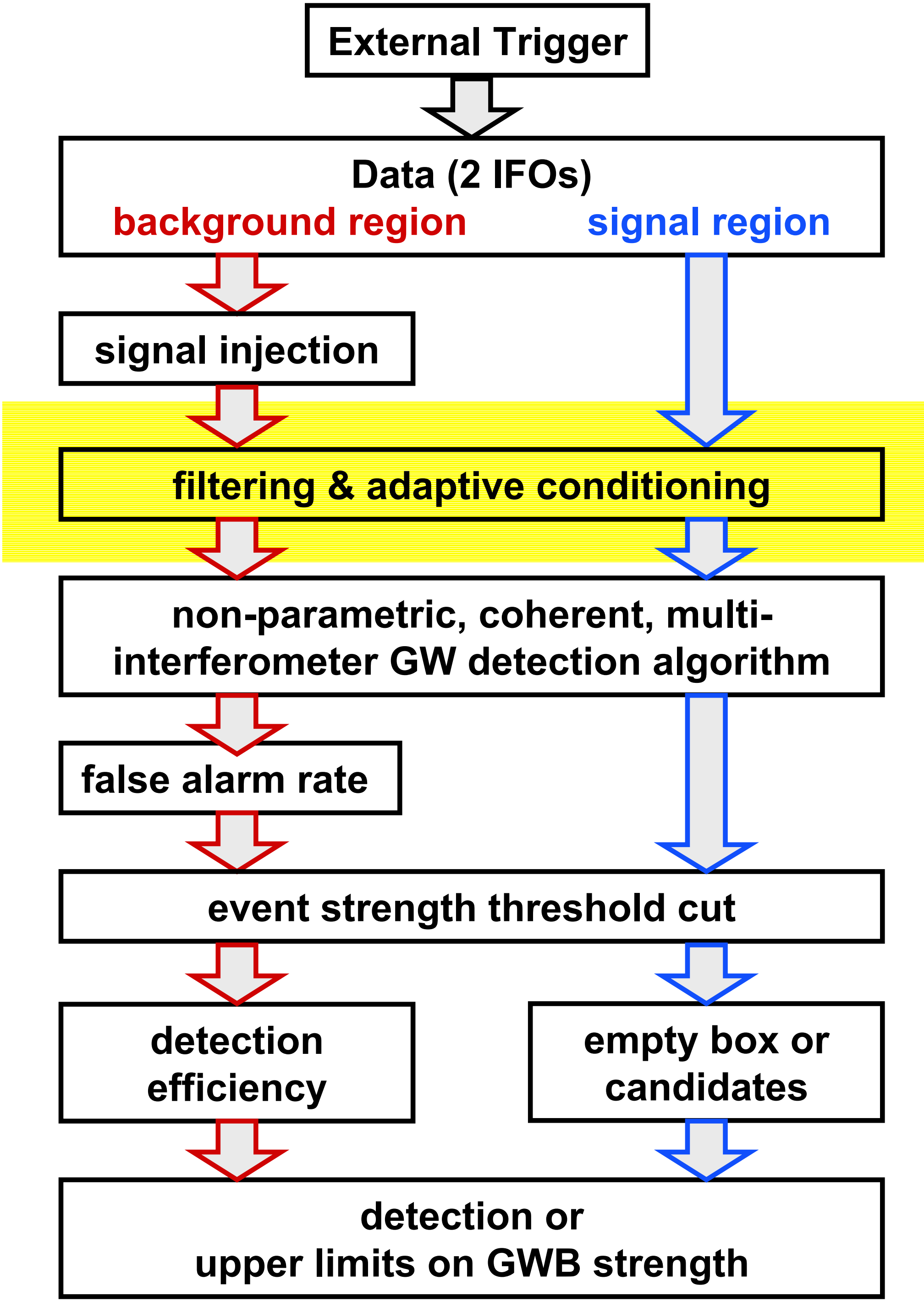
LIGO

- Signal Injection:
  - » May add simulated signals to background data
  - » Use to measure detection efficiencies, tune analysis



LIGO

- Data Conditioning:
  - » whiten data
  - » remove lines (coherent features)

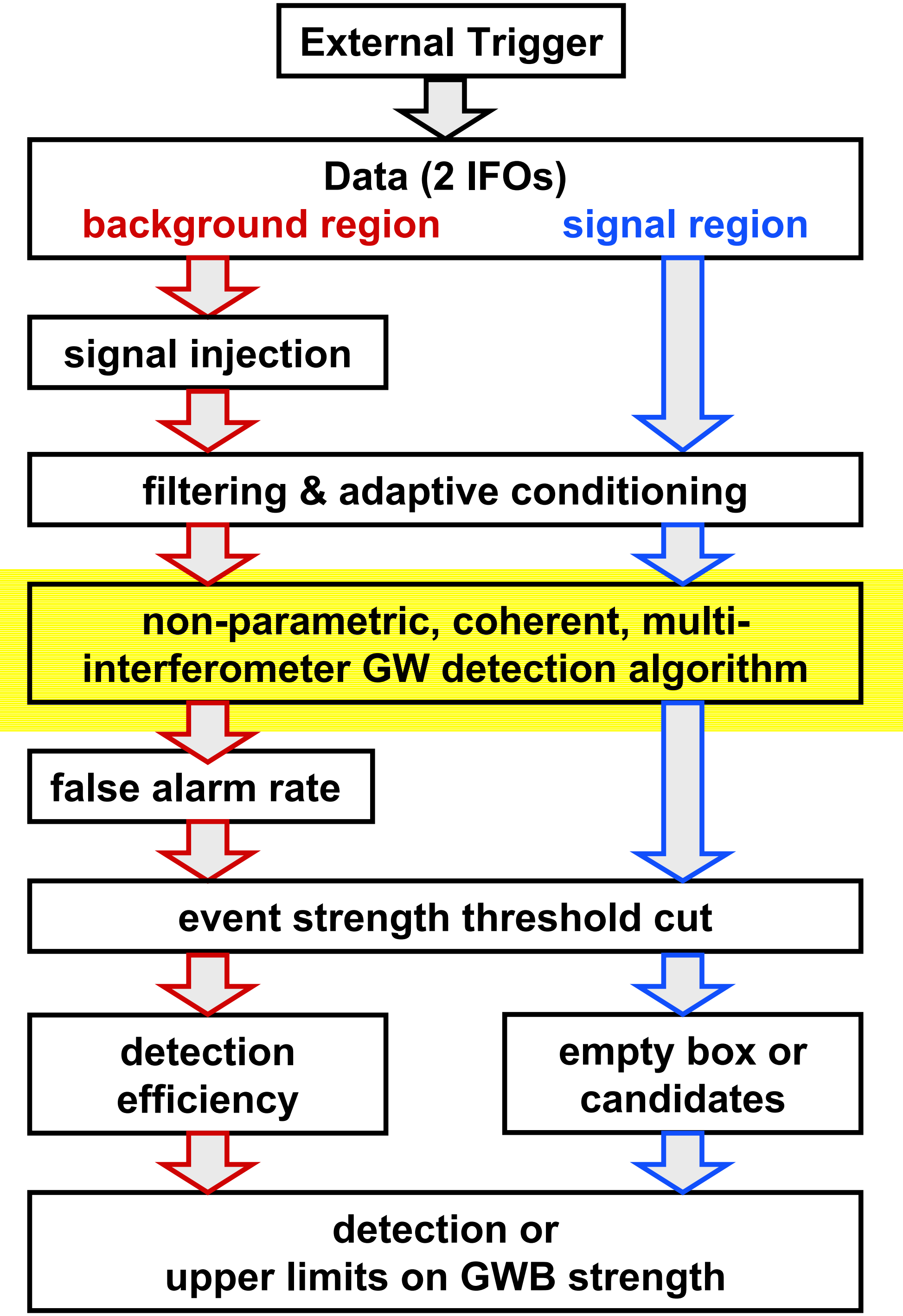


LIGO

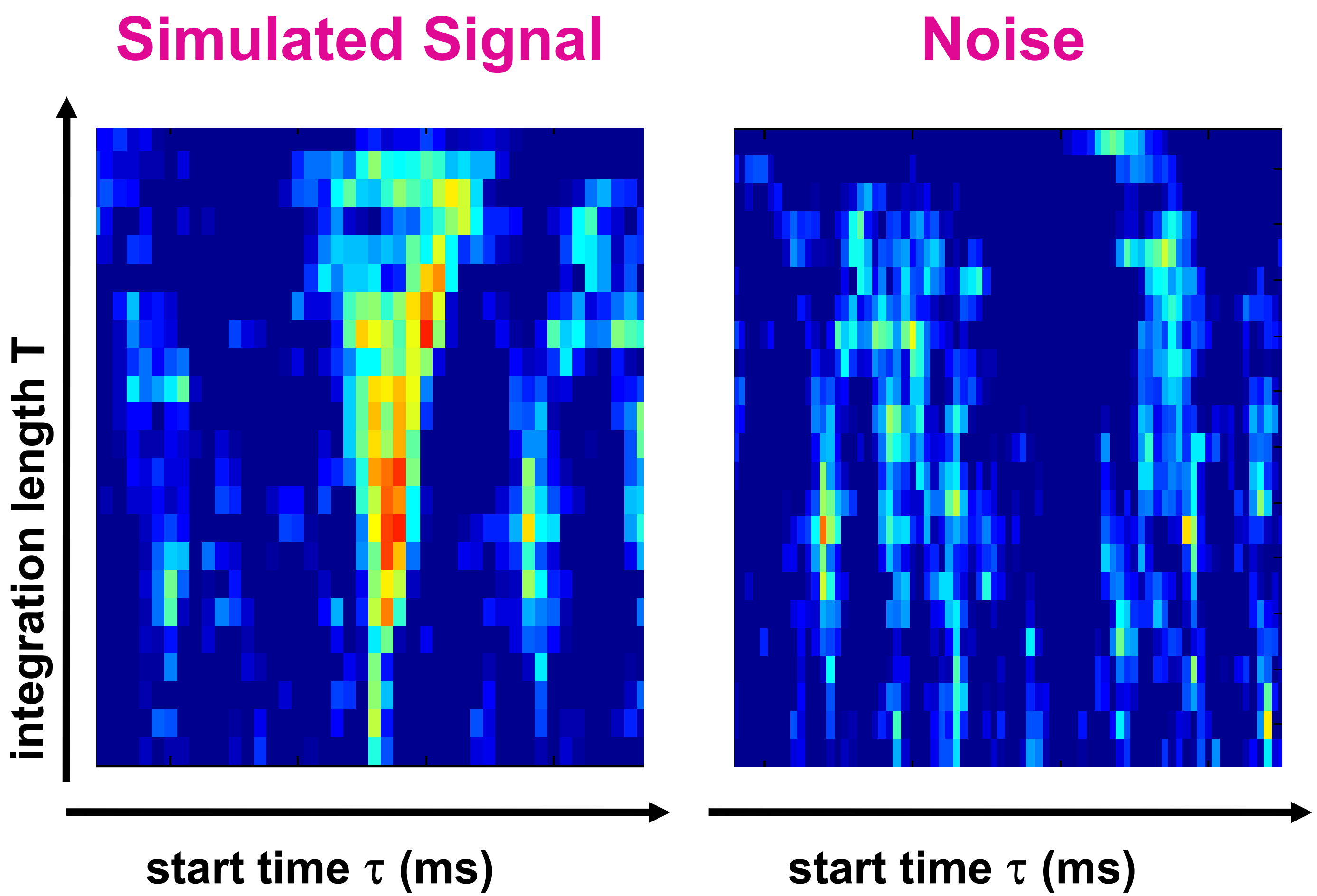
- Cross correlation of data streams *x*, *y* at time τ, offset Δt, integration time *T*:

$$S(\tau, T) = \int_{-T/2}^{T/2} dt\, x(\tau + t) y(\tau + t + \Delta t)$$

- Scan over values:
  - » start time τ: [-120,60]s around GRB time
  - » integration length T: [1,128]ms for short signals
  - » offset Δt: average over [-5,5]ms to allow for calibration uncertainties (ideally Δt = 0)

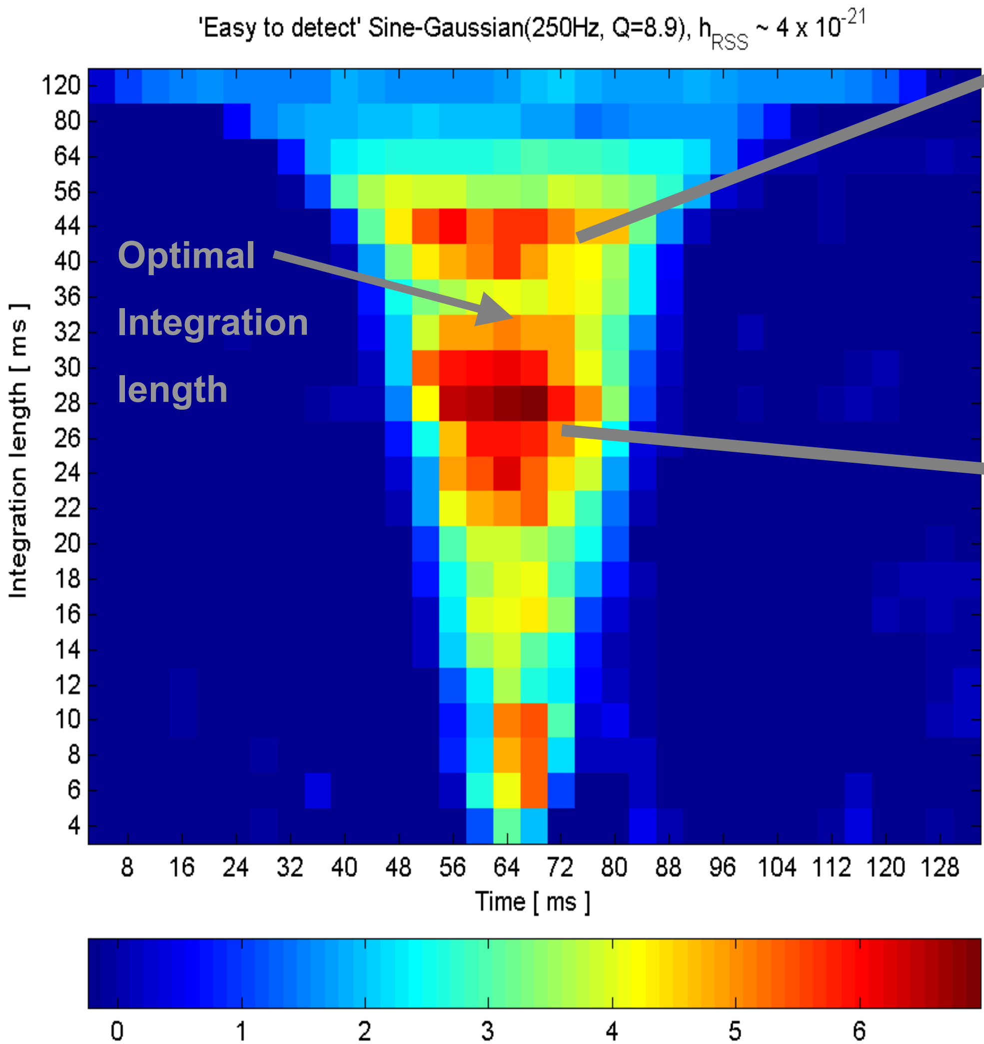


Cross-Correlation Power



Cross correlation for each start time, integration length

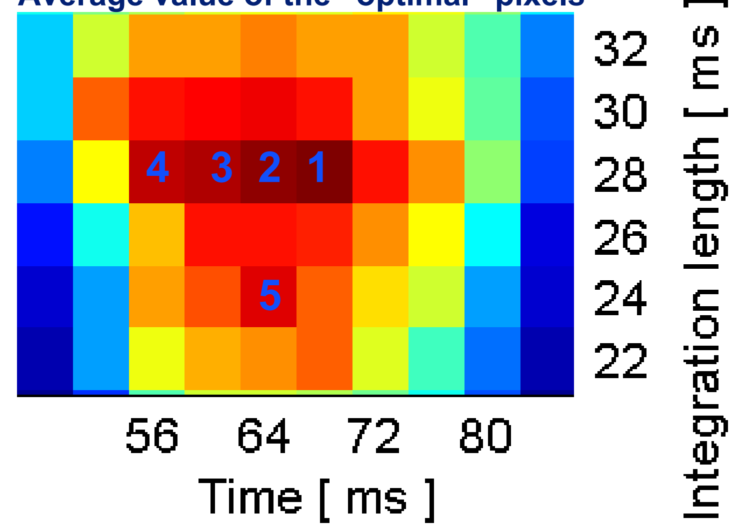
Signal Anatomy (Simulated)



Color coding: "Number of variances above mean" [ES']

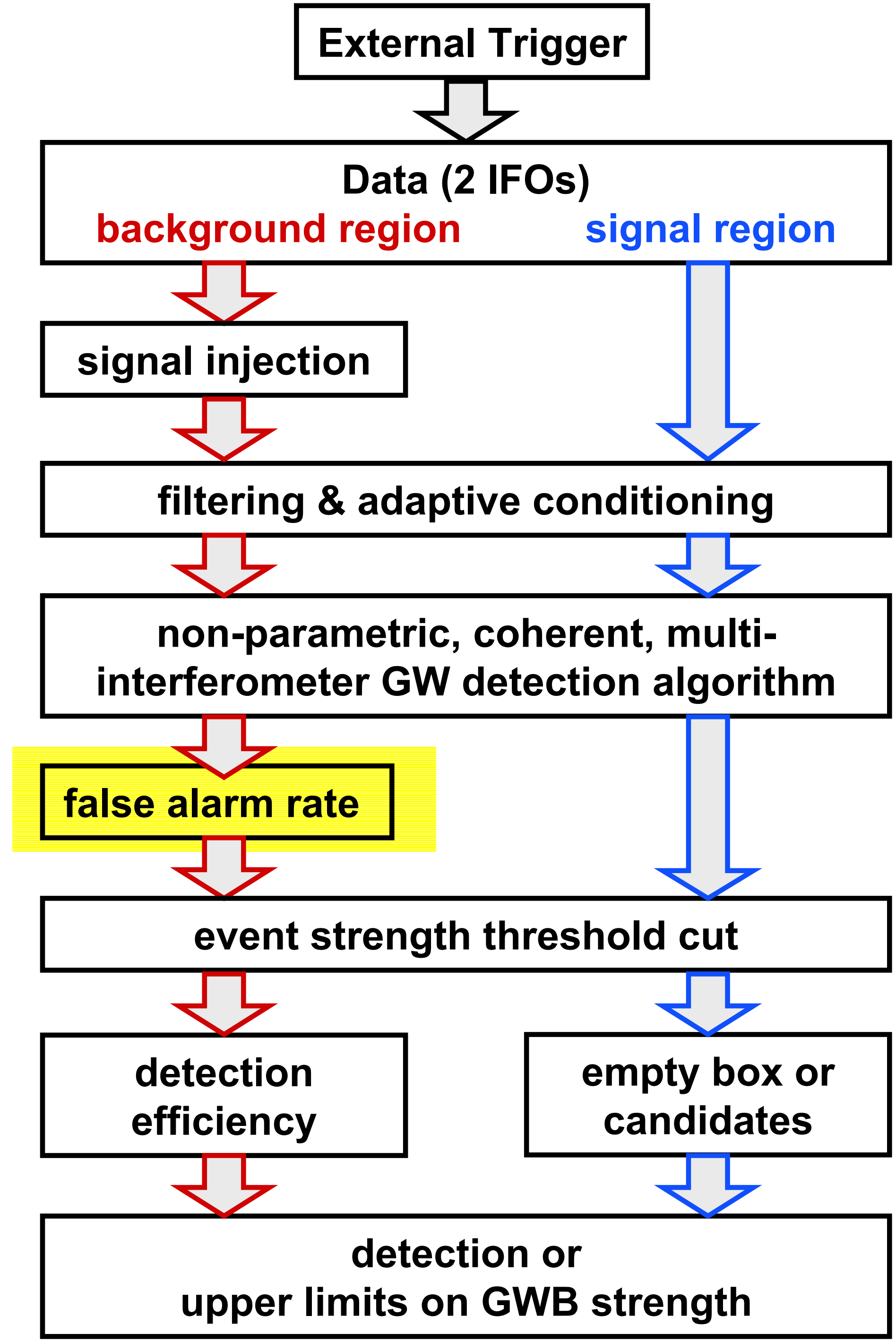
Event strength [ES] calculation:

Average value of the "optimal" pixels

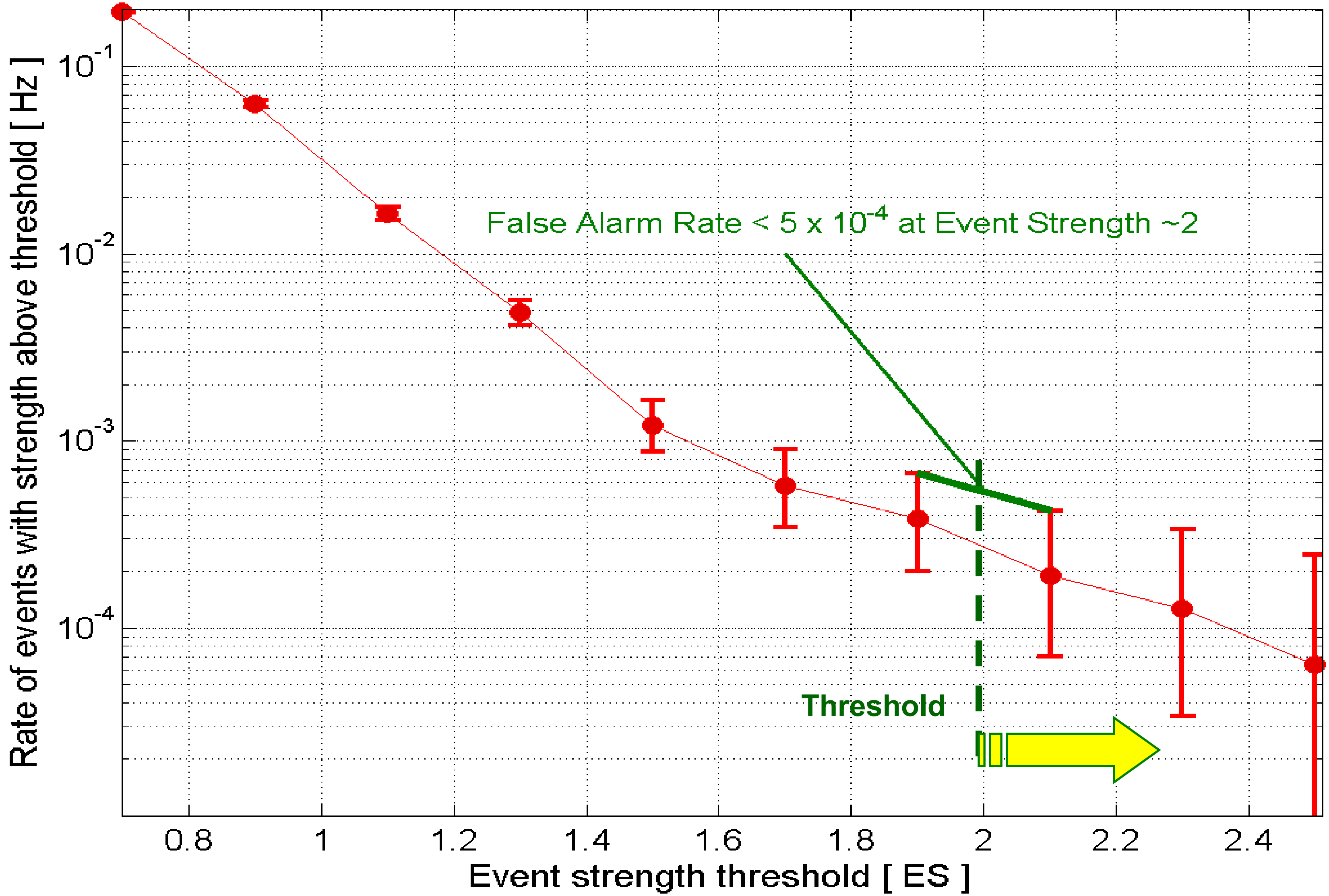


Signal strength = average of strongest pixels

- False alarm rate:
  - » Use background cross-correlations to estimate false alarm rate vs signal strength threshold
  - » Set threshold so false alarm rate is < 0.1/(180s) (10% false alarm probability)

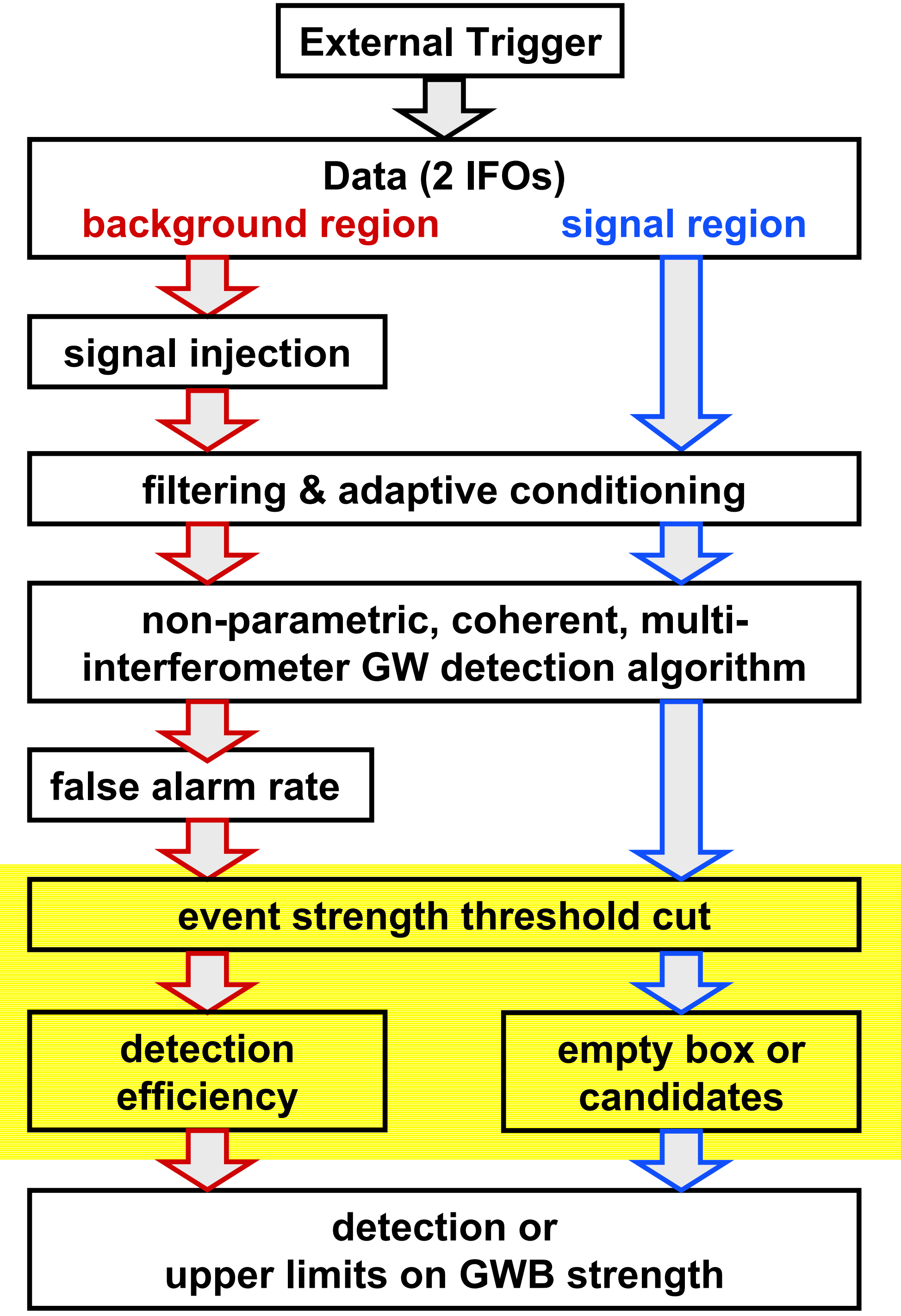


False Alarm Rate Limit

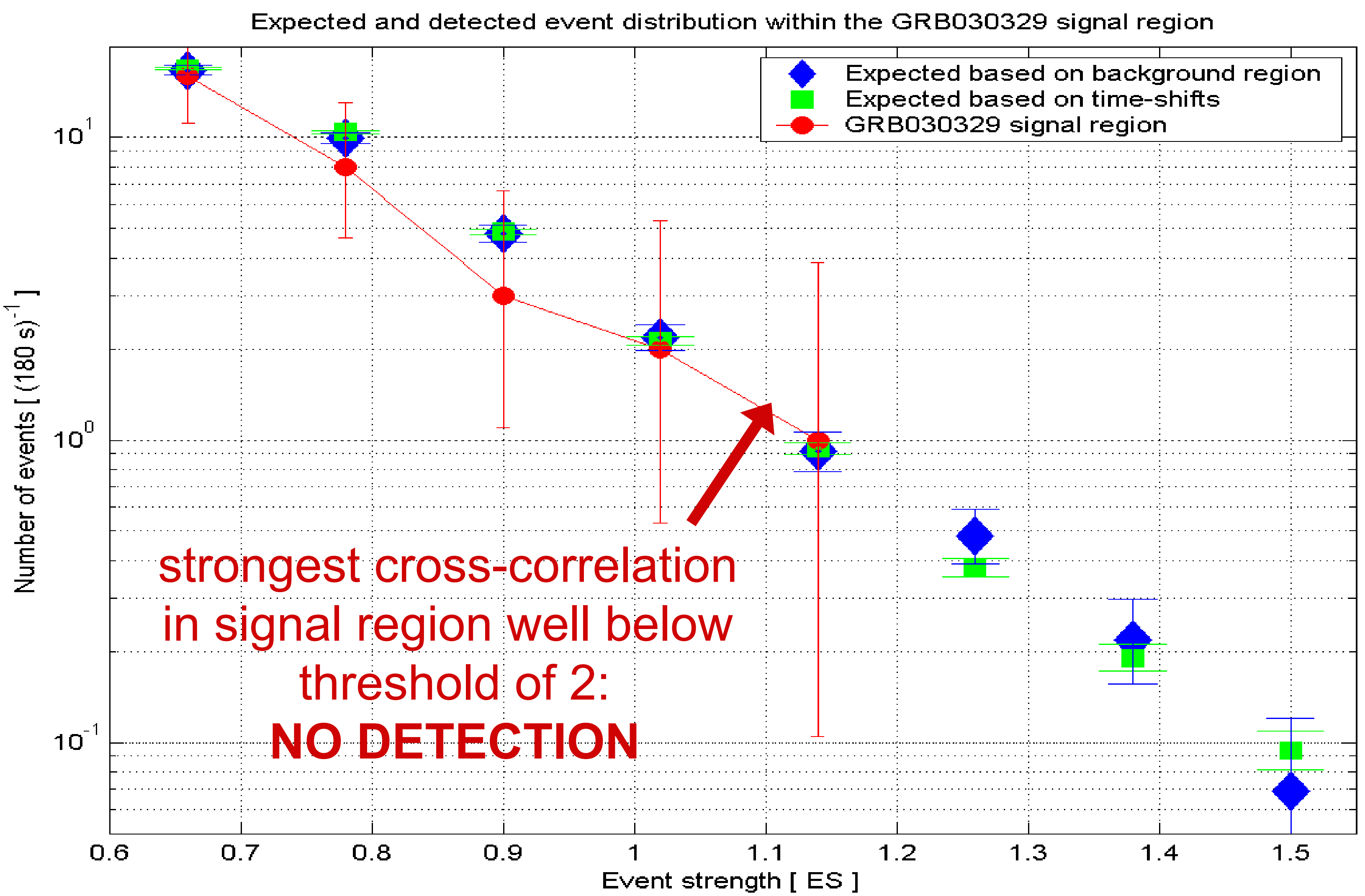


LIGO

- Threshold on cross-correlation strength:
  - » Background region: simulated signals seen or missed
  - » Signal region: No GWBs or potential detection.

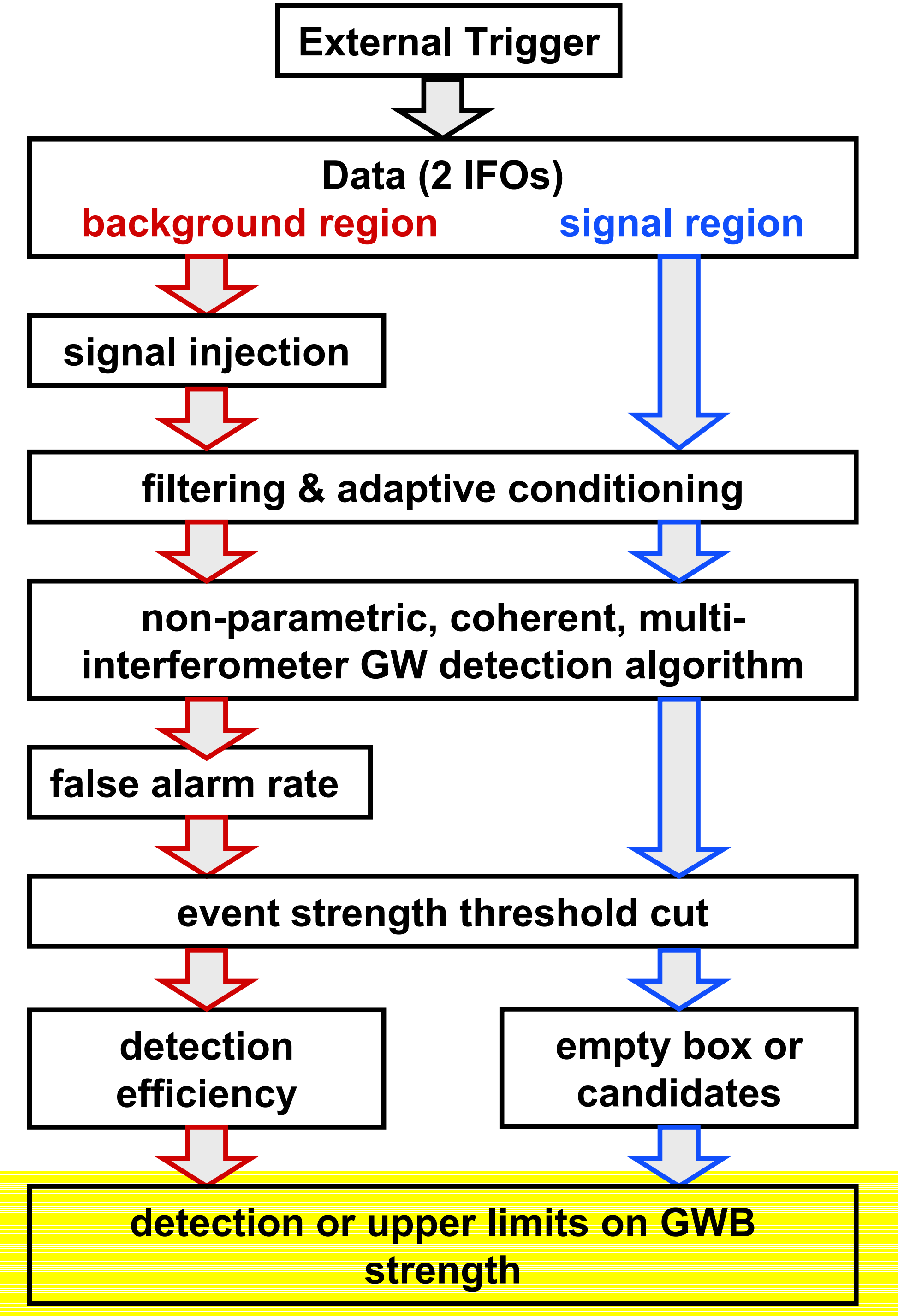


GRB 030329 Results

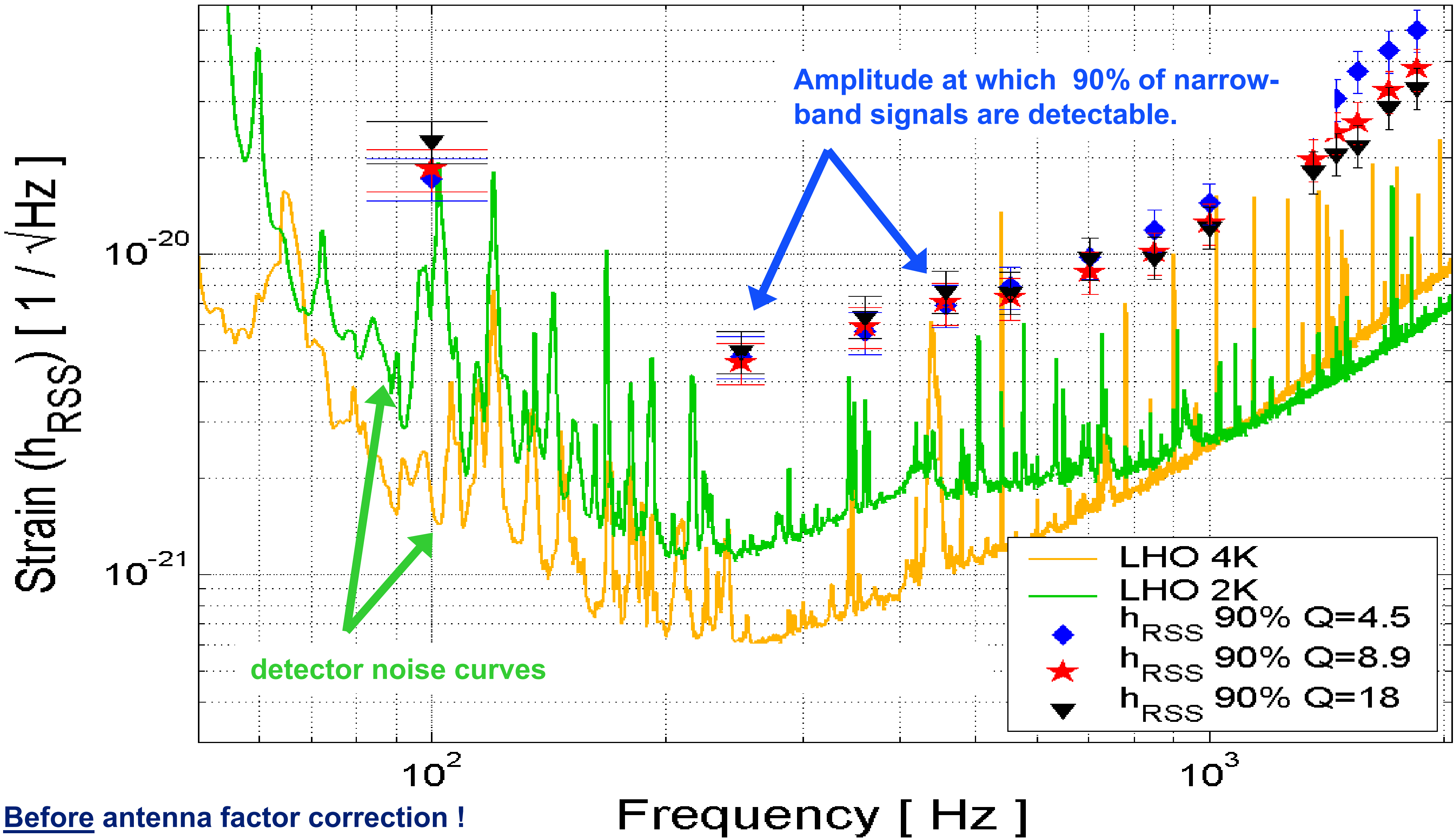


LIGO

- Detection or upper limit:
  - » GRB 030329: no candidates, so use simulations to set upper limit on GWB strength



Efficiency Measurements (Sine-Gaussians)



Before antenna factor correction !

Limit on GW Energy

- Energy in GWB (distance d from source):

$$E_{GW} = \left(\frac{2\pi^2 c^3}{G}\right) d^2 \int_0^\infty f^2 |\tilde{h}(f)|^2 df$$

- Strain h(f) depends on signal model:
  - » Polarization: antenna attenuation factor ~0.37 for optimal case.
  - » d ≈ 800Mpc (known)
  - » For h(t) sine-Gaussian at ~250 Hz, $h_{rss} \sim 6\times10^{-21}\,\mathrm{Hz}^{-1/2}$

- Order-of-magnitude estimate:

$$E_{GW} \approx 10^5\, M_O$$

Future Limits

- Energy in GWB (distance d from source):

$$E_{GW} = \left(\frac{2\pi^2 c^3}{G}\right) d^2 \int_0^\infty f^2 |\tilde{h}(f)|^2 df$$

- Best-case scenario:
  - » Optimal sky position, polarization: antenna attenuation $\Rightarrow$1.
  - » Closest GRB observed: d $\Rightarrow$ 38Mpc
  - » Initial LIGO design sensitivity: $h_{rss} \sim 2\text{x}10^{-22}\text{Hz}^{-1/2}$

- Order-of-magnitude estimate:

$$E_{GW} \approx 0.1\ M_O$$

Summary

- LIGO searches for gravitational wave bursts have begun:
  - » Targets: generic short duration (<1s) transients with power in LIGO's sensitive band of ~100-4000 Hz
  - » Un-triggered search scans entire data set looking for coincident signals in each detector
  - » Triggered search involves intensive examination of data around times of observed astronomical event (eg, GRBs)

Summary: Un-triggered Search

- Many improvements in both data quality and analysis sophistication since first search:
  - » Better data conditioning
  - » Better time resolution
  - » Use multiple GWB detection codes
  - » Cross-correlation test of candidate GWBs
- Analysis in final stages:
  - » Expect x10 improvement in rate upper limit and amplitude sensitivity (if no actual detections).

Summary: Triggered Search

- Demonstrated a cross-correlation based search for GWBs associated with GRB030329:
  - » Observed no candidates with gravitational-wave signal strength larger than a pre-determined threshold
  - » Frequency dependent sensitivity of our search at the detector was ~10-21/√Hz
  - » Set upper limits on the associated gravitational wave strength at the detector
  - » May achieve sub-solar-mass upper limits on GWB energy with initial LIGO detectors.

In Development

- Un-triggered modeled searches using optimal filtering (black-hole ringdowns, supernovae)
- Collaborative searches with TAMA300, GEO600 interferometers
- Collaborative GRB-triggered search with HETE (in negotiation).