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

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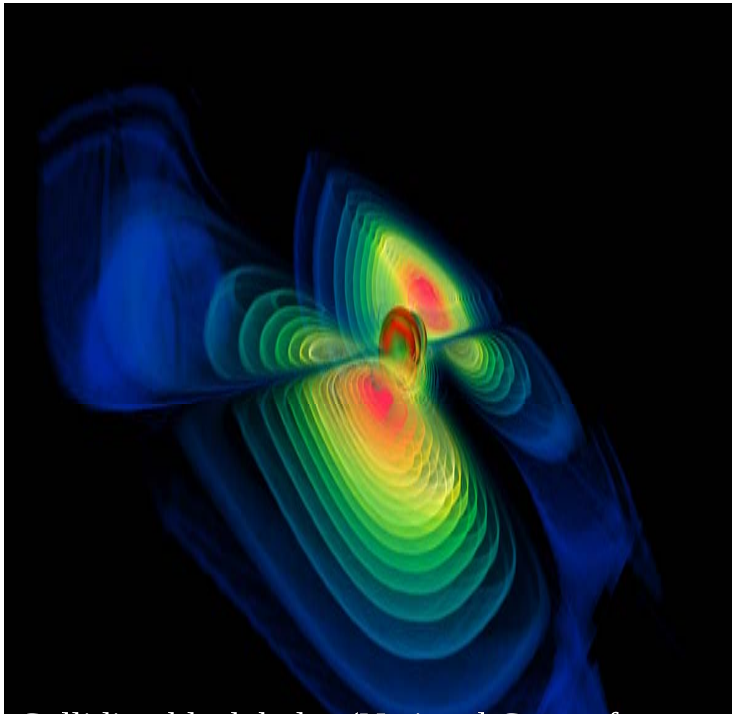
LIGO-G040232-02-Z

# 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 in the LIGO frequency band:
  - » core-collapse supernovae
  - » merging, perturbed, or accreting black holes
  - » gamma-ray burst engines
  - » others?
- Gravitational waves could provide probe of these relativistic systems.

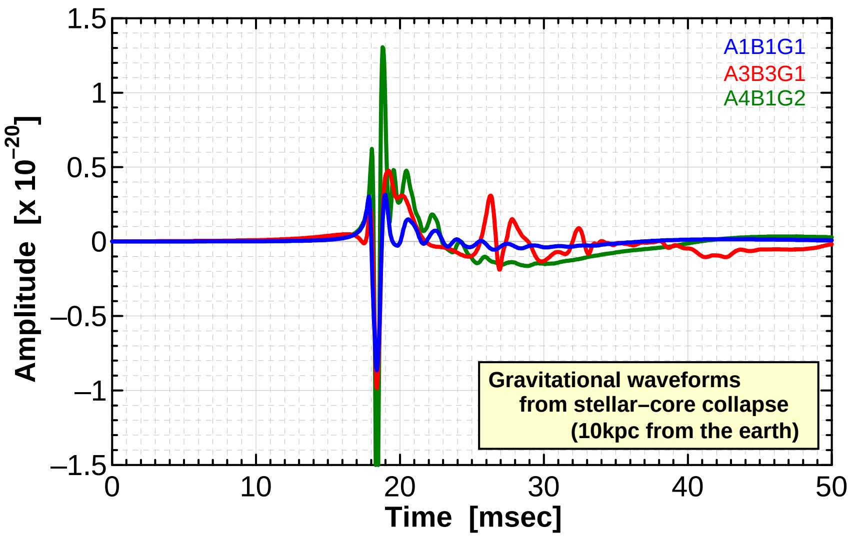


Colliding black holes (National Center for Supercomputing Applications)

# 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: *we do not use templates in our searches!*
  - » Search for generic GWBs of duration ~1ms-1s, frequency ~100-4000Hz.

**possible supernova waveforms T. Zwerger & E. Muller, Astron. Astrophys. *320* 209 (1997)**



# Bursts Analysis: Goals

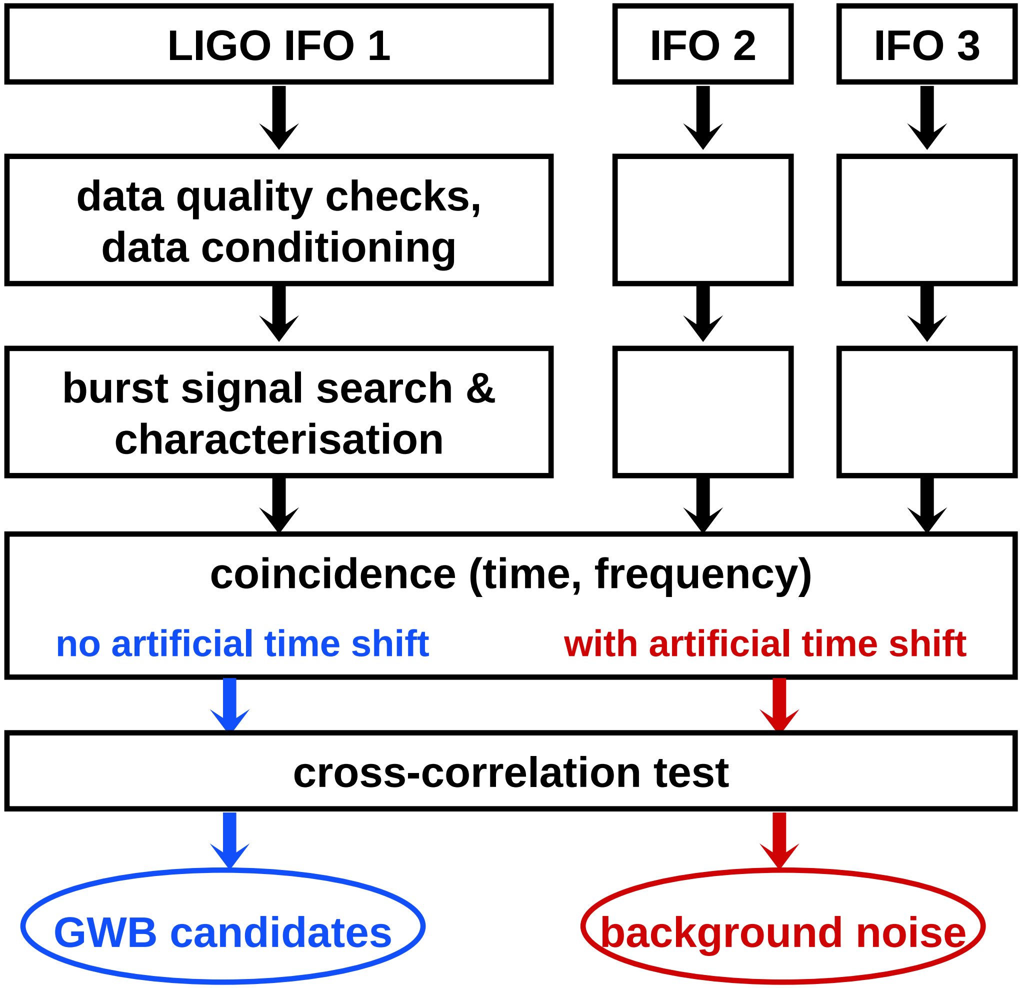
- Detect or set upper limit on the rate of detectable GWBs.
  - » Detect or set upper limit on strength of GWBs associated with specific astronomical events (triggered search).
- Interpret in terms of source and population models.
- Establish methodology and validate procedures.

# Un-triggered searches for GWBs in the LIGO S2 data

# Un-triggered Search: Methodology

- Count number of potential GWBs in the data
  - » Require GW candidates to be coincident in all detectors
- Estimate false alarm rate due to background noise
  - » Repeat coincidence test 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

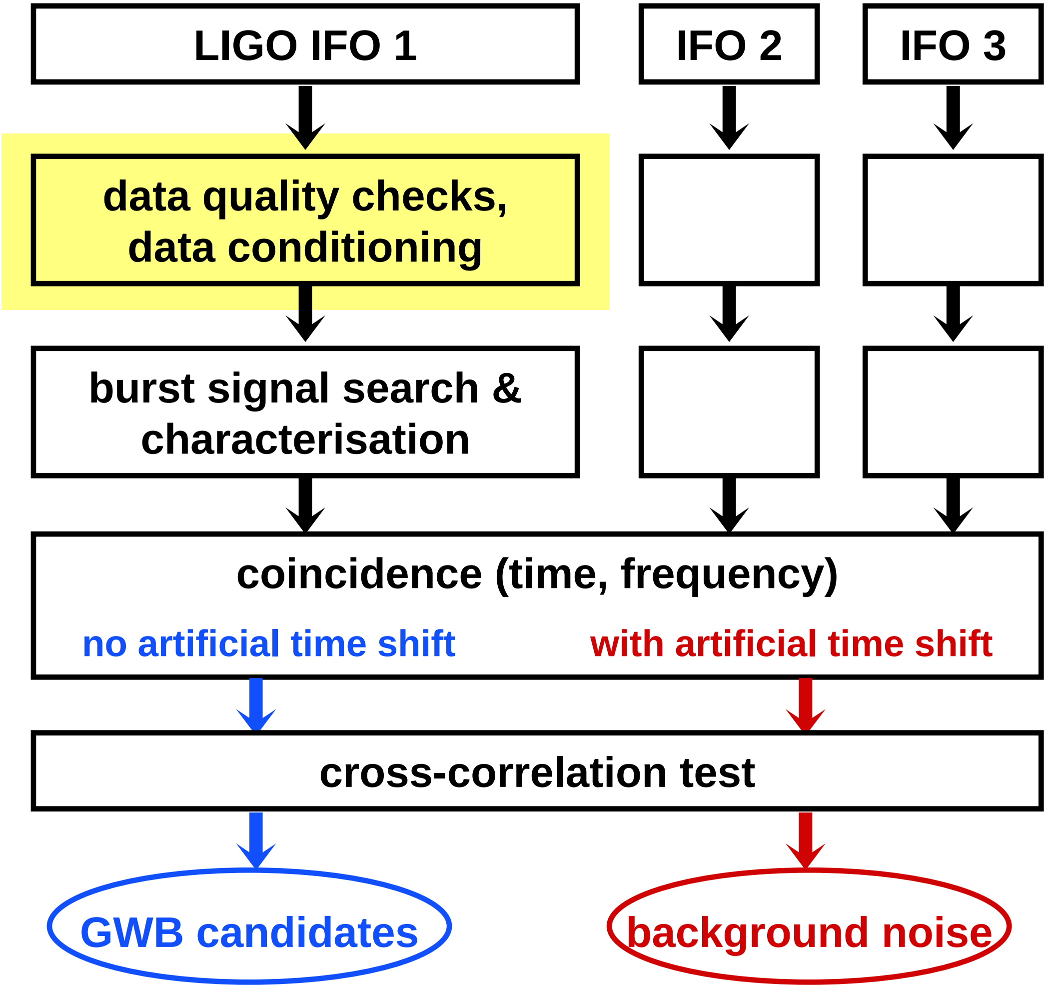
# Un-triggered Analysis Procedure



# Data Quality & Conditioning

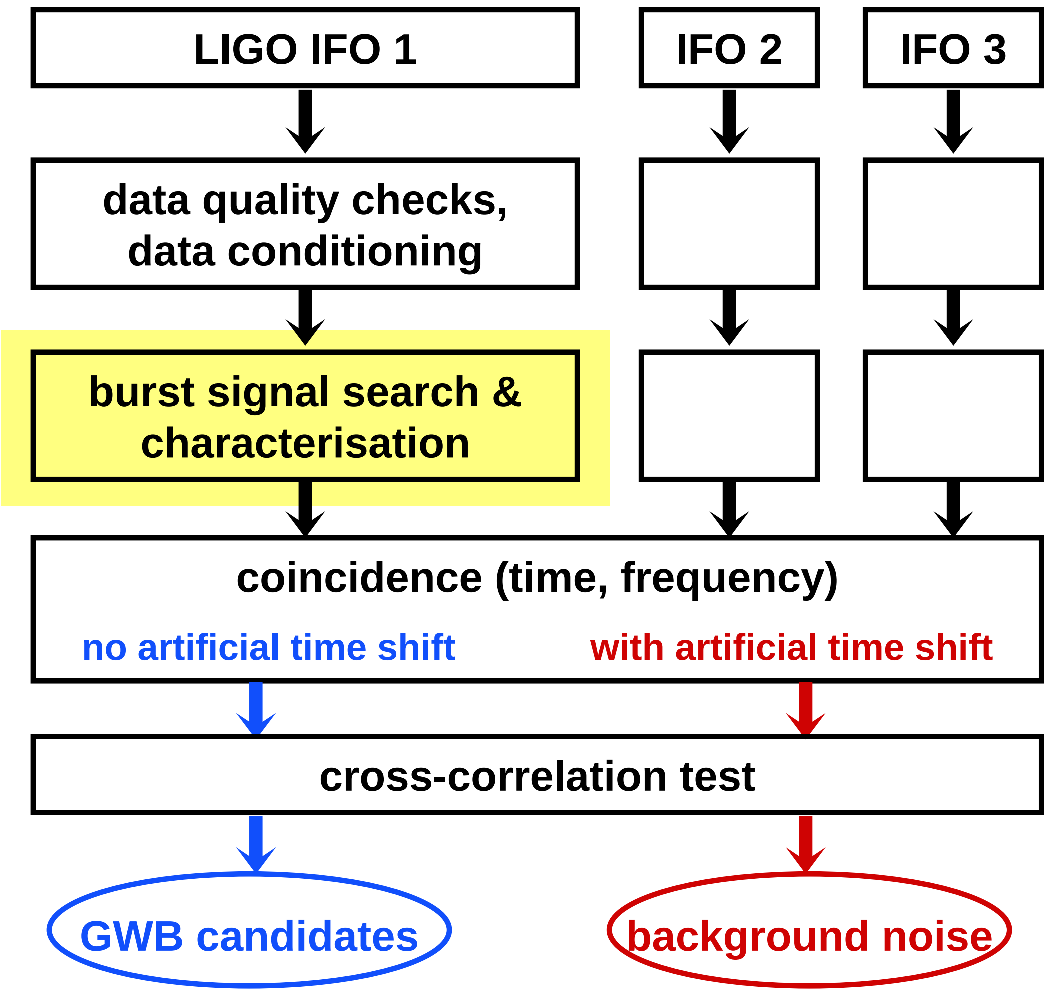
- Discard data that do not pass quality criteria (eg, noise levels) - few %
- High-pass filtering
- Base-banding
- Line removal
- Whitening using linear predictor filters

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

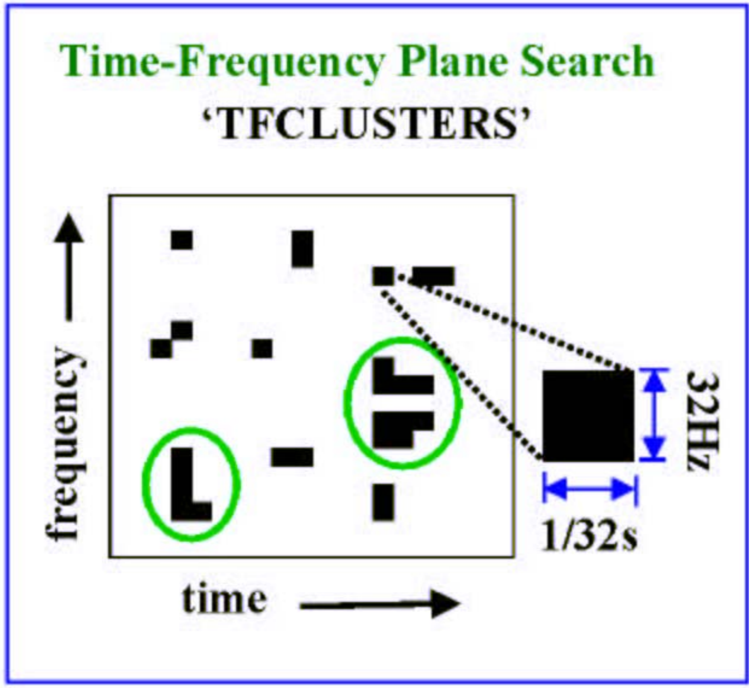


# Burst Signal Identification

- » Multiple detection codes:
  - – TFClusters (freq domain)
  - – Excess Power (freq domain)
  - – WaveBurst (wavelet domain)
  - – BlockNormal (time domain)
- » Adaptive thresholds to handle non-stationary noise
- » Tuned for maximum sensitivity 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.

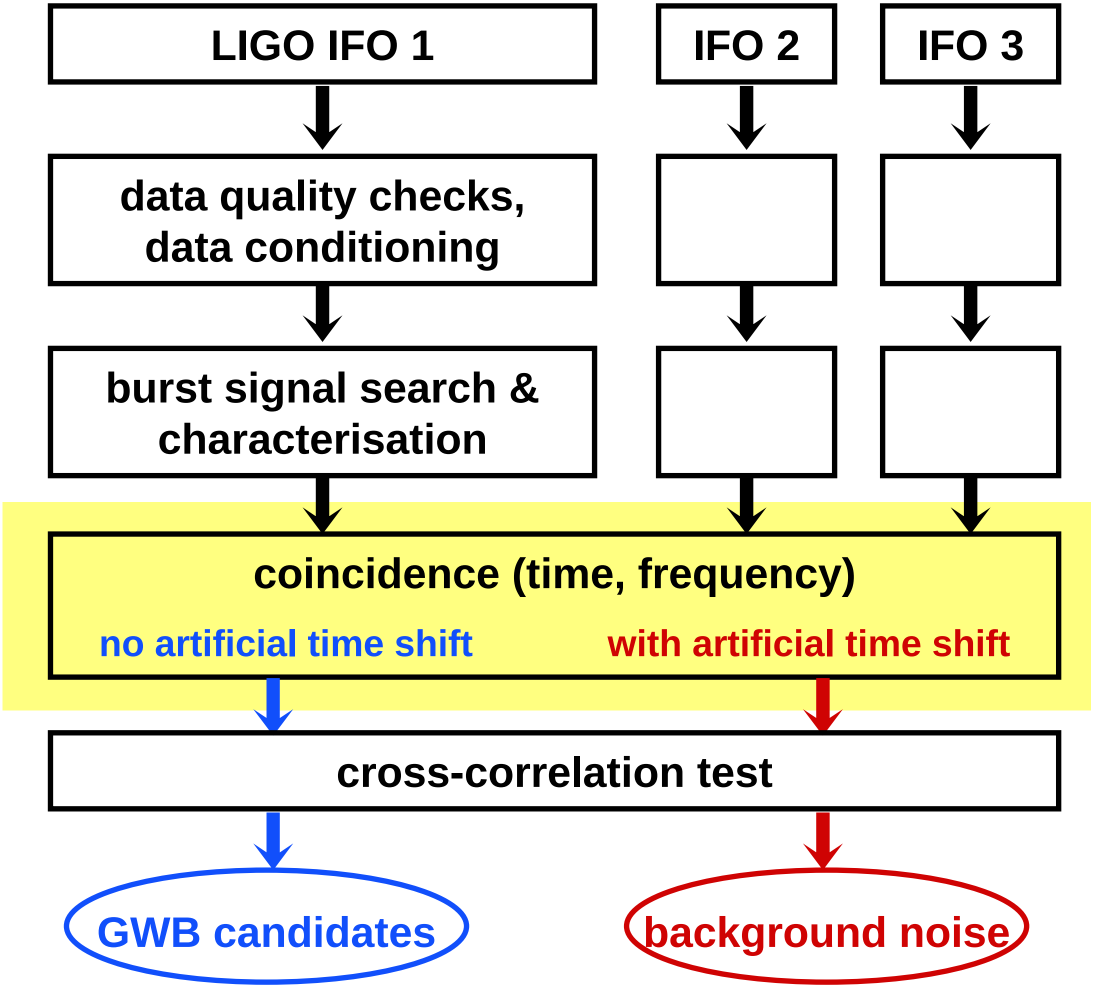
**J. Sylvestre, Phys. Rev. D *66* 102004 (2002)**

# Coincidence

- » Require simultaneous detection in each IFO (typically within ~30ms)
- » Require frequency match

- » Estimate rate of accidental coincidence of noise fluctuations (false alarms) using artificial time shifts

- » S1: 500ms coincidence window (!)

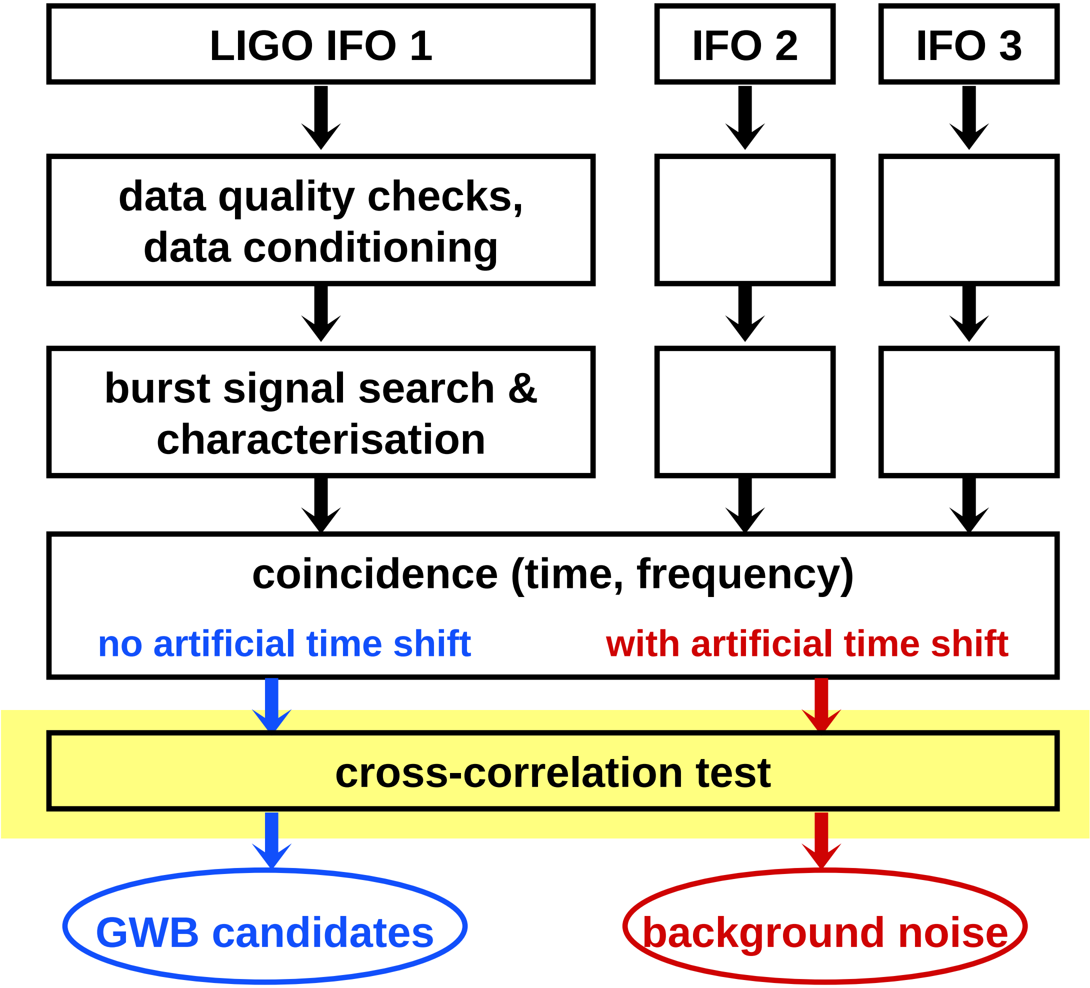


# Cross-Correlation Test

- » Test waveform consistency between detectors
- » 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
- » Entirely new since S1



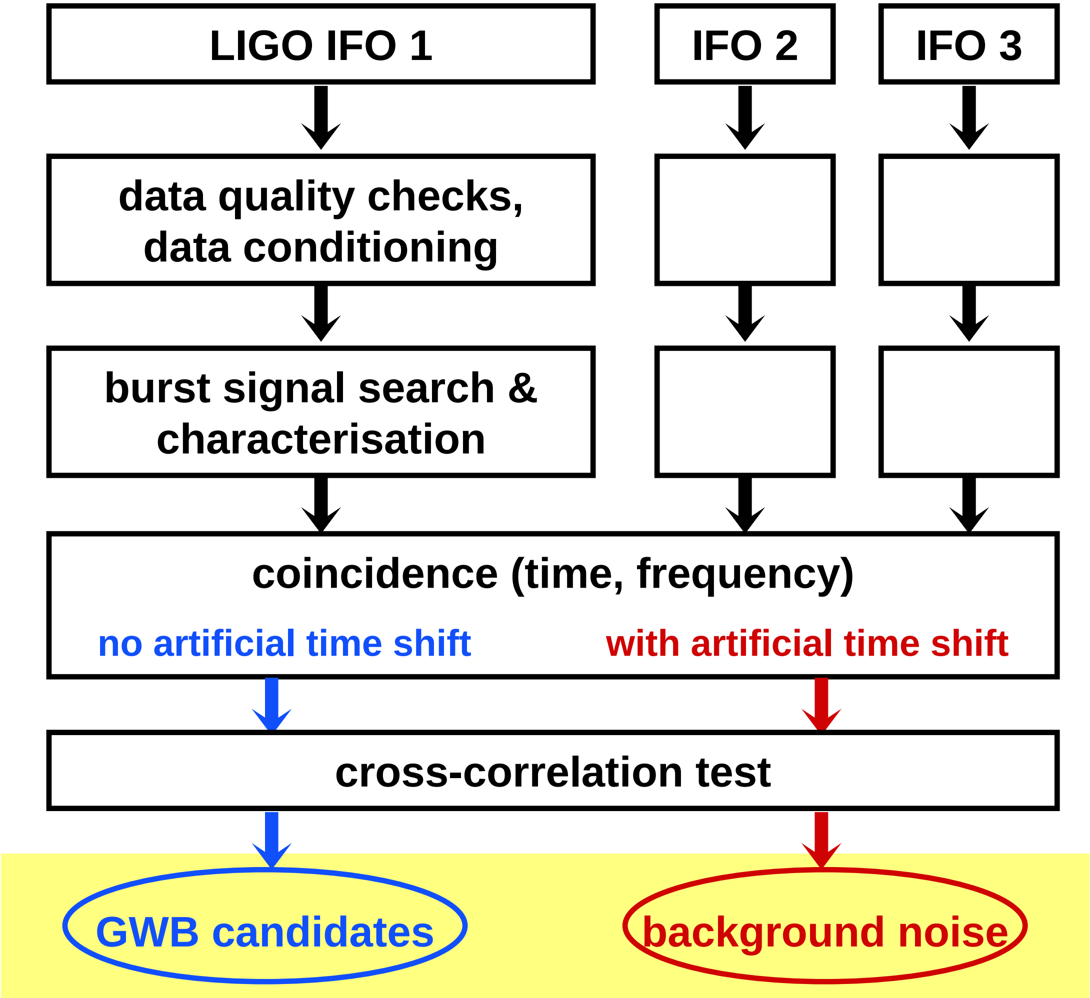
# Detection / Upper Limit

» Compare number of coincident events to that expected from background noise

**[G. Feldman & R. Cousins, Phys. Rev. D 57 3873 (1998)]**

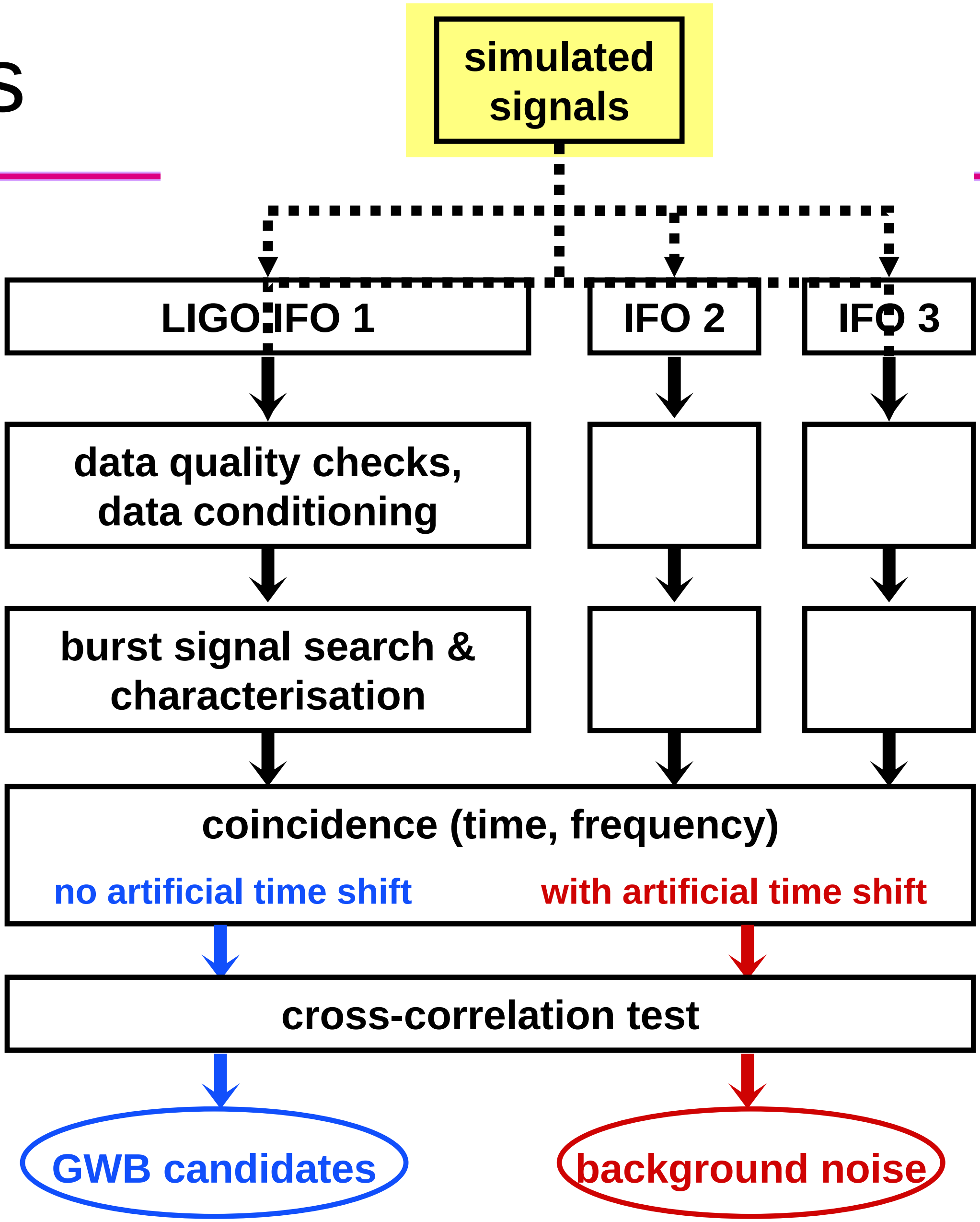
» Significant excess is possible detection

» No excess ⇒ upper limit



LIGO

# Simulations



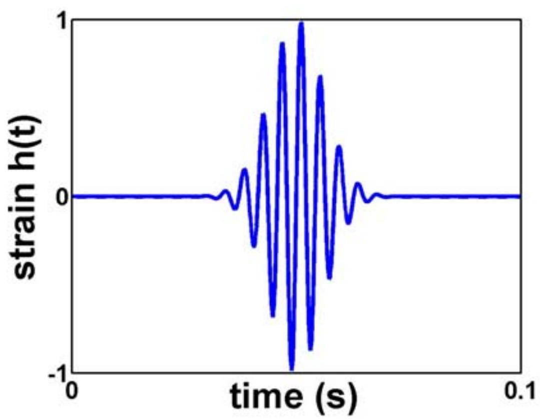

» Add simulated GWBs to IFO control signals or output data

» Used to estimate sensitivity to real GWBs & to tune analysis (eg: coincidence windows).

# Ex: Gaussian-modulated sinusoids

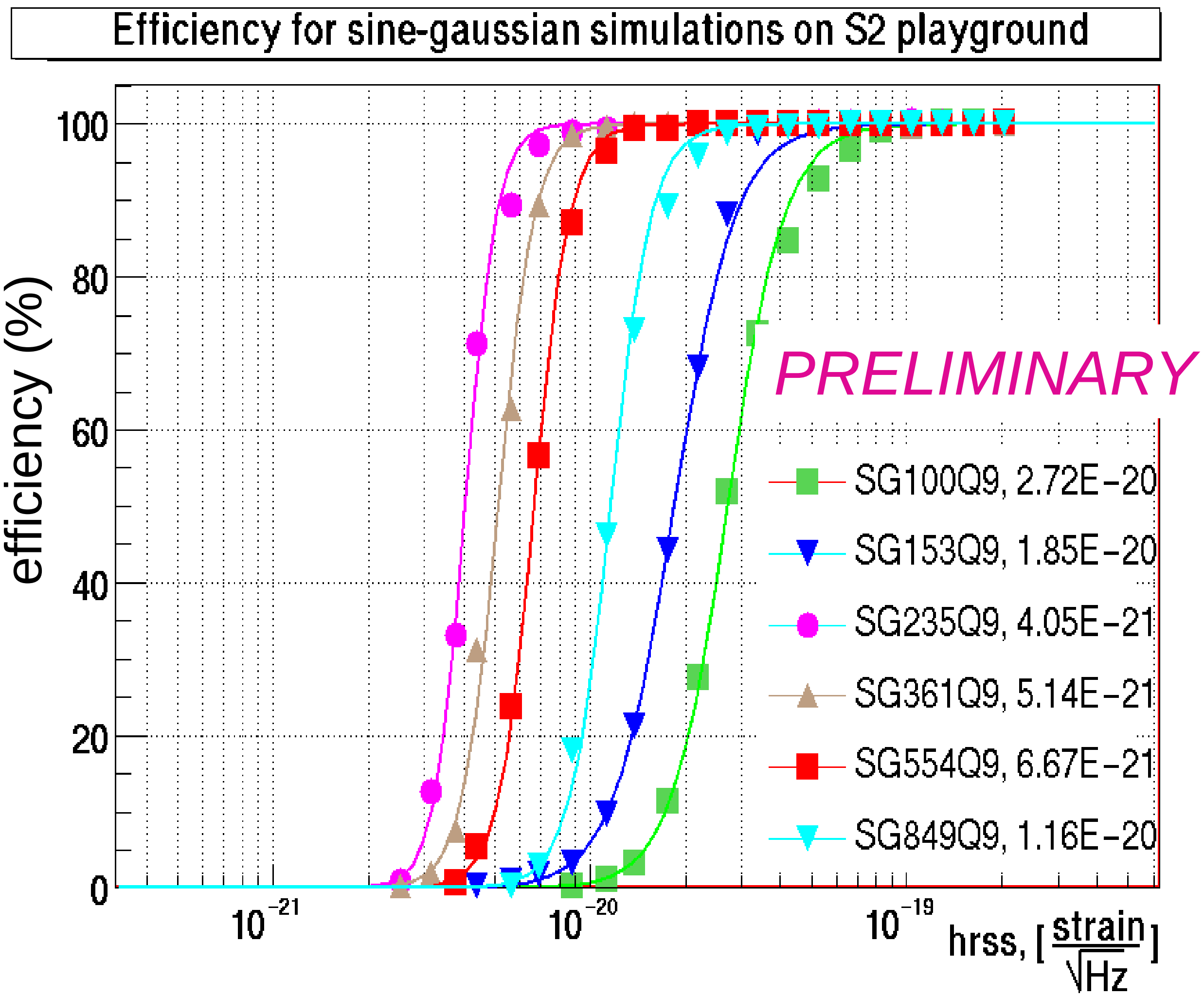
WaveBurst search code (wavelet based).

Injected Signals:




Amplitude Measure:

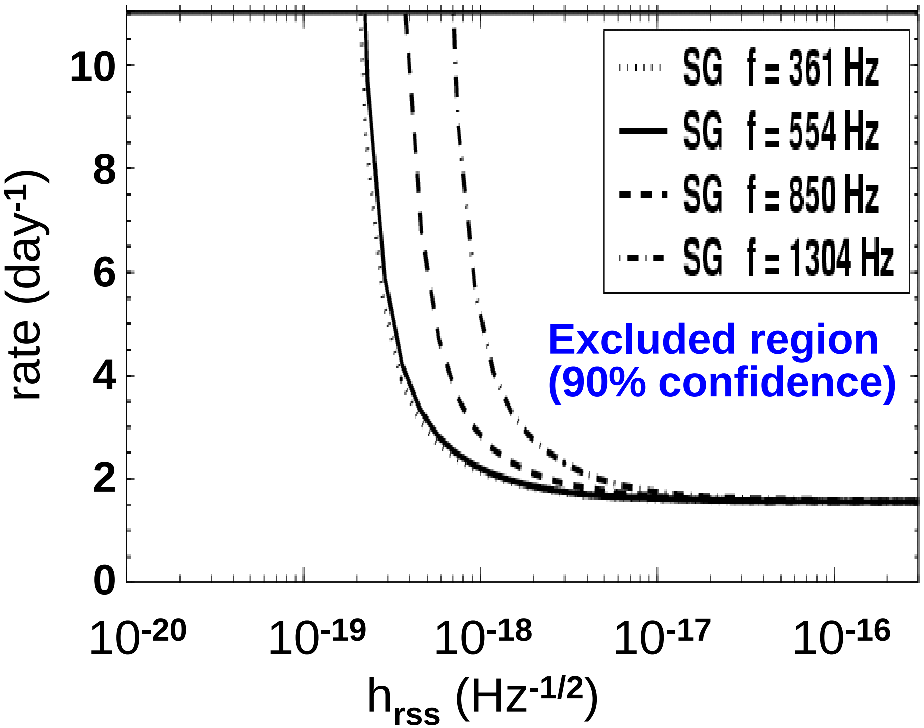
$$h_{rss} = \sqrt{\int_0^\infty |h(t)|^2 dt}$$



# Upper Limits

- Upper limit on rate is a function of signal strength.
- LIGO Science Run 1:
  - » rate: R ≲ 1.6/day
  - » sensitivity*: $h_{rss}$ ≳ $4\times10^{-19}$ $Hz^{-1/2}$
- LIGO Science Run 2:
  - » ***Analysis in final stages.***
  - » ***Expected rate:*** R ≲ 0.2/day
  - » ***Expected sensitivity*:*** $h_{rss}$ ≳ $O(10^{-20})$ $Hz^{-1/2}$

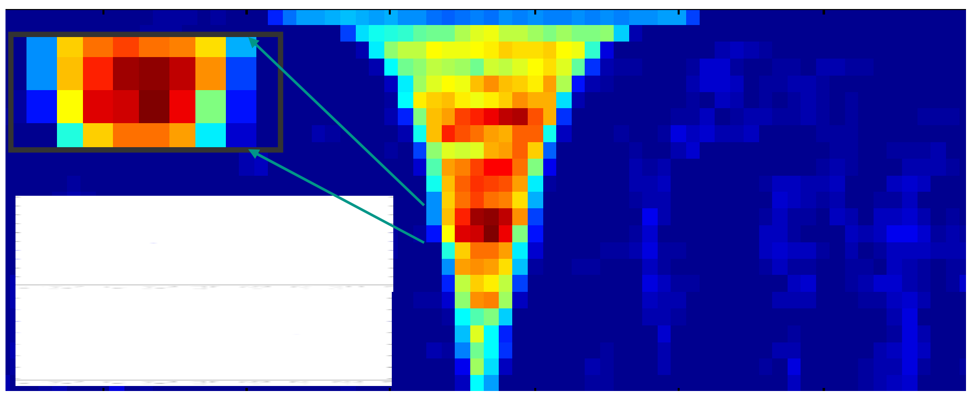
**S1 Example: sine-Gaussian impulses**




* averaged over sky directions, signal polarization

**gr-qc/0312056, Phys. Rev. D (to appear)**

# Search for the gravitational-wave signature of GRB030329



# Externally initiated searches for gravitational waves

- Many events which may produce GWBs are also visible in EM or neutrino bands
  - » supernovae
  - » gamma-ray bursts (GRBs)

- Opportunity for targeted coherent search for gravitational-wave counterpart
  - » Concentrate on one extraordinary event: GRB030329

# Gamma-Ray Bursts

Known:

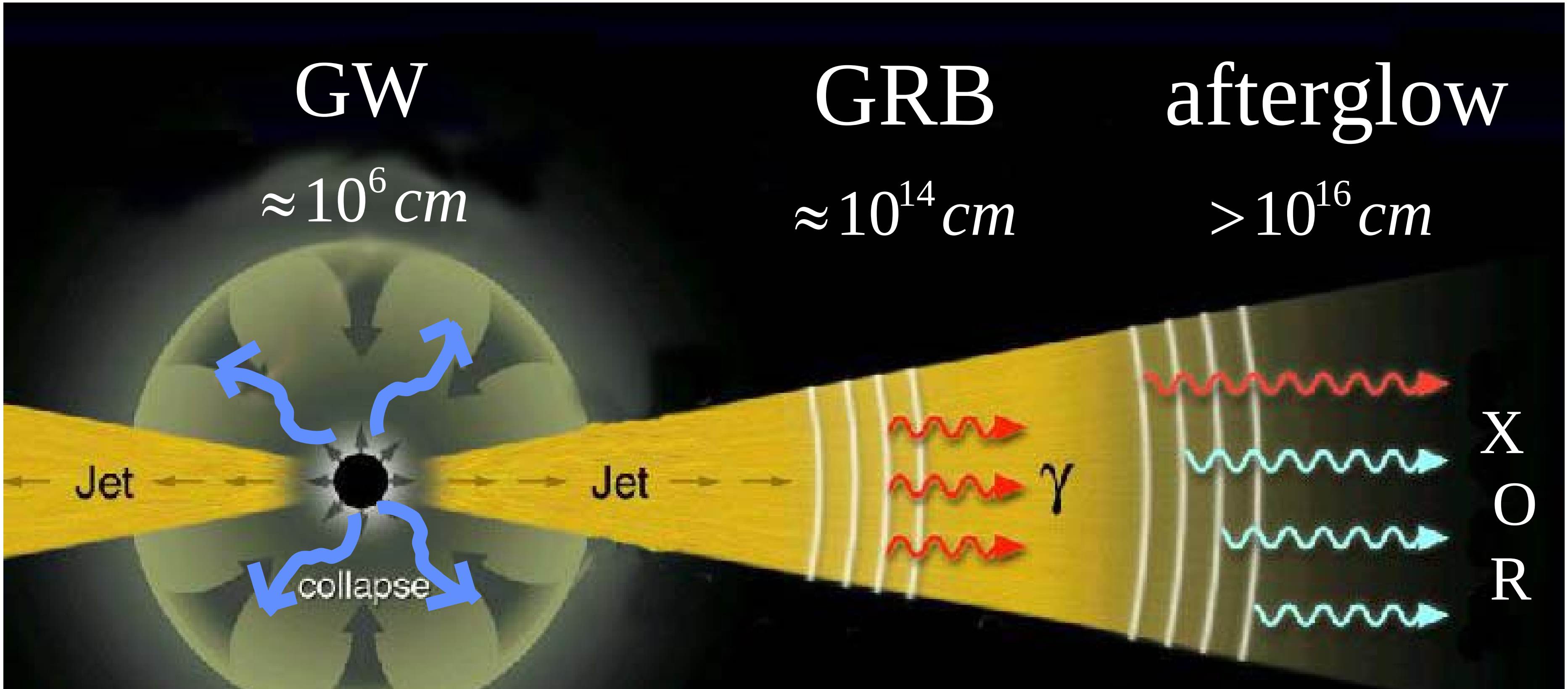
- Bright, transient bursts of gamma rays
- Observed at rate ~1/day
- Duration: 0.01-2s (short), 2-100s (long)
- "Afterglow" seen in other wavelengths (long-duration GRBs)
    - cosmological distances (z~1)
    - highly energetic (~$10^{51}$ergs)
    - beamed (1 GRB visible out of every ~500)

Thought:

- Central engine is solar-mass accreting black hole, perhaps resulting from hypernova/collapsar or compact binary inspiral.
    - » Violent, strongly relativistic processes may dump significant fraction of a solar mass into gravitational waves in the LIGO band

**P. Meszaros, Ann. Rev. Astron. Astrophys. *40* (2002)**

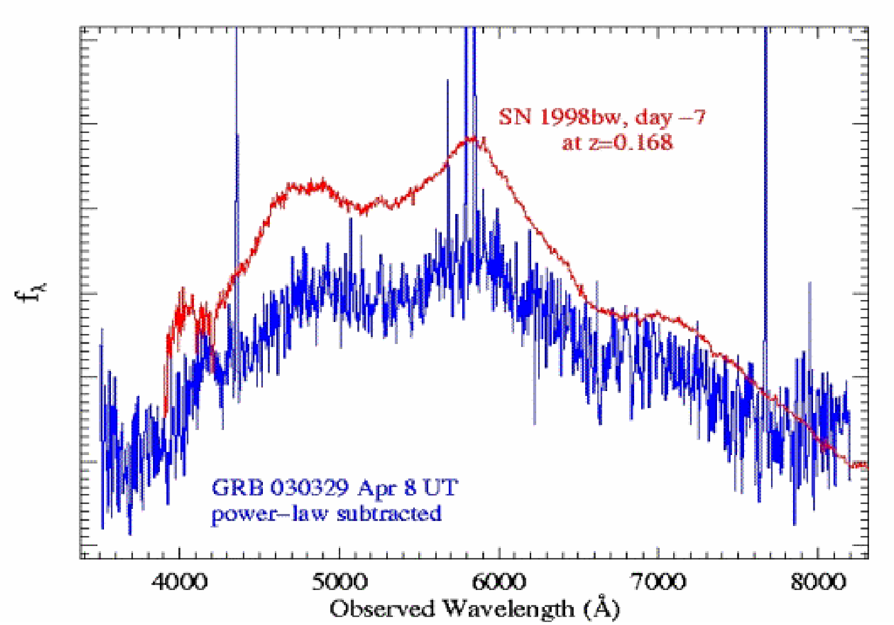
# Fireball Shock Model (long GRBs)




GWs could provide most direct probe of GRB physics

# GRB030329: “Monster GRB”

- Detected March 29 2003 by HETE-2 & Wind satellites
- One of closest ever seen with known distance
  - » z=0.1685
  - » d=800Mpc
- Provides strong evidence for supernova origin of long GRBs.
- LIGO was operating!
  - » Hanford 2km & 4km
  - » look for GWB!




**http://cfa-www.harvard.edu/~tmatheson/compgrb.jpg**

# 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")
  - » possible detection if cross-correlation around trigger time crosses threshold

**L. Finn, S. Mohanty, J. Romano, Phys. Rev. D *60* 121101 (1999)**

**P. Astone et al, Phys. Rev. D 66 102002 (2002): NAUTILUS & EXPLORER + 47 GRBs from BeppoSAX: $h_{rms} < 6.5 \times 10^{-19}$ at 95% confidence.**

# Signal Region for GRB030329

- Relative delay between GWB and GRB is predicted to be ~O(s)

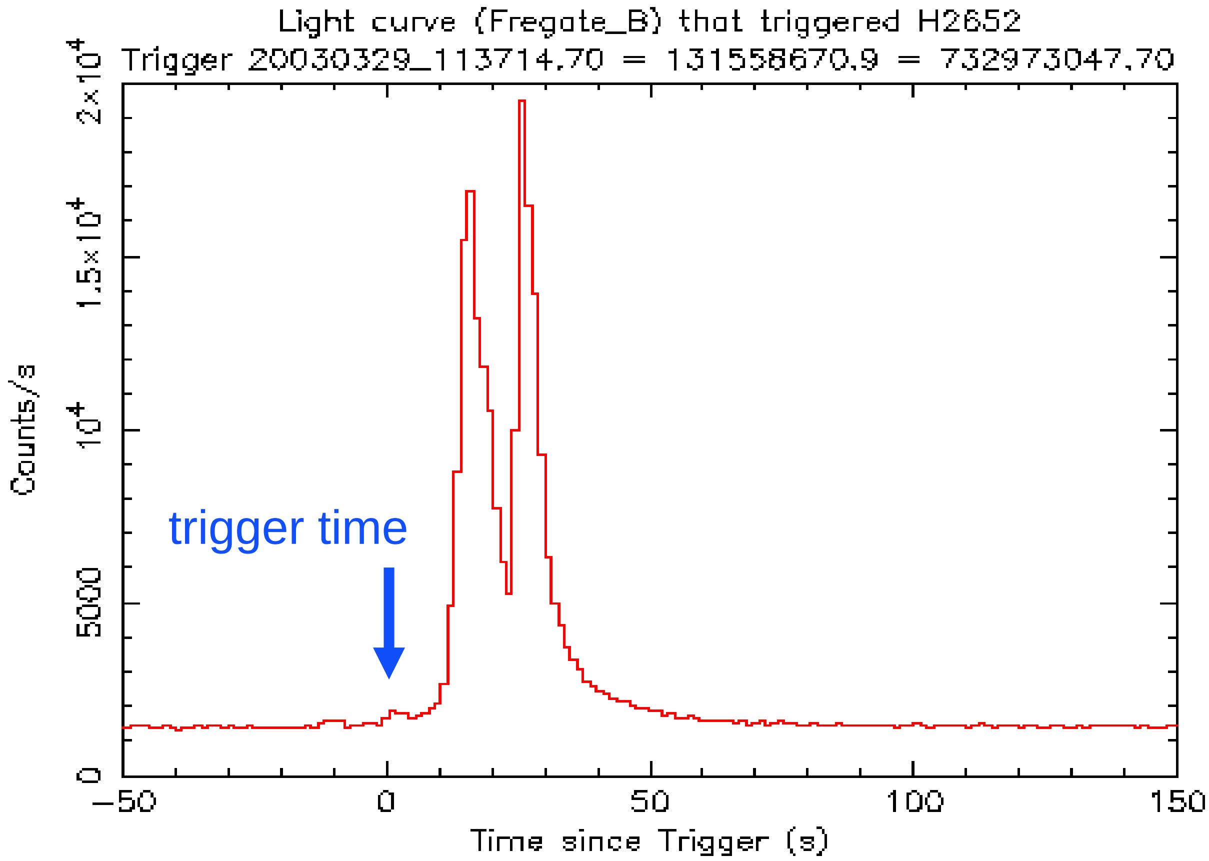
signal region: [ $t_0$-120s, $t_0$+60s ]

background region: [ $t_0$-12000s, $t_0$+4000s ]
(excluding signal region)

- GWB duration predictions vary from O(10ms) to O(1s)
  - » Concentrate on short bursts: ~1-200ms

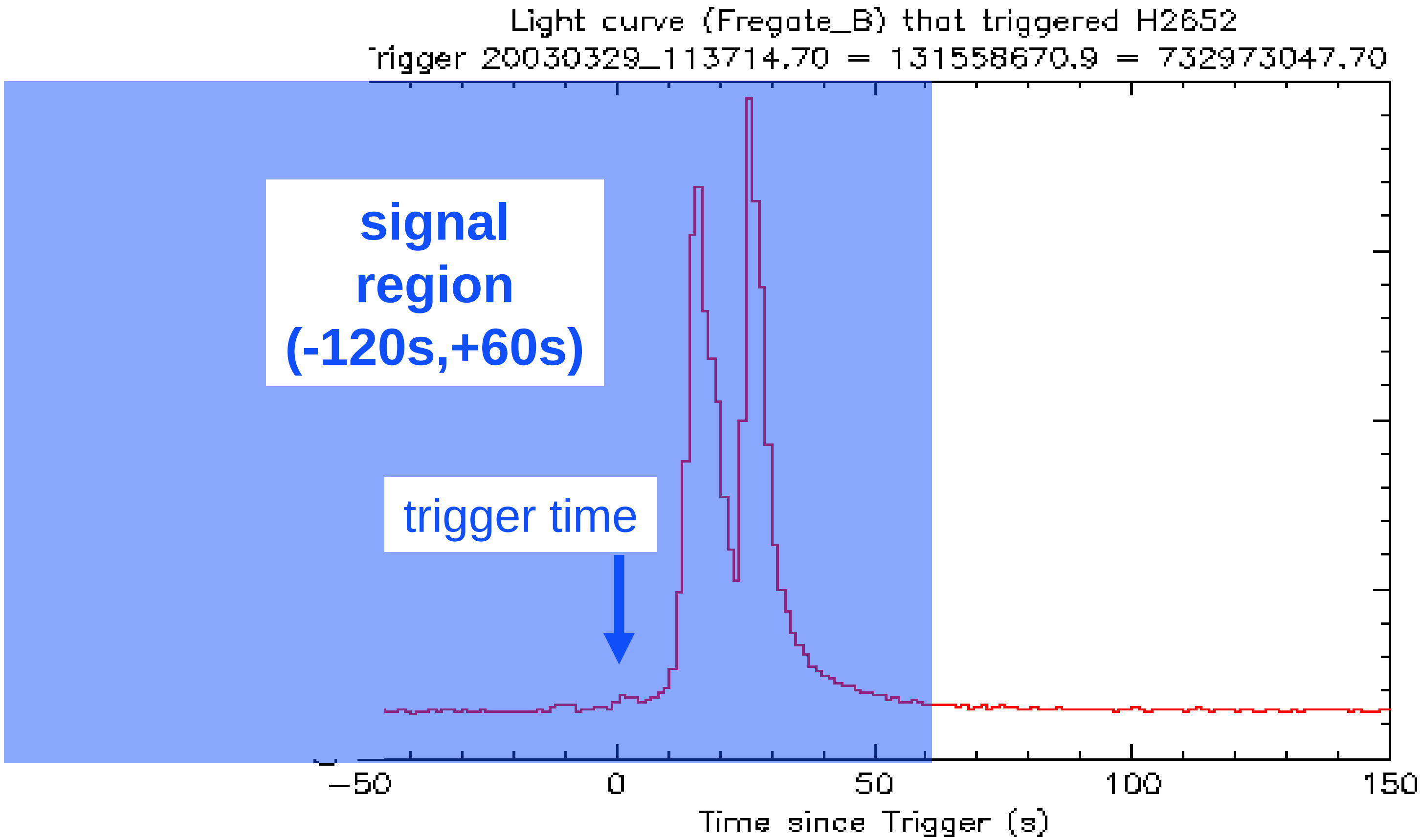
# Signal Region for GRB030329

Gamma-ray flux measured by HETE satellite (5-120 keV band)



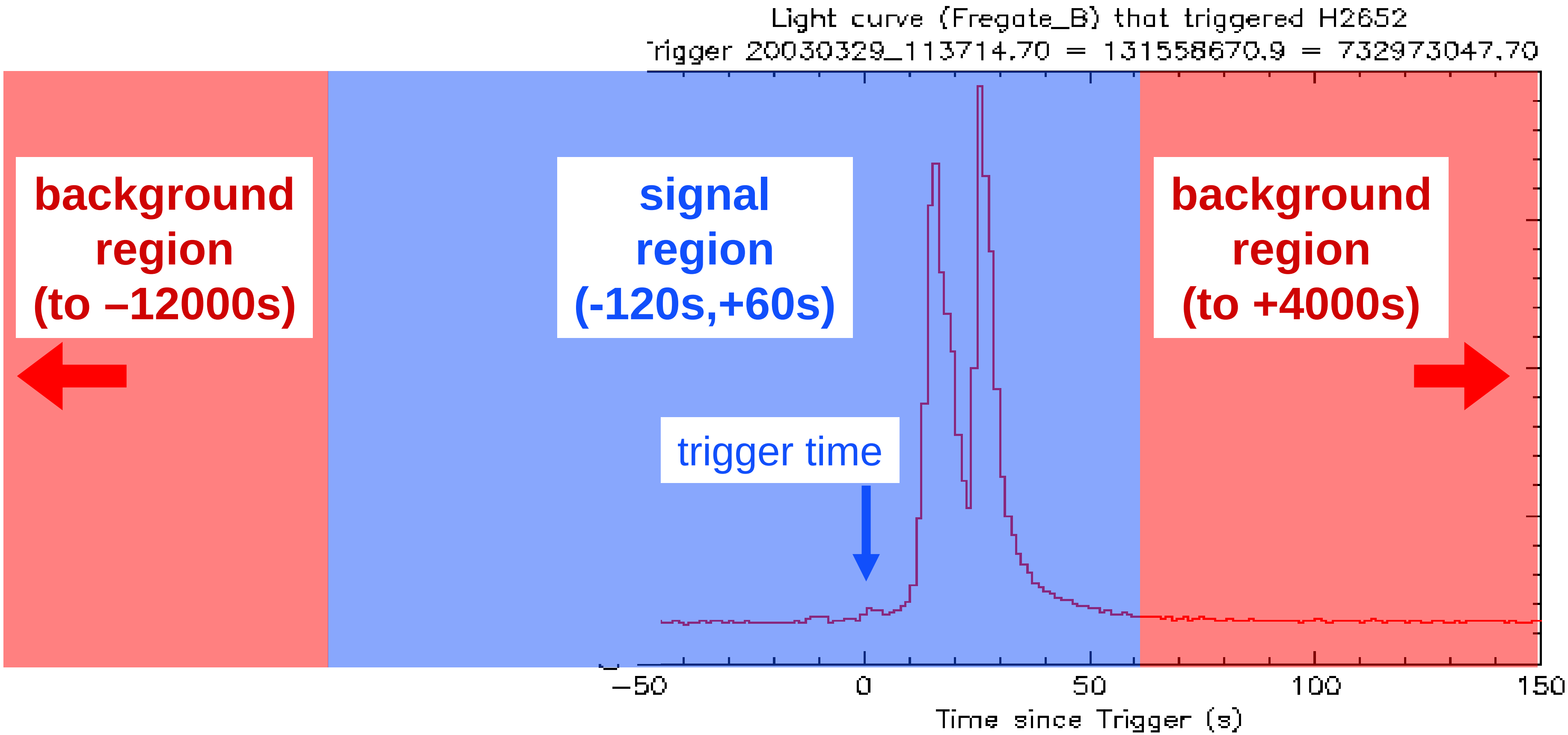

**http://space.mit.edu/HETE/Bursts/GRB030329/**

# Signal Region for GRB030329




**http://space.mit.edu/HETE/Bursts/GRB030329/**

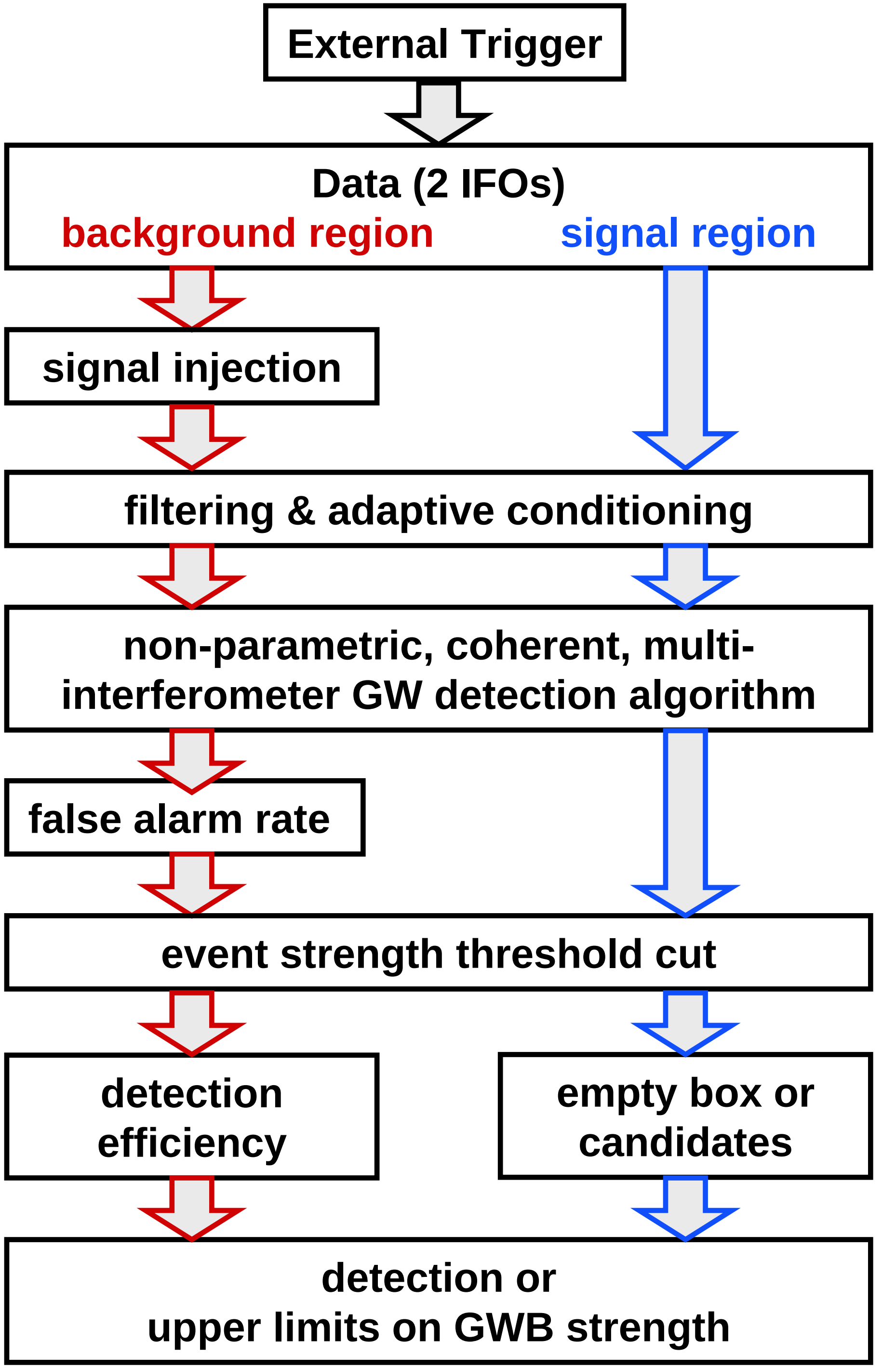
# Signal Region for GRB030329




**http://space.mit.edu/HETE/Bursts/GRB030329/**

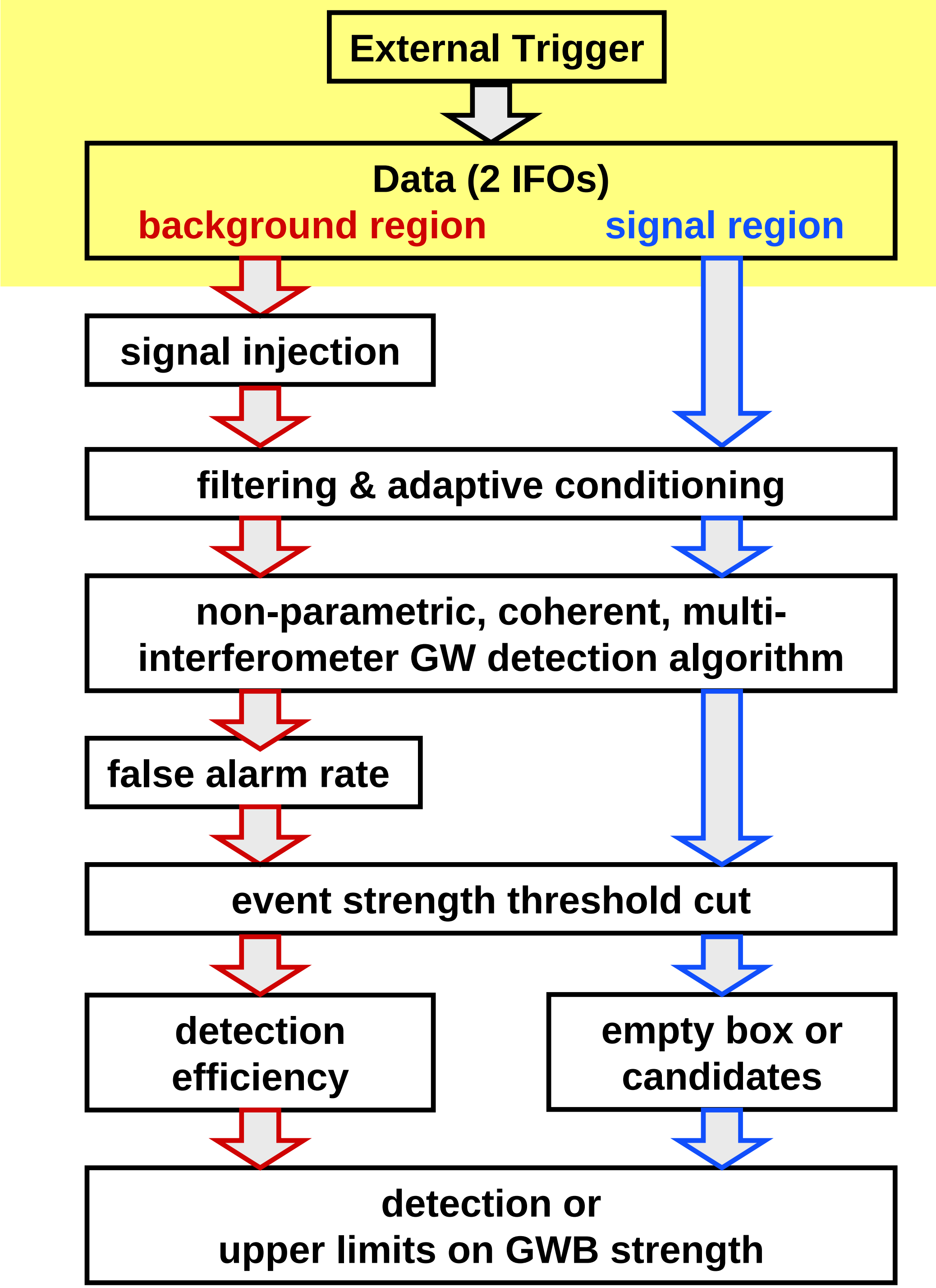
LIGO

# Externally Triggered Analysis Procedure



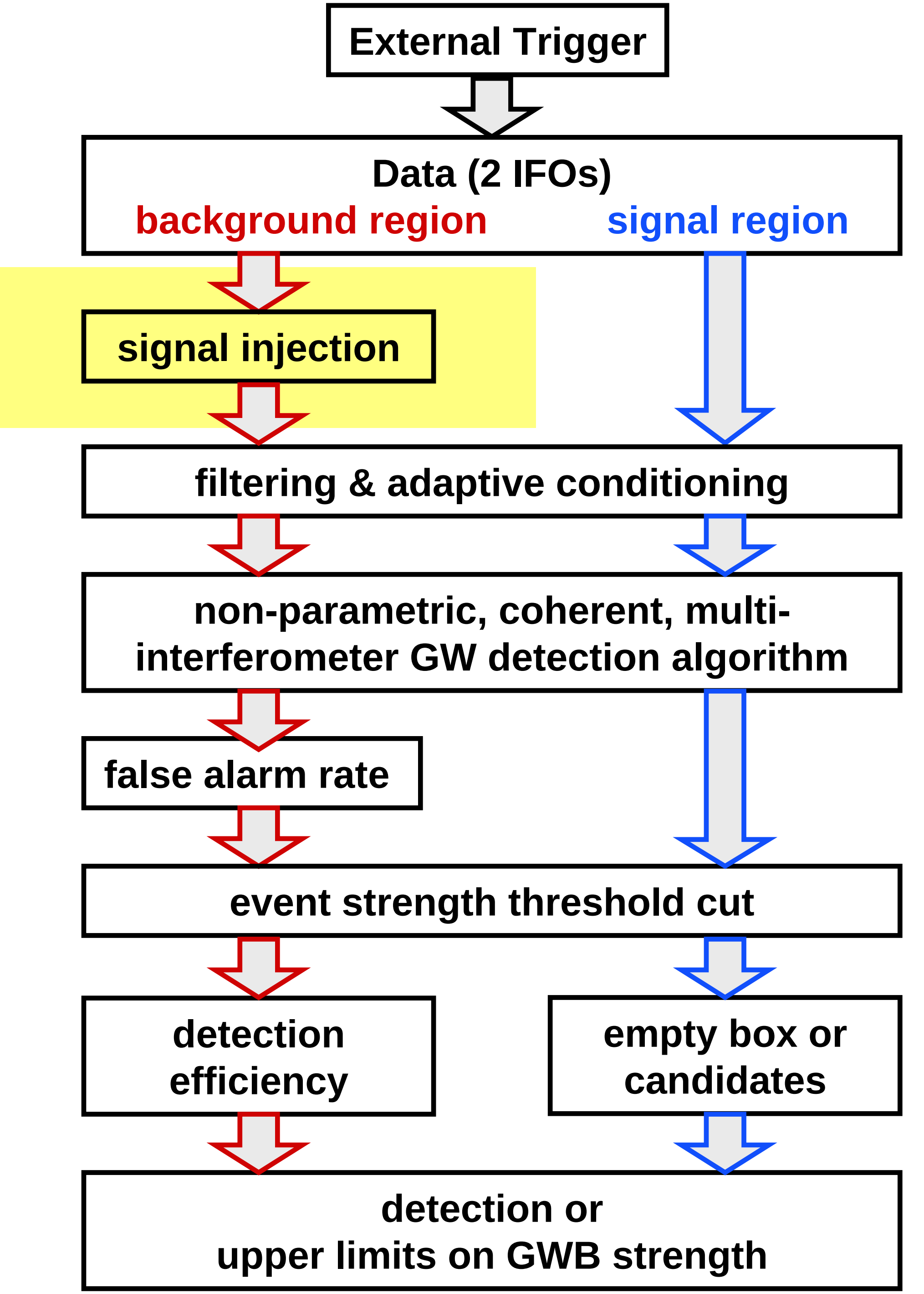
LIGO

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

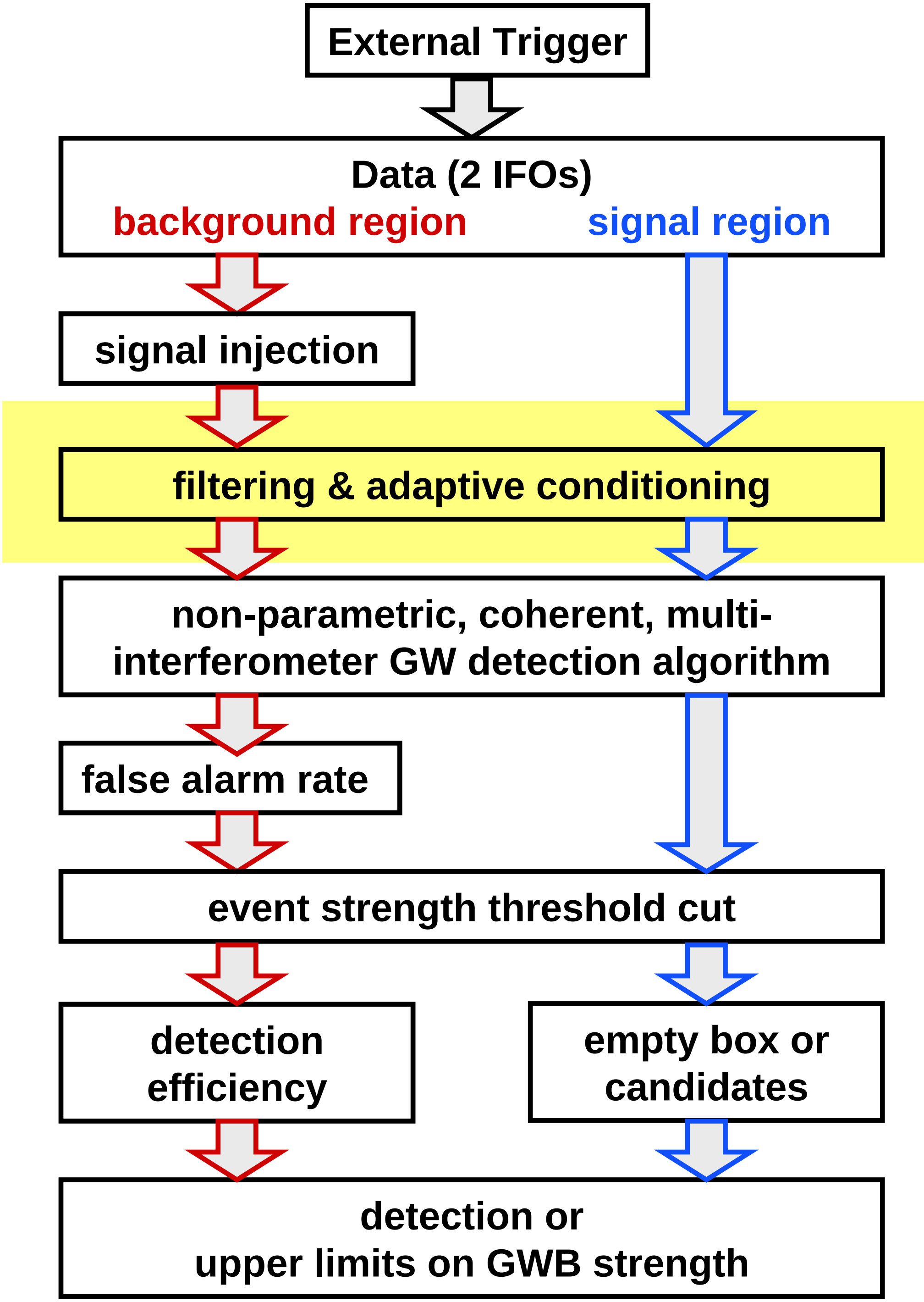


LIGO

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



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

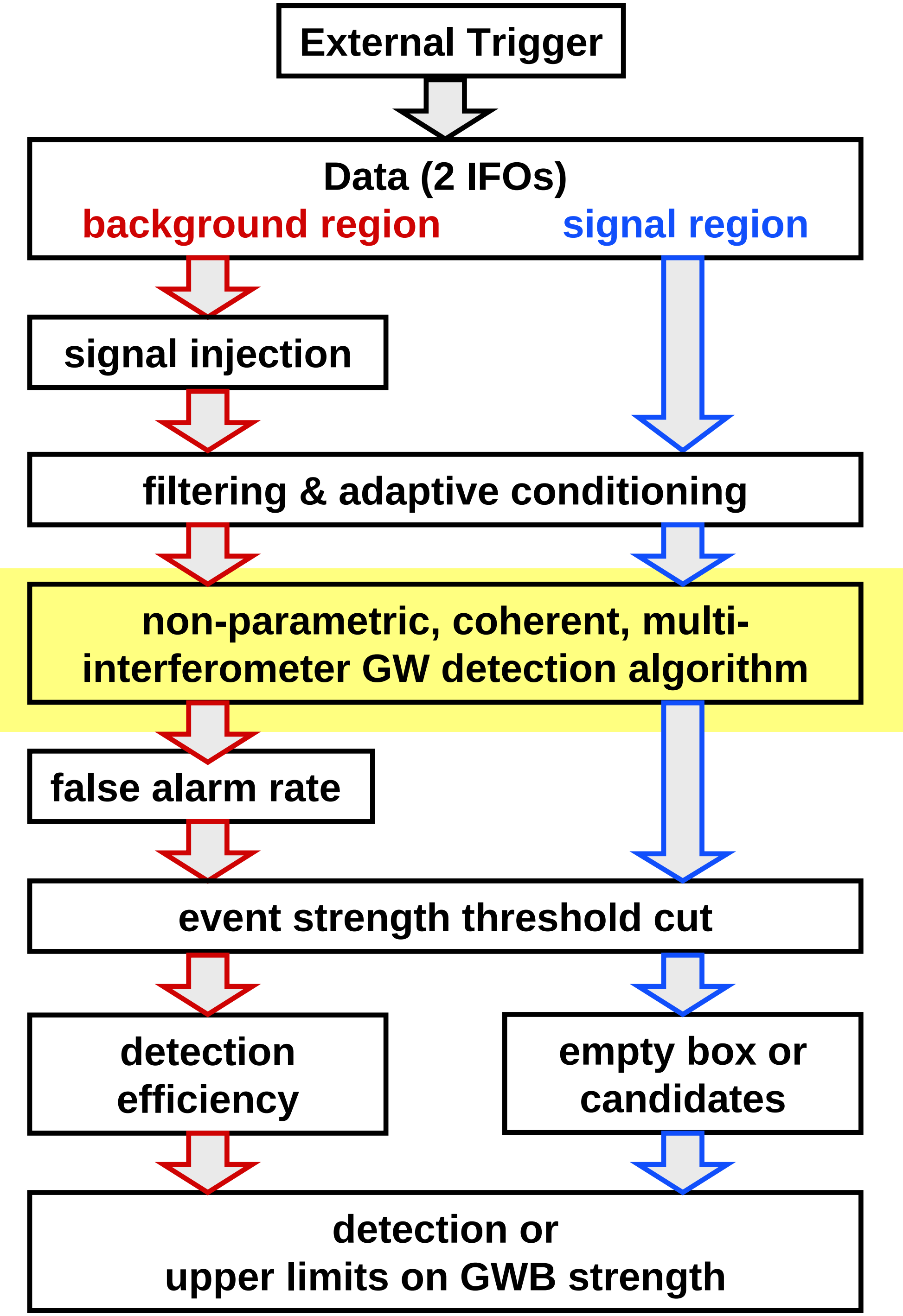


LIGO

- Cross correlation of data streams $x$, $y$ at time $\tau$, offset $\Delta t$, integration time $T$:

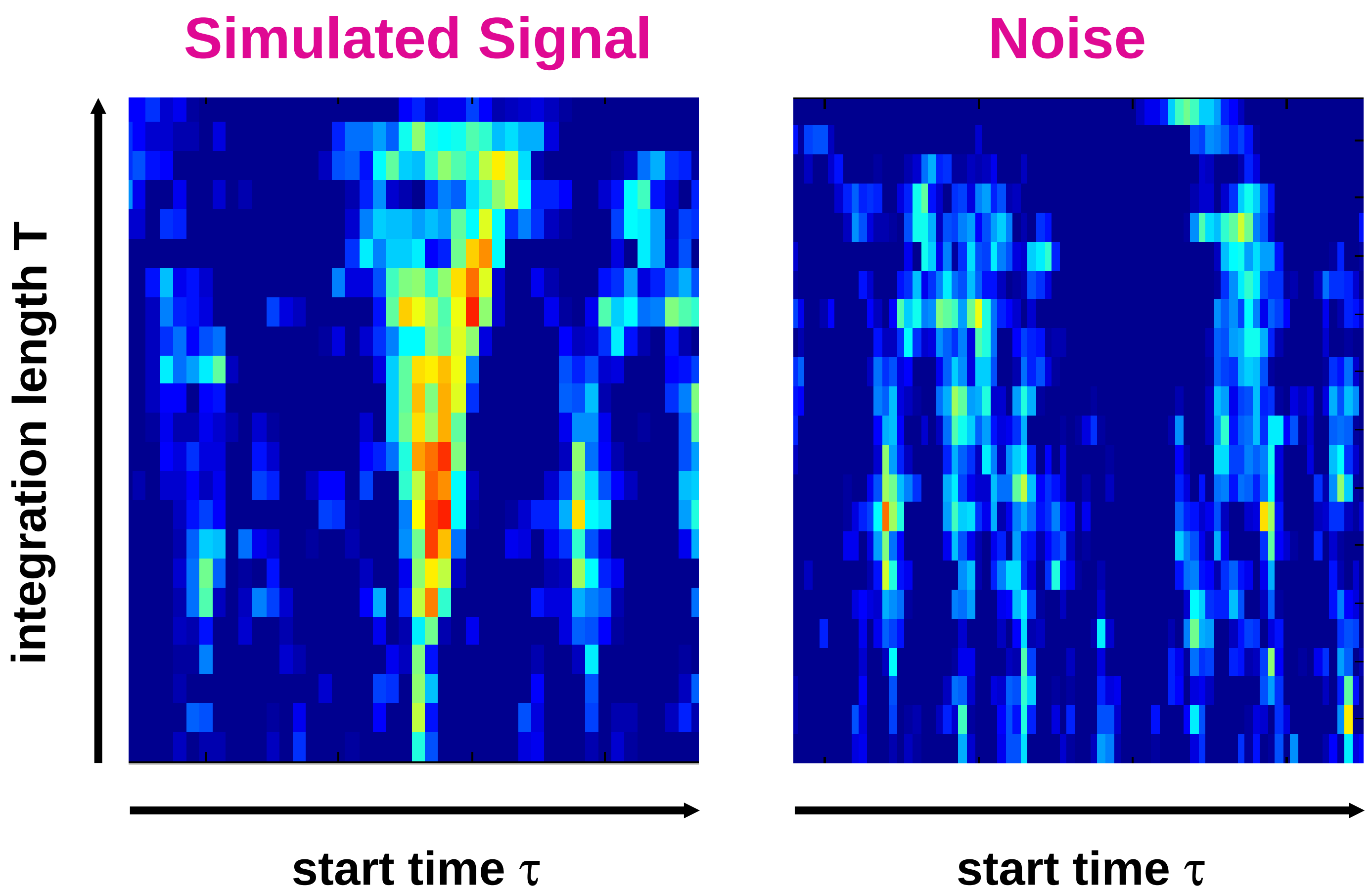
$$S(\tau, T) = \int_{-T/2}^{T/2} dt\, x(\tau + t) y(\tau + t + \Delta t)$$

- Scan over values:
  - » start time $\tau$: [-120,60]s around GRB time
  - » integration length $T$: [4,128]ms for short signals
  - » offset $\Delta t$: average over [-5,5]ms to allow for calibration uncertainties (ideally $\Delta t = 0$)

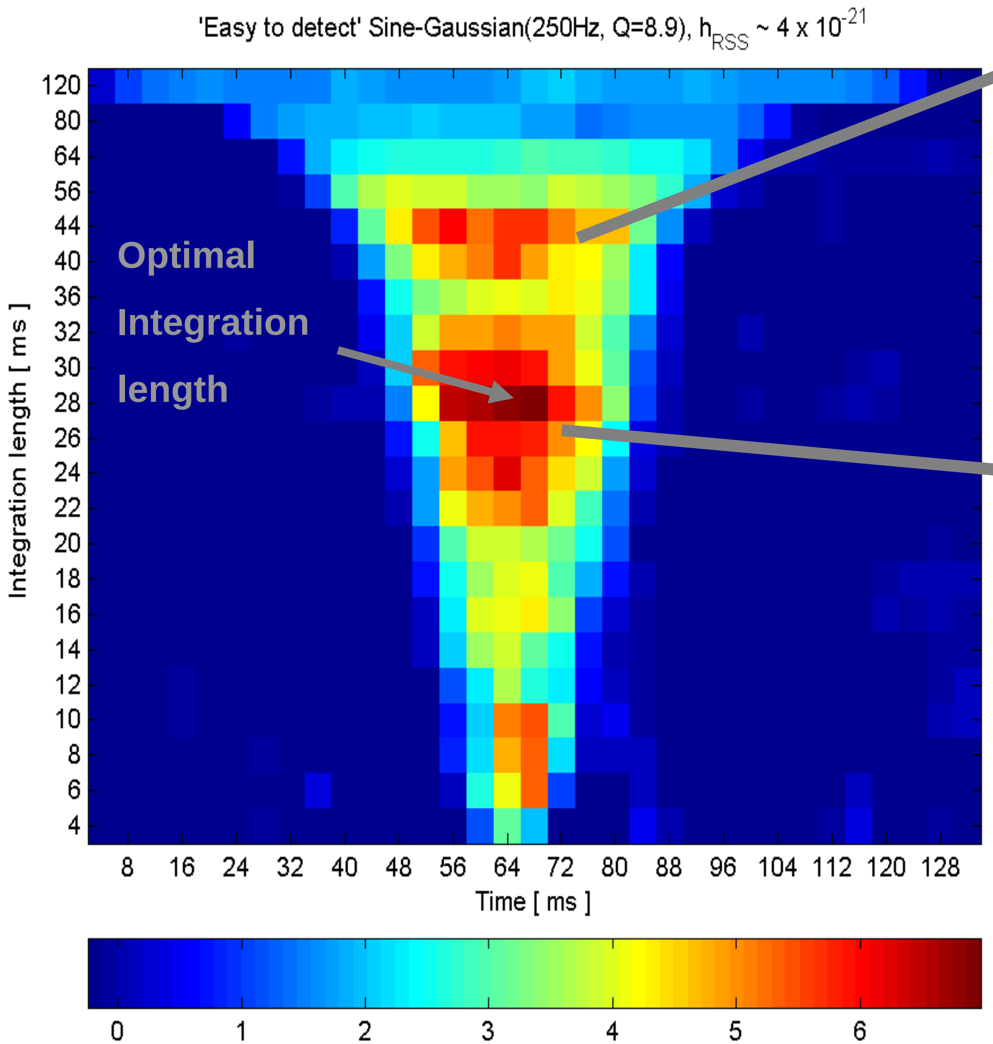


# Cross-Correlation Power

Cross correlation for each start time τ, integration length T:



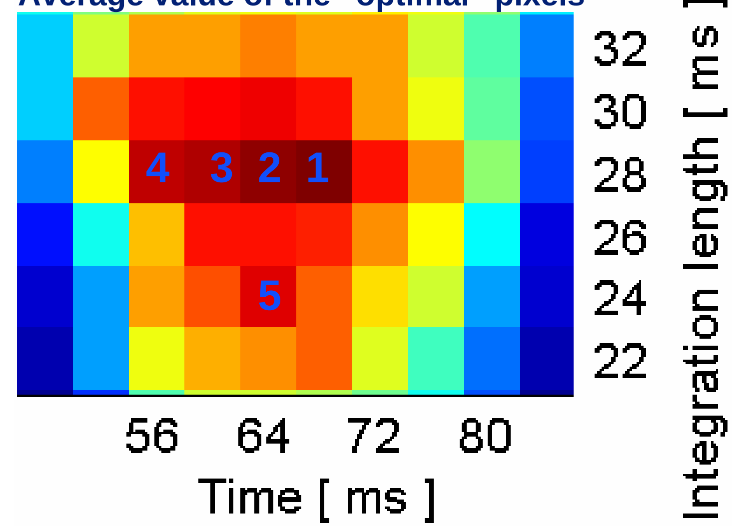
# Signal Anatomy (Simulated)




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

**<u>Event strength</u> [ES] calculation:**

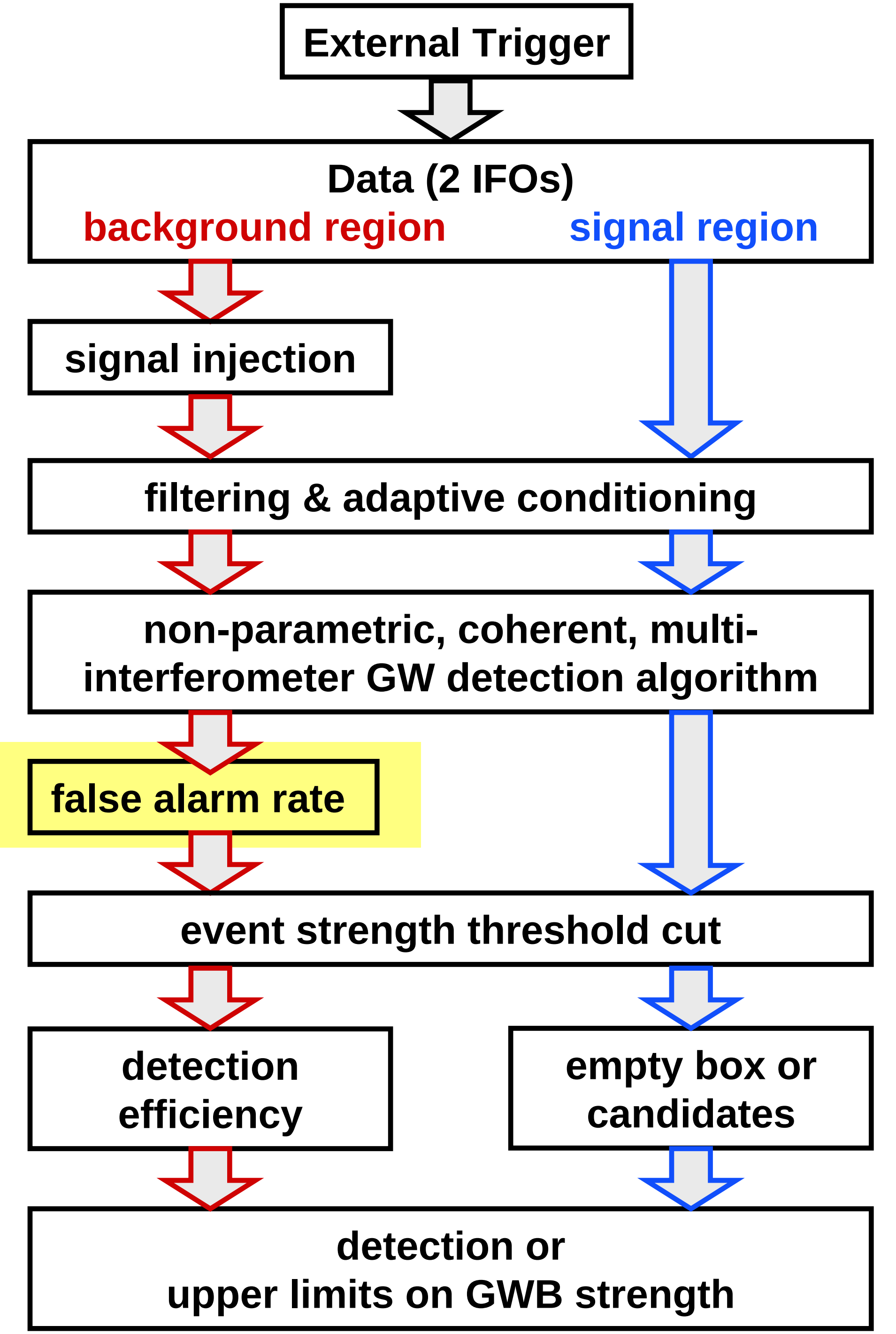
**Average value of the "optimal" pixels**



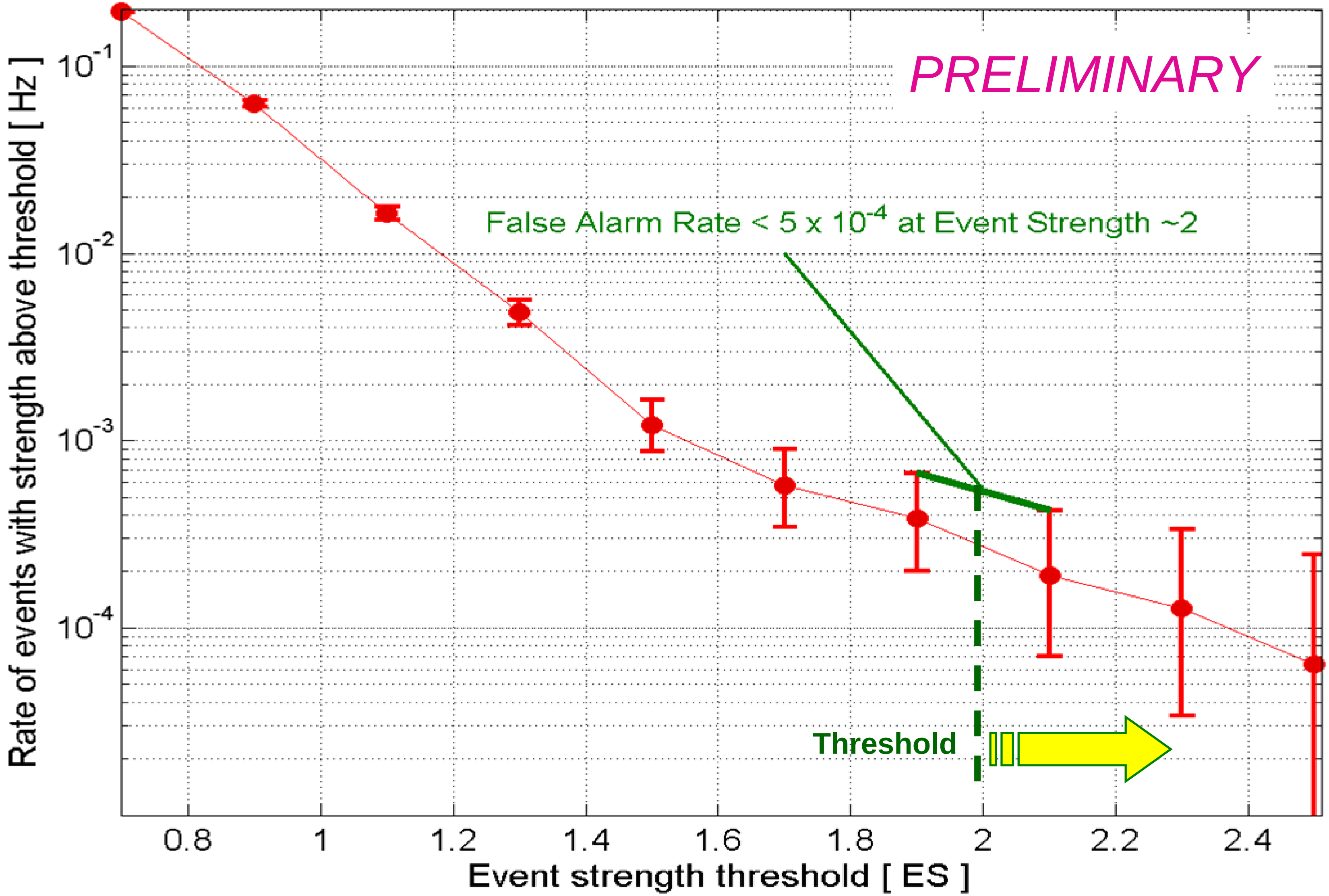

signal strength = average of 5 strongest pixels

LIGO

- 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)

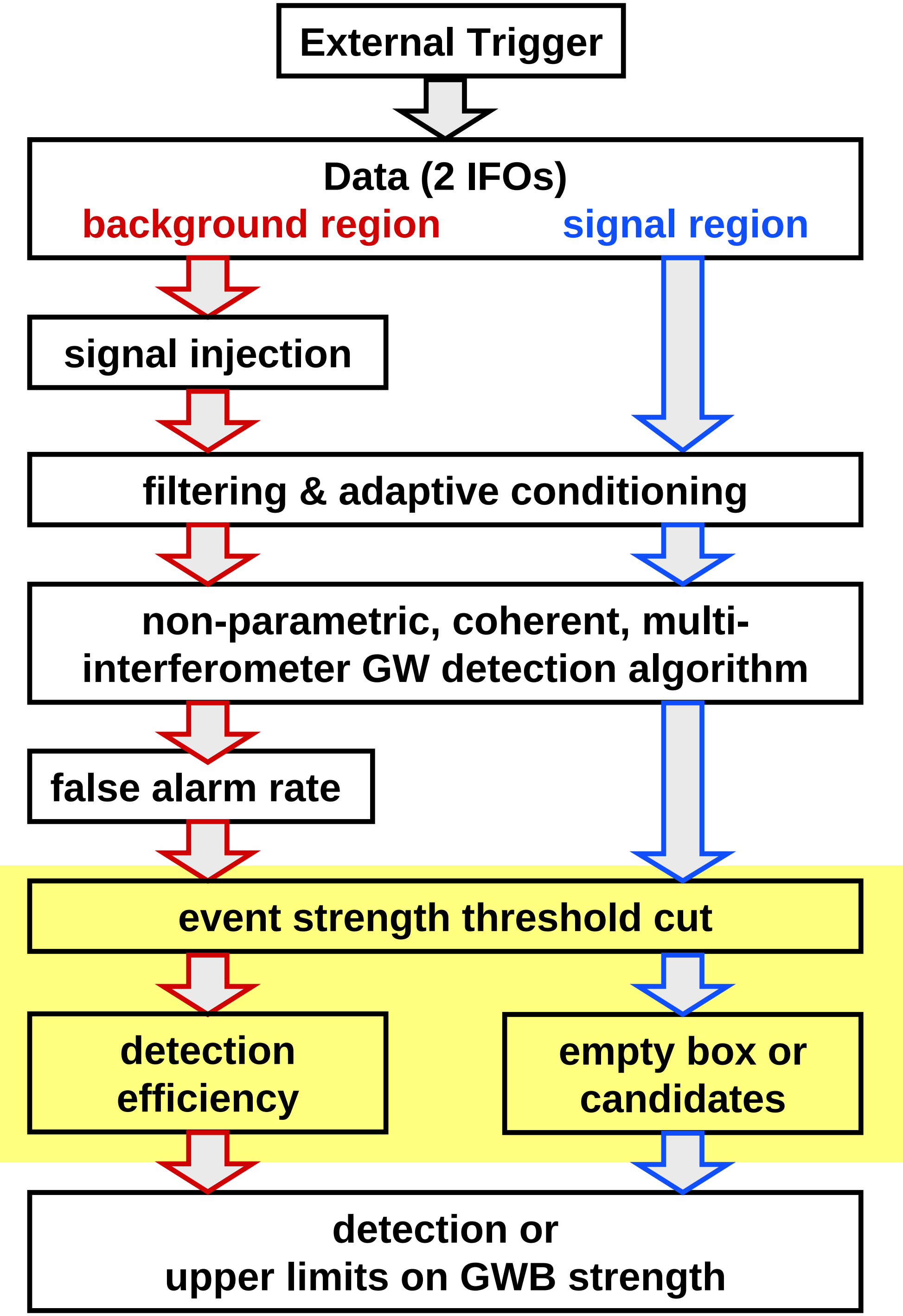


# False Alarm Rate Limit

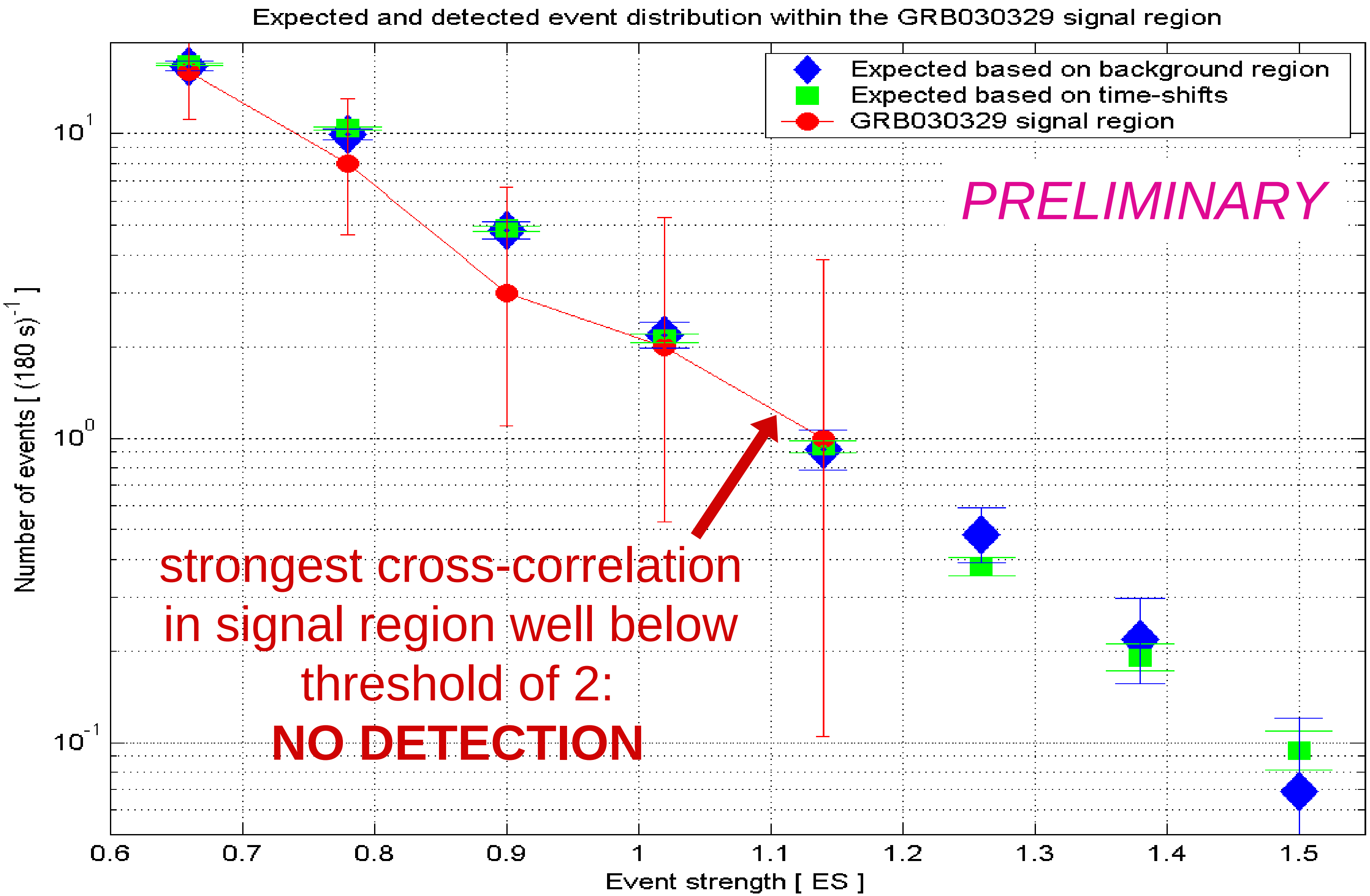


LIGO

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

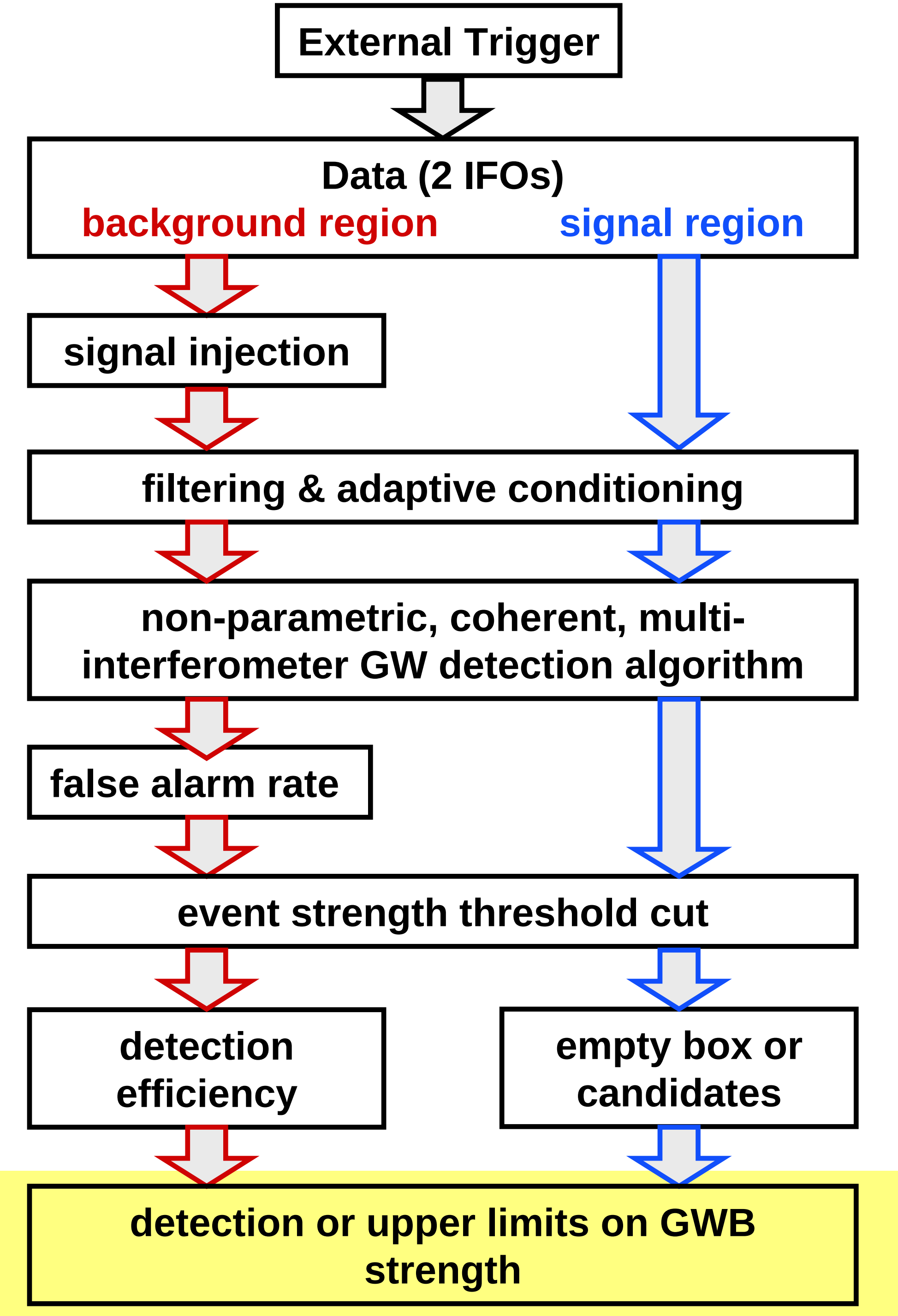


# GRB 030329 Results

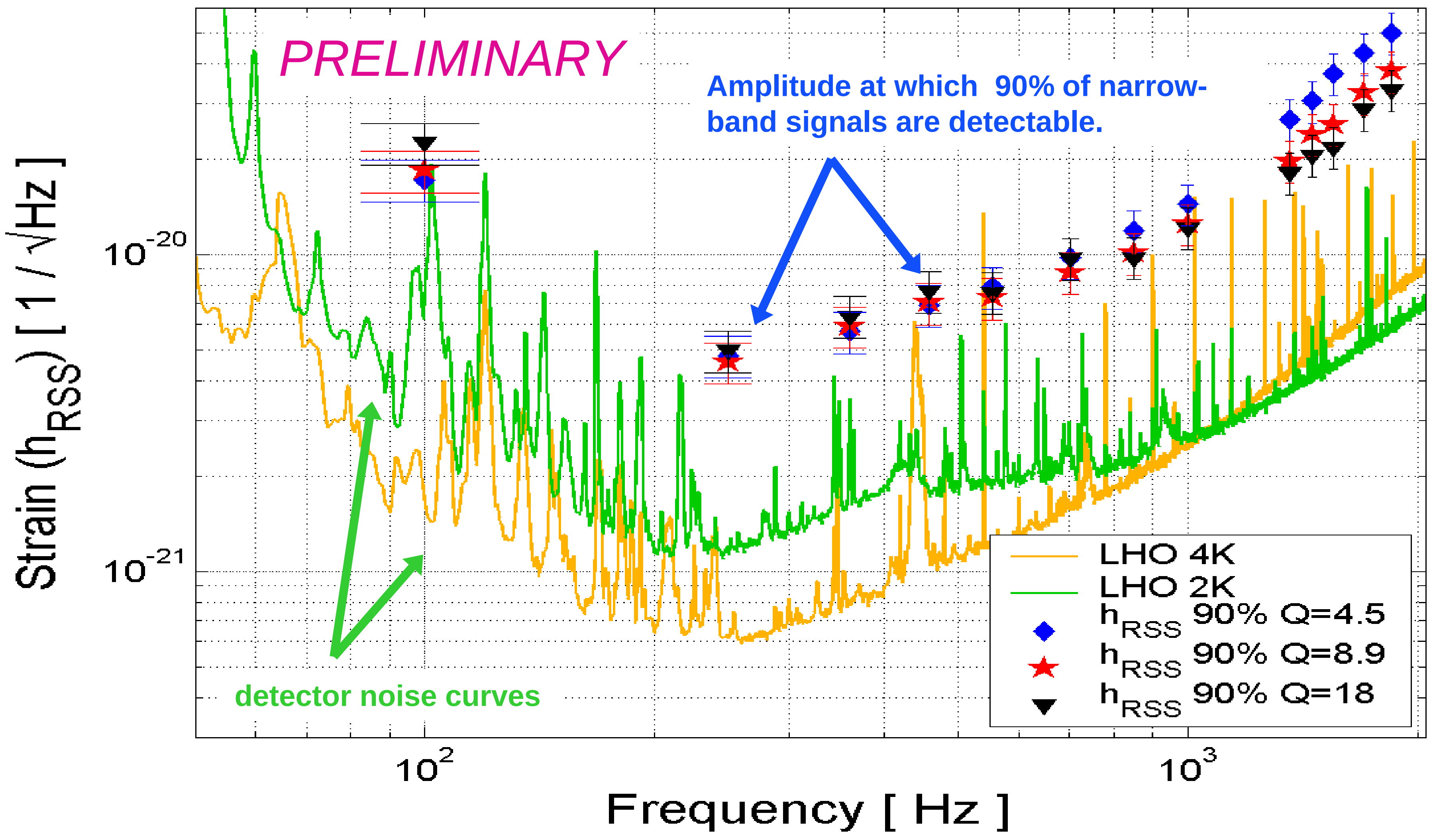


LIGO

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



# Efficiency Measurements (Sine-Gaussians)



# GWB Energetics

- 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:
  - » d ≈ 800Mpc (known)
  - » For h(t) sine-Gaussian at ~250 Hz, $h_{rss} \sim 6\text{x}10^{-21}\text{Hz}^{-1/2}$

- Minimum energy in LIGO band to have been detectable:

$$E_{GW} \gtrsim 10^5\ M_\odot$$

*PRELIMINARY*

# Future Sensitivity

- 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:
  - » Closest GRB with known distance: d $\Rightarrow$ 38Mpc
  - » Initial LIGO design sensitivity: $h_{rss} \sim 2\text{x}10^{-22}\text{Hz}^{-1/2}$

- Minimum energy in LIGO band to be detectable:

$$E_{GW} \gtrsim 0.1\ M_\odot$$

# Summary

- LIGO searches for gravitational wave bursts have begun:
  - » Targets: generic short duration (<1s) transients with power in LIGO's sensitive band of ~100-2000 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 nominal x10 improvement in rate upper limit and amplitude sensitivity.

# 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 $h_{rss} \sim 10^{-20}\ Hz^{-1/2}$
  - » May achieve sensitivity to sub-solar-mass GWB energies with initial LIGO detectors.

# In Development

- Un-triggered modeled searches using optimal filtering (black-hole ringdowns, supernovae)
- Collaborative searches with TAMA300, GEO600 interferometers, AURIGA resonant mass detector
- Collaborative GRB-triggered search with HETE