

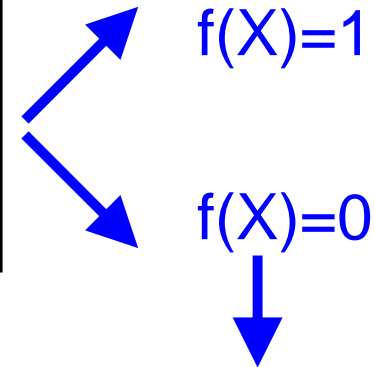
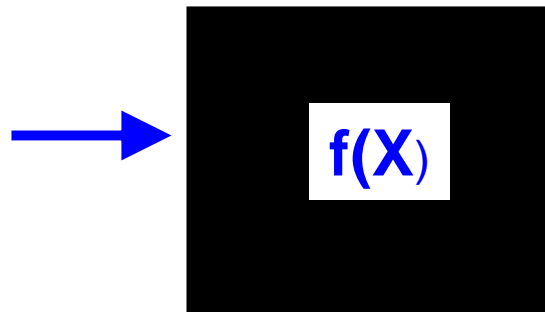
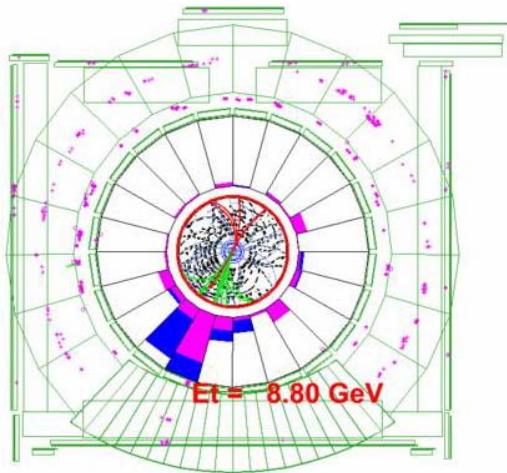
Detection confidence in searches for gravitational wave transients

Erik Katsavounidis
MIT
for the LIGO Scientific Collaboration

CaJAGWR Seminar
Caltech, May 27, 2008

The problem: a canonical counting experiment

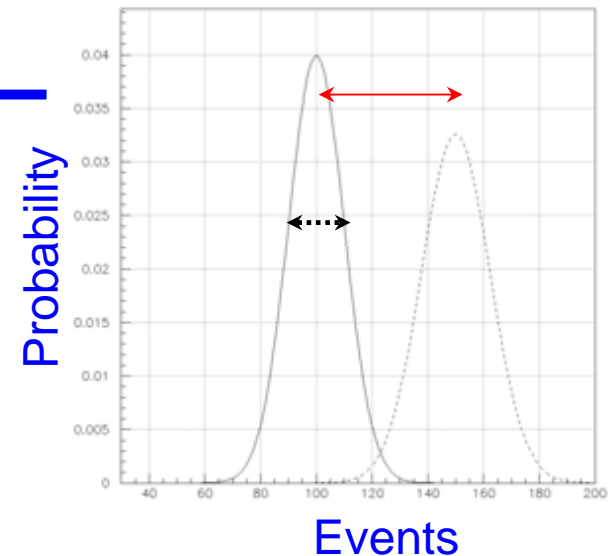
- An apparatus records “events” $X = (x_1, x_2, \dots, x_n)$
- Apply cuts
- Measure signal, predict background



- Find the probability $p = \text{Poisson}(n \geq x|b)$



- Set a threshold $p < \alpha$ in order to claim a detection



Is this the end game?

Pronunciation

Spellings

Etymology

Quotations

Date chart

1. The mental attitude of trusting in or relying on a person or thing; firm trust, reliance, faith. Const. *in* (†*to*, *on*, *upon*).

c1430 LYDG. in *Pol. Rel. & L. Poems* 47 Alle verteu..Made stable in god by gostly confidence. **1490** CAXTON *Eneydos* xxv. 93 The whiche goddes, hauynge confydenge in trustynge his sayd promysse. **1535** COVERDALE *Ps.* cxvii. 9 It is better to trust in the Lorde, then to put eny confidence in man. **1557** NORTH tr. *Gueuara's Diall Pr.* 133b/1 The sonne..will not haue to his father any great confidence. **1593** SHAKES. *Rich. II.* II. iv. 6 The King reposesh all his confidence in thee. **1649** BP. REYNOLDS *Hosea* iv. 48 Confidence..in foraigne ayde. **1774** GOLDSM. *Grecian Hist.* I. 310 The king would place more confidence in the engagements of the nobility than upon those of the..capricious multitude. **1837** BARONESS BUNSEN in *Hare Life* I. x. 448 He..never abused the most implicit confidence.

2. a. The feeling sure or certain of a fact or issue; assurance, certitude; assured expectation

Can this be only behind *p*

1555 EDEN *Decades* III. III. 104 They..with no lesse confydenge licke their lippes secreately in hope of their praye. **1611** SHAKES. *Wint. T.* I. ii. 414 He thinkes, nay with all confidence he swears, As he had seen't. **a1698** TEMPLE *Ess. Heroic Virtue* Wks. 1731 I. 230 The very Confidence of Victory..makes Armies victorious. **1790** BEATSON *Nav. & Mil. Mem.* I. 209 Wrapped up in a vain confidence of his own abilities. **1872** FREEMAN *Hist. Ess.* (ed. 3) 12 This story..I affirm with less confidence.

LIGO Detection and Physical Interpretation

- All p tells us is the probability of claiming a detection in the absence of a true signal can be as low as we define to be *assuming we know the background perfectly*
 - » How do we decide how low p should be?
- Ultimately, a detection has to be accompanied by a physical interpretation
 - » events $X = (x_1, x_2, \dots, x_n)$ come with characteristics (properties), instruments measure besides X , also the $P(X | \theta_i)$, the probability of observing X assuming a model θ_i
 - » use these to perform parameter estimation, i.e., estimate the values of the one or more parameters θ_i of the source model if unknown or poorly known, or, hypothesis testing, i.e., decide if θ_i is consistent with the known parameters θ_i^{ref}
- Confidence in a detection may not come only by a low p value

Pollock, *Phys. Rev. A* **24**, 1544 (1981).

³F. J. Rogers, H. E. De Witt, and D. B. Boercker, *Phys. Lett.* **82A**, 331 (1981); D. B. Boercker, *Phys. Rev. A* **23**, 1969 (1981); D. B. Boercker, F. J. Rogers, and H. E. De Witt, *Phys. Rev. A* **25**, 1623 (1982).

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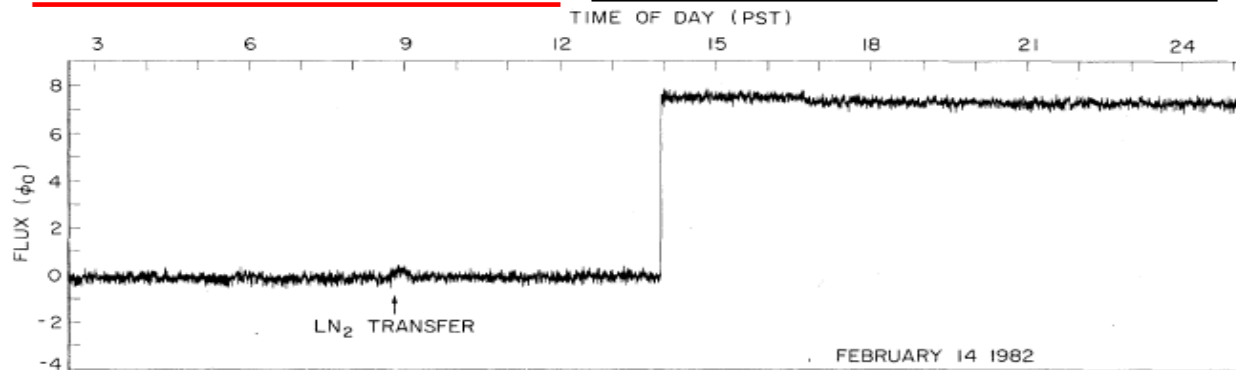
First Results from a Superconductive Detector for Moving Magnetic Monopoles

Blas Cabrera

Physics Department, Stanford University, Stanford, California 94305

(Received 5 April 1982)

A velocity- and mass-independent search for moving magnetic monopoles is being performed by continuously monitoring the current in a 20-cm²-area superconducting loop. A single candidate event, consistent with one Dirac unit of magnetic charge, has been detected during five runs totaling 151 days.



(b)

FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.



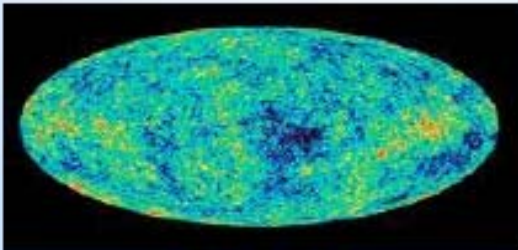
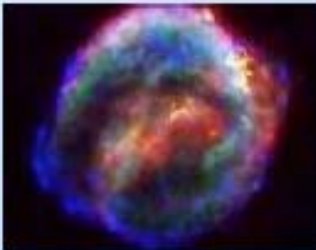
- Instrumental
 - » Calibration (detector response)
 - » Line voltage fluctuations
 - » RF interference
 - » External magnetic field
 - » Ferromagnetic contamination
 - » Critical current of the loop
 - » Mechanically induced offsets
 - » Seismic disturbance
 - » Energetic cosmic rays
 - » Spontaneous and large external mechanical impulse
 - » Spontaneous internal stress release mechanism
- Physical interpretation
 - » Flux consistent with one Dirac unit of magnetic charge
 - » Local missing mass density: $0.05 M_{\text{solar}}/\text{pc}^3$ made up of monopole of mass 10^{16}GeV at $300\text{km}/\text{sec}$ would result in 1.5 events per year through his detector



- Laser Interferometer Gravitational-wave Observatory (3 instruments), GEO600 and Virgo use kilometer-scale interferometry to detect gravitational waves
- Collected data in their most recent and most sensitive runs: “S5” Nov 4, 2005 – Oct 1, 2007 and “VSR1” May 18, 2007 – Oct 1, 2007
- Analyses of these data are well underway
- Basic detection notion: coincidence → multi-site information increases confidence and allows the properties of the wave and its source to be measure



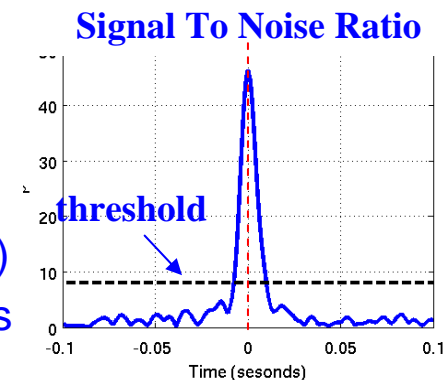
Sources and searches

	Long duration	Short duration
Matched filter	 <p>Pulsars</p>	 <p>Compact Binary Inspirals</p>
Template-less methods	 <p>Stochastic Background</p>	 <p>Bursts</p>

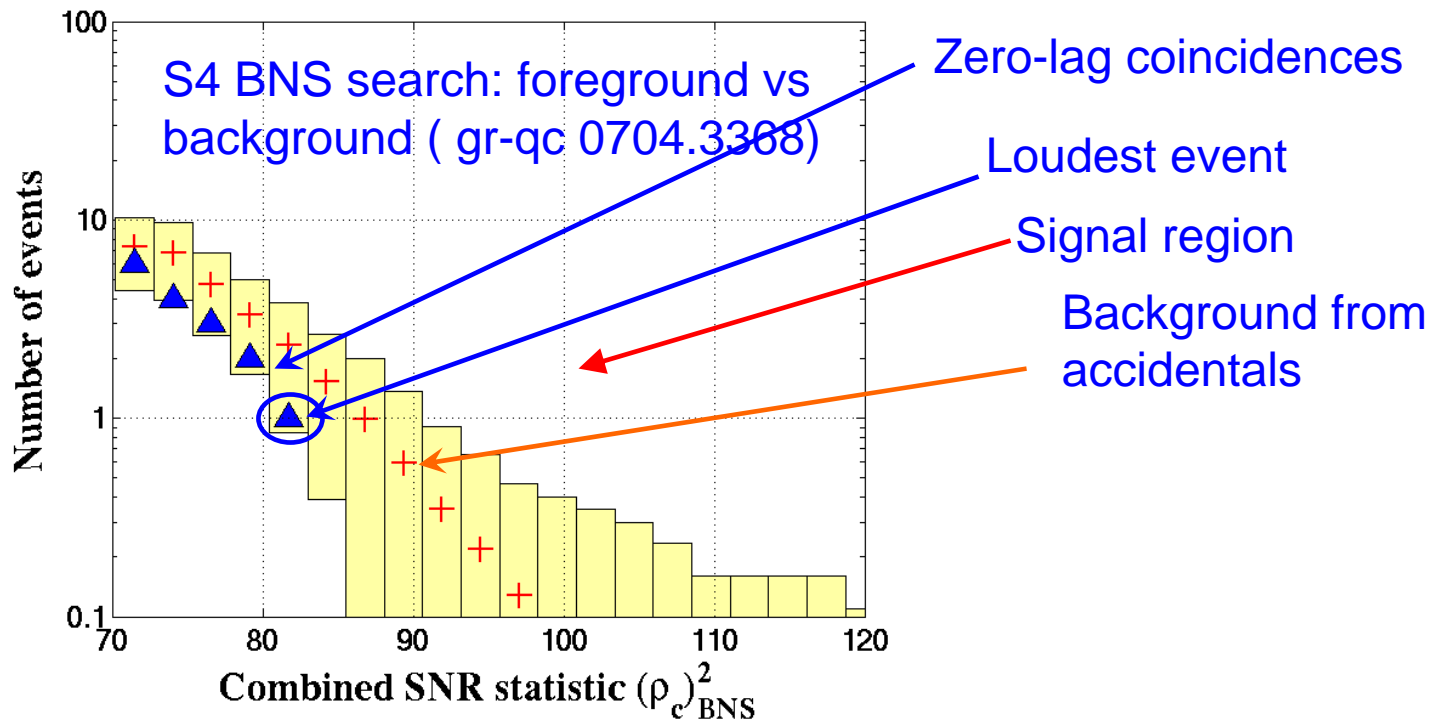
LIGO Event counting searches: inspirals



- The search
 - » Look for up to tens of seconds long signals corresponding to the final inspiral of binary neutron stars and potentially binary black holes
 - » This is the most well understood source for gravitational-wave detectors; waveforms are known thus allowing use of optimal matched filtering
- Science goals
 - » Detect, or place an upper limit on the rate of compact binary coalescence
 - » Study properties of their population
- Methodology
 - » Use a **template bank** of thousands of waveforms to cover parameter space of target signals
 - » Look for maxima of $|z(t)|$ above some threshold → **triggers**
 - » Identify template (masses) and coalescence time of the binary
 - » Require **coincidence** to make a detection
 - » Check for consistency between data and detected waveform (χ^2 test)
 - » Triggers in multiple interferometers with consistent signal parameters



- Analysis for BNS/BBH during S3+S4 science runs now complete [Preprint arXiv:0704.3368]
 - » ~59 days of livetime
 - » Binary neutron star signal could be detected out to ~17 Mpc (optimal case)
 - » Binary black hole signals out to tens of Mpc
- Use loudest event for upper limit calculation → could this be a detection candidate?





LIGO Event-counting searches: bursts



- The search

- » An as open as possible search for signals lasting from few milliseconds to few seconds in the 100Hz- few kHz frequency range that is not tied up on specific source or waveform
- » A targeted search around the time (and direction) of electromagnetic transients (GRBs, X-ray glitches, optical, etc)
- » Makes minimal assumption about the candidate signal

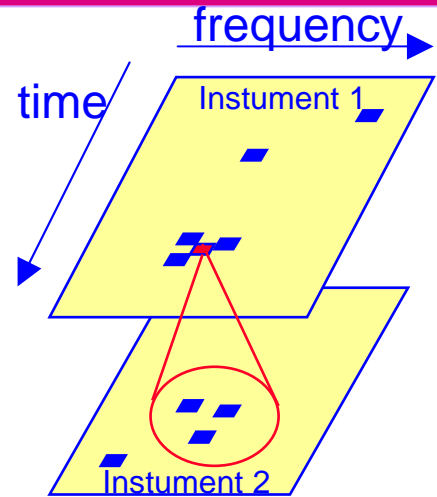
- Science goals

- » Direct detection of astrophysical sources like core-collapse supernovae, binary mergers, neutron star instabilities, cosmic string cusps and kinks, or otherwise upper limits on their flux and constraints on the energy emitted into gravitational waves

- Methodology

- » Search using excess power, coincidence, cross-correlation etc (next slide)
- » Work together with the inspiral group in the pursue of the full evolution of binary compact stars from their inspiralling phase through merger to the ringdown. The latter being burst-like events suggests a coincidence

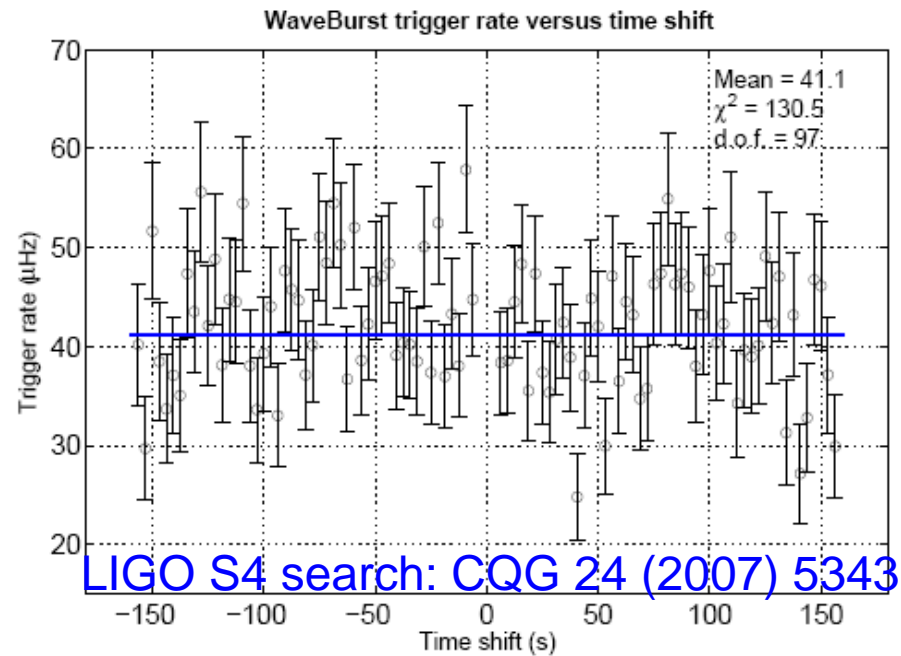
- Basic assumption: multi-interferometer response consistent with a plane wave-front incident on network of detectors
- Time-frequency decomposition of data
 - » Project data stream on a Fourier or wavelet basis
 - » Normalize to noise, threshold on power and form clusters
 - » Require coincidence (time, frequency)



- Require trigger clusters to fall within some frequency band and have excess signal power
- Repeat this for $O(100)$ “time-shifts” of all data

- » Tuning and background studies
- » Set threshold to yield $O(0.01)$

accidentals
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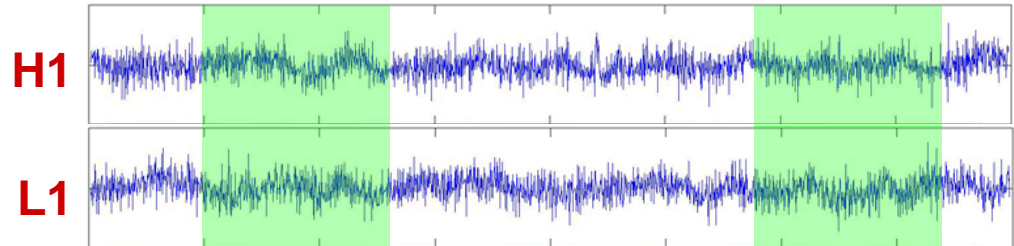


LIGO Burst methodology in a nutshell



- Data quality and vetoes
 - » high seismic noise, wind, jets, calibration line drop-outs, last 30 seconds of each segment
- Consistency checks
 - » Amplitude (h) reconstruction by the two co-located Hanford detectors
 - » Cross-correlation of h(t) data from pairs of detectors (20, 50 and 100ms)

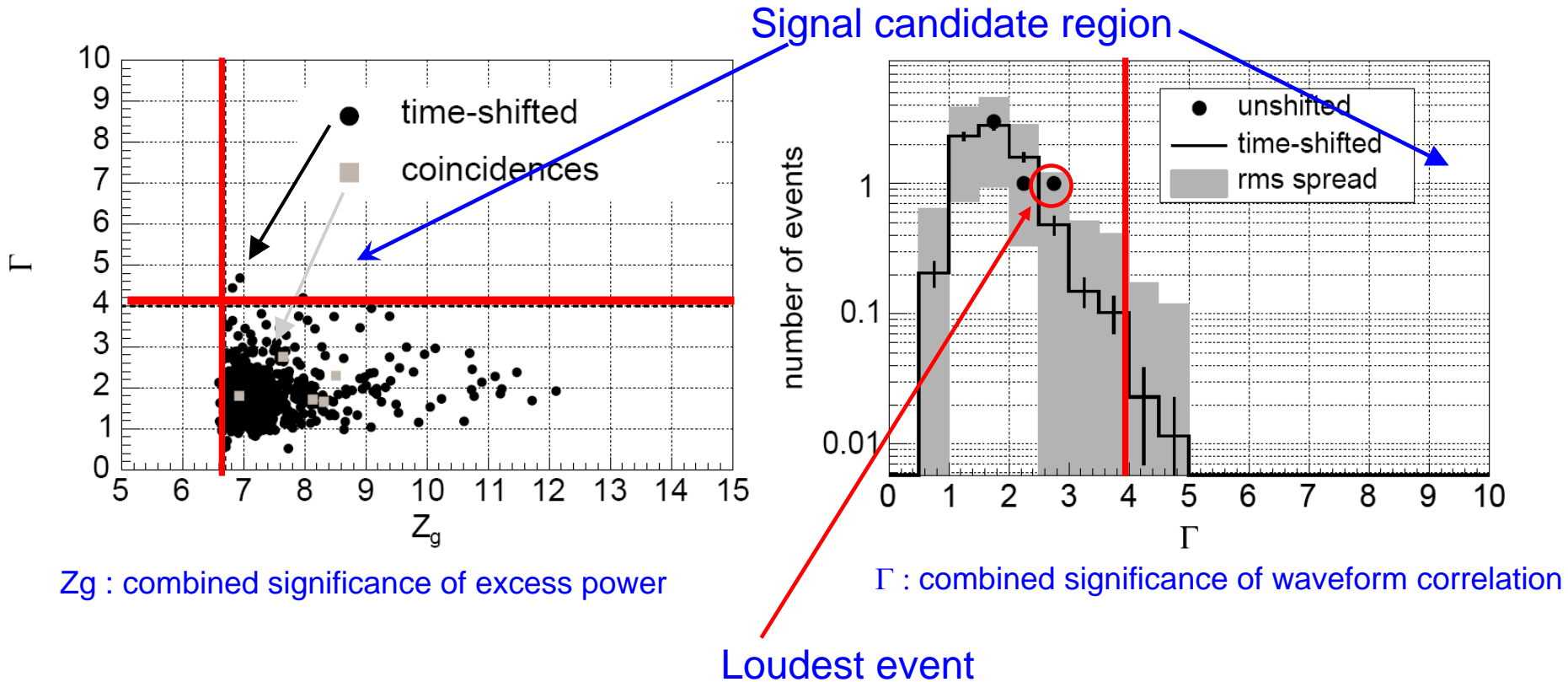
$$r_k = \frac{\sum_i (x_i - \bar{x})(y_{i+k} - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2} \sqrt{\sum_i (y_{i+k} - \bar{y})^2}}$$



- » Sign of H1-H2 correlation
- End result: coincidence events characterized by a statistical significance, time, frequency, amplitude and waveform similarity among detector sites
 - » For “zero-lag” between the sites (i.e., where astrophysical signal may be present)
 - » For “time-delayed” between the sites (i.e., where astrophysical signal can not be present)

How do we identify burst candidates? the LIGO S4 search example

LIGO S4 search: CQG 24 (2007) 5343



Z_g : combined significance of excess power

Γ : combined significance of waveform correlation

- No event passed all analysis cuts (background of 3 events out of ~ 77 effective S4 runs)

gravitational wave counting experiments

- Searches may operate at a fairly high p (false detection probability)
- Detection and upper limit searches proceed in parallel: set upper limit and then follow up candidates
- Upper limits are typically set at the 90% confidence level, detection confidence probably needs to be much higher
- Complex instruments, with thousands of channels, almost impossible to fold upstream every single bit of information in the $f(X)$
- Even if not leading to a detection, event follow up may lead to understanding of detector systematics/overall instrument diagnostics
- Need to have a comprehensive list of tests a candidate will have to withstand, tests that will allow to assess our confidence to it → detection checklist

Blind analyses and a posteriori event inspection

- Upper limit searches are performed with blind analyses
 - » Time-slided data, or small fraction (“playground”) of the full data-set is used to define all selection cuts
 - » Usually the tuning process balances false alarm rate and detection efficiency
 - » Important for the analysis to be fixed before opening the signal region (“zero lag box”)
 - » Upper limit setting procedure is legitimate and can provide the claimed coverage
- A posteriori event inspection
 - » Does not affect the upper limit-setting procedure as long as the blind selection of events is not revisited in order to reflect findings of the a posteriori inspection
 - » May come with biases reflecting one’s priors

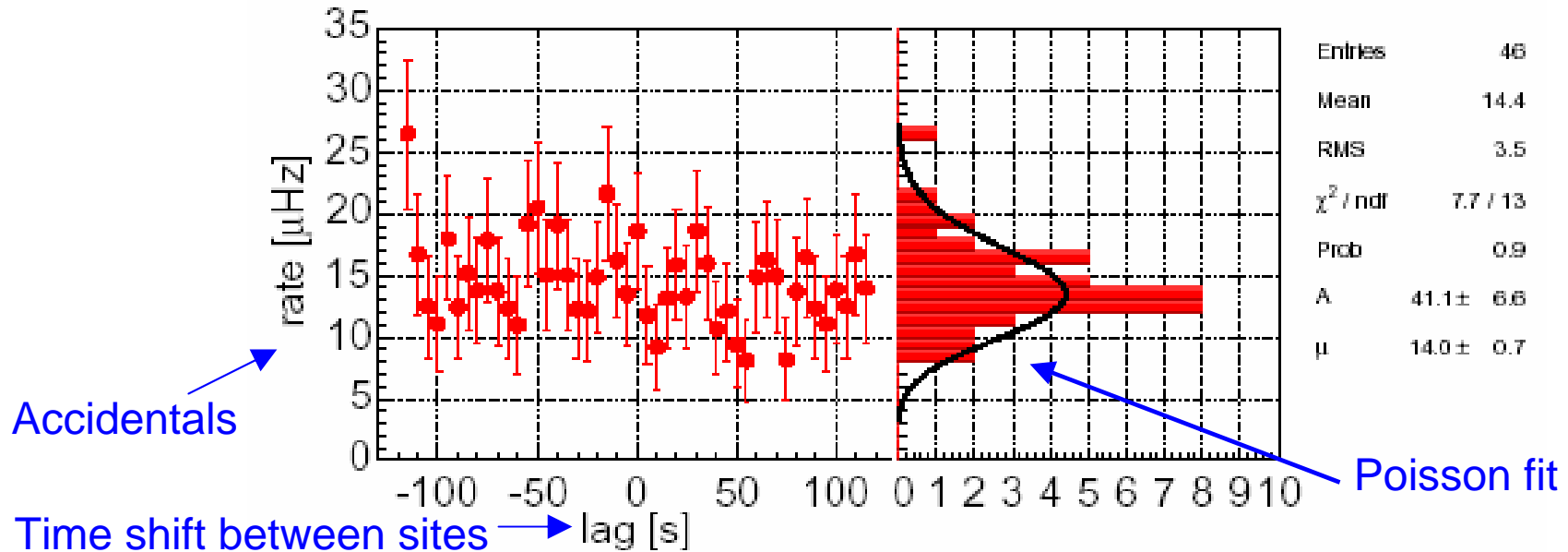
- Instrumental
 - » Statistical significance
 - » Environmental and interferometric vetoes
 - » Detector status and data integrity
 - » Calibration errors
 - » Event scrutiny and multi-instrument response
 - » Multiple analysis methods
- Phenomenology
 - » Best fit waveform and the source model
 - » Electromagnetic counterparts
 - » Directional source analysis
 - » Distributional analysis
 - » Bayesian analysis

- Need a reliable estimate of the background, i.e., the number of chance coincidences
- Statistical and systematic errors in the background
 - » Ideally, once should switch off all gravitational wave sources ... not an option. It is reasonable to assume that true gravitational wave events are only a negligible part of the event sample.
 - » Is time-shifting events of one detector w/r/t the other creating independent data-sets?
 - Yes, if system is ergodic
 - Yes, if stride is longer than the maximum coincidence window
 - Yes, if single detector events are not auto-correlated up to the maximum time-shift
- Testing Poissonianity of time-shifted coincidences

$$P(n|\mu_t) = \frac{\mu_t^n}{n!} e^{-\mu_t}$$

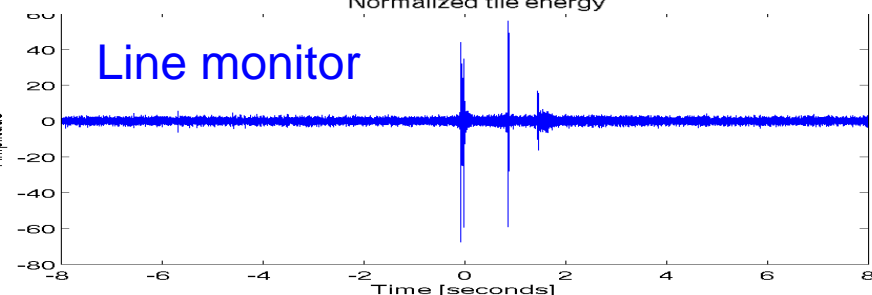
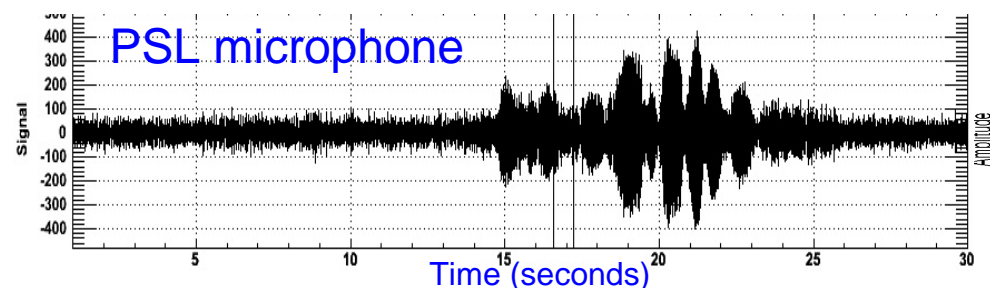
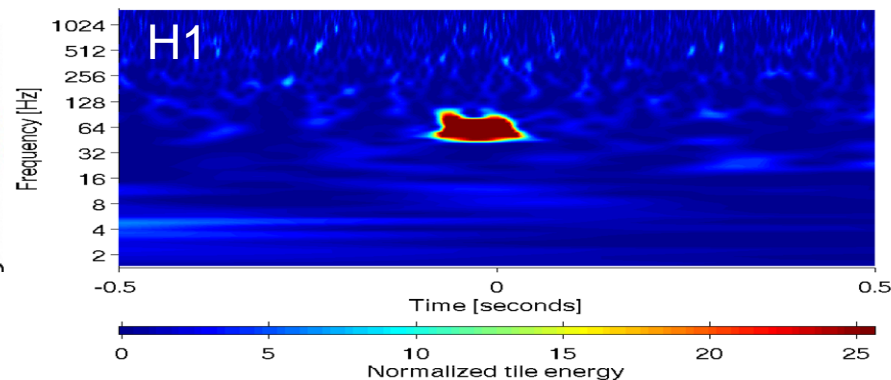
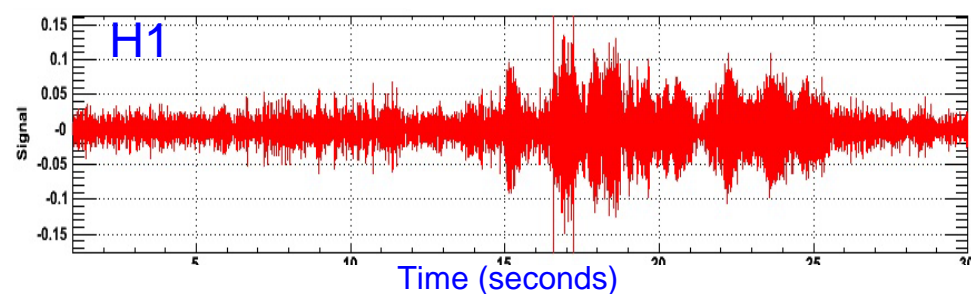
Confidence in the background estimate

- An example from the LIGO S2 burst search (PRD 72 (062001) 2005)



- A detection candidate will have to withstand questions on background systematics:
 - » Robustness against different strides (e.g., 3s, 5s, sqrt(17)s, random) used for time-shifts
 - » Is the ergodicity hypothesis holding?
 - » How does the background compare with back-of-the-envelope calculation based on singles rate and a given coincidence window?
- Are the $1-\sigma$ systematics 0.01, 0.1 or 1 event?

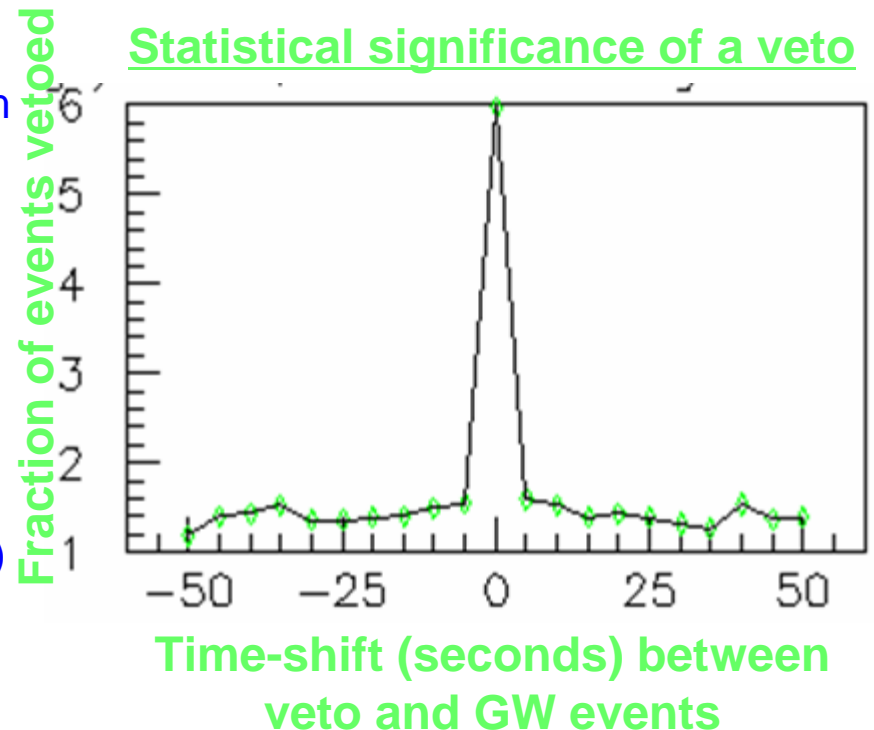
- Searches generally fold *a priori* “smoking-gun” and “debugged” vetoes based on information from environmental and interferometric channels of the detectors, i.e., a set of conditions that under no circumstances permit us to consider a detection



- Vetoes are established both statistically and by considering coupling mechanisms between the auxiliary channel and the dark port of the interferometer
- False dismissal probability is of paramount importance
- Many reasons for which an outlier event may call for revisiting veto strategy
 - » Number of channels available for establishing veto/data quality conditions is huge— not all of them are studied a priori
 - » Phase space of the parameters in veto/data quality equally huge— impossible to exhaust it all a priori
 - » Event under examination may have specific morphology (time-frequency volume, waveform) for which a specific veto analysis may be required

Environmental and interferometric vetoes (cont'd)

- There will always be “something” in the detectors’ auxiliary channels that may hint a correlation with the instruments’ environment/interferometry
- No conclusion can be drawn from a single event
- In order to proceed with accepting a post-facto veto condition
 - » Veto has to have a “small” false dismissal probability
 - » Veto amplitude (environmental or instrumental) has to match expectation from known or measured couplings
- In order to proceed with not accepting a post-facto veto condition
 - » Veto has to have a “high” false dismissal probability
 - » Take measured amplitude in auxiliary (veto) channel and show that expected signal in the dark port is much less than the one observed

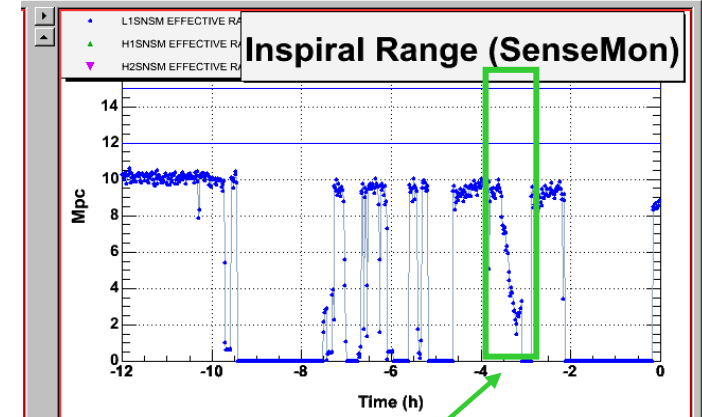
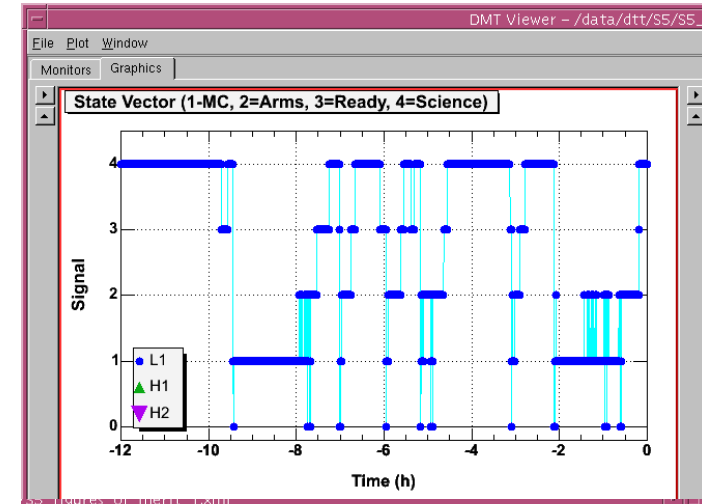


Other veto considerations (not easily quantifiable)

- Demonstrate auxiliary channels were indeed functioning properly at the time of a candidate detection
- Check for environmental disturbances that might have been missed or unclear in local environmental monitors
 - » Earthquakes
 - » Information from power companies regarding known (to them) glitches
 - » Switching on/off of major electrical equipment (locally)
 - » Weather conditions
 - » Records for overflying civilian/military airplanes
 - » Cosmic rays

LIGO Detector status and data integrity

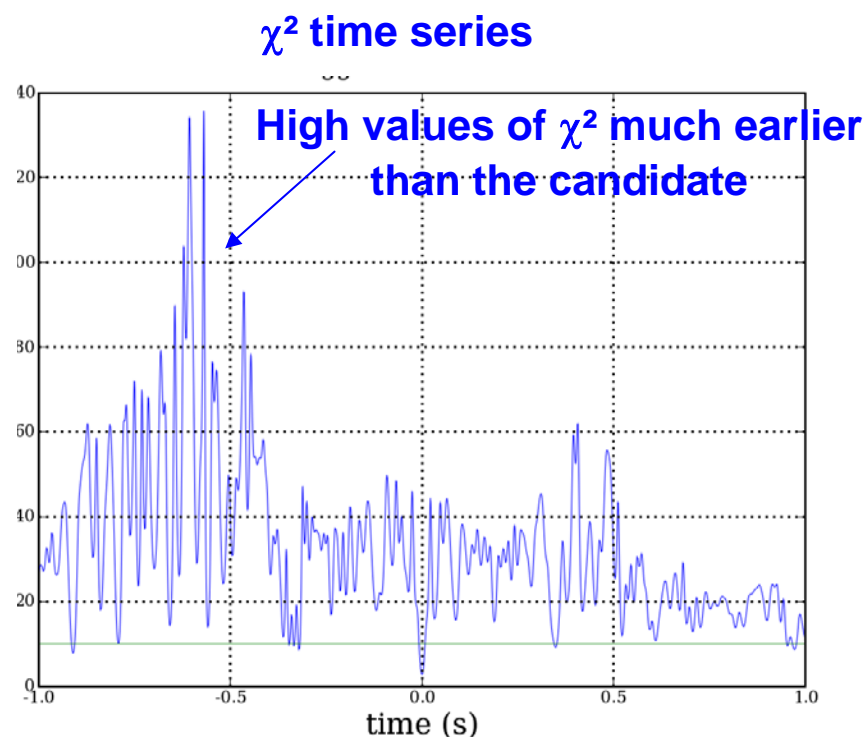
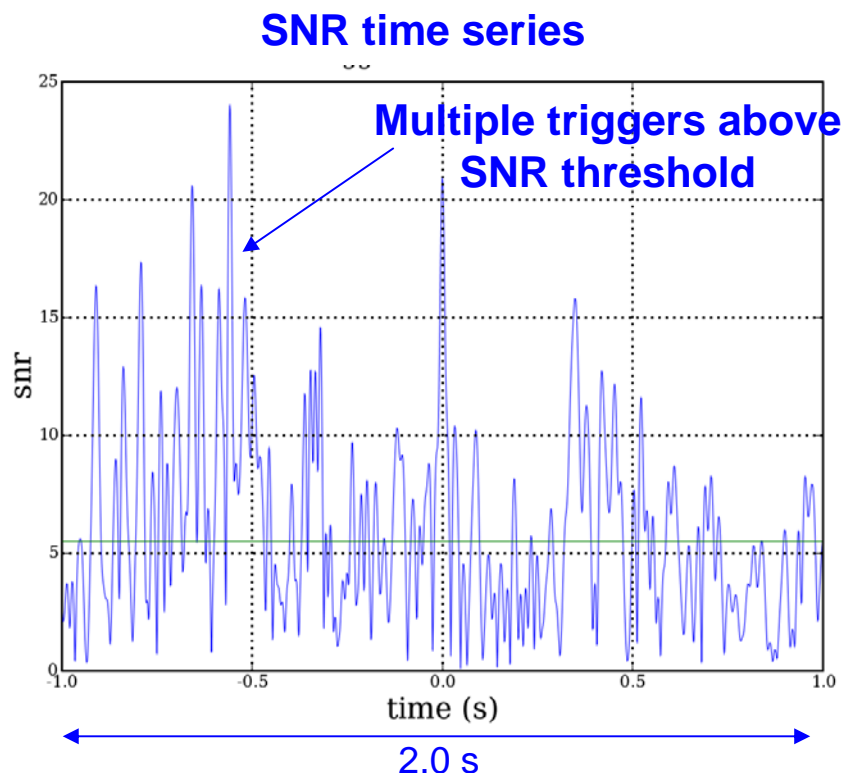
- Generally this is auxiliary and not easily quantifiable information when it comes to stating by how much it adds or increases our “confidence”— typically a verification step of facts that most analyses should check automatically. For example:
 - » instruments were indeed in observing mode, without any hardware injections taking place
 - » scan detector’s log for any anomalies reported by control room personnel
 - » check detector’s figures-of-merit, i.e., quantities that reflect the instantaneous sensitivity and glitchiness (notice, these are nominally folded in any intelligent analysis)
 - » how close is an event to a segment-start or segment-end, a hardware injection; is this a short segment or a long segment?
 - » Look for bit corruption in recorded data streams, various checksums of raw, intermediate and final data products used in the analysis



Low sensitivity to BNS

- What is the calibration constants and errors around this event?
- Any fast fluctuation nearby?
- How robust is the event analysis against calibration version?
- What can hardware injections in nearby times can tell us about calibration errors?

- What was going on in the antisymmetric port of the instruments around the time of a candidate event
 - » Example: a background inspiral trigger in L1
 - » Check SNR and CHISQ time series after match filtering the data
 - » A very noisy interval!

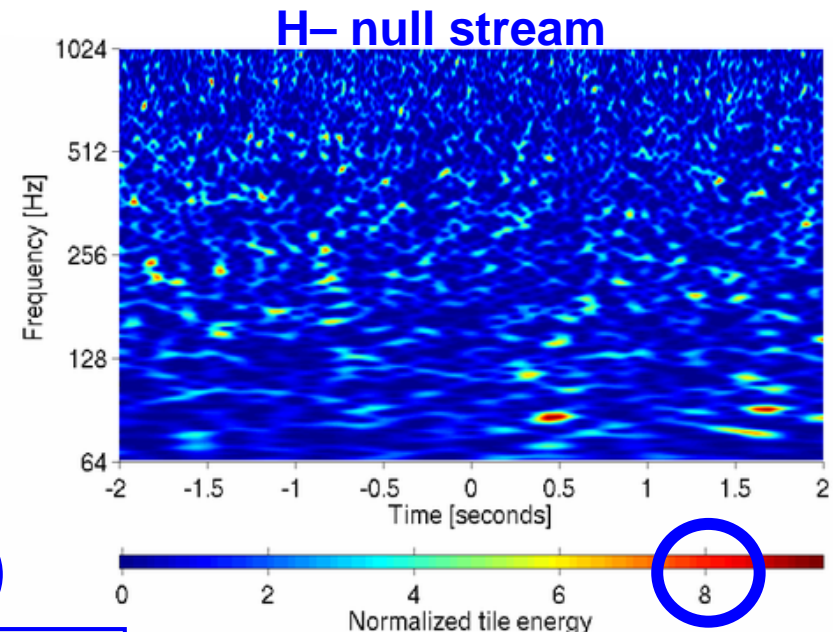
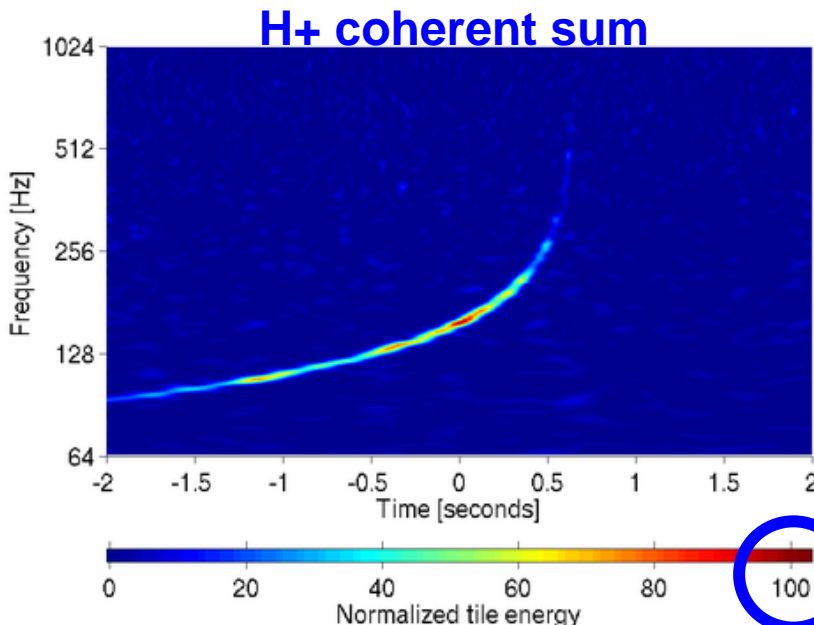


Event scrutiny (cont'd)

- How stationary were the instruments around that time?
- How sensitive is it in the boundaries and size of the analysis block?
- Has there been any trigger clustering and if yes how sensitive is the result on the clustering criteria?

- Is the event consistent among all instruments?
 - » Time-frequency volume
 - » How amplitude and signal morphologies compare?
- Perform fully coherent follow up
 - » H1-H2 collocated detectors
 - » Coherent analysis methods ala Gursel and Tinto [PRD 40 (1989) 3884] for the entire available detector network

Simulated 1.4/1.4 M_{\odot} inspiral injected at 5Mpc



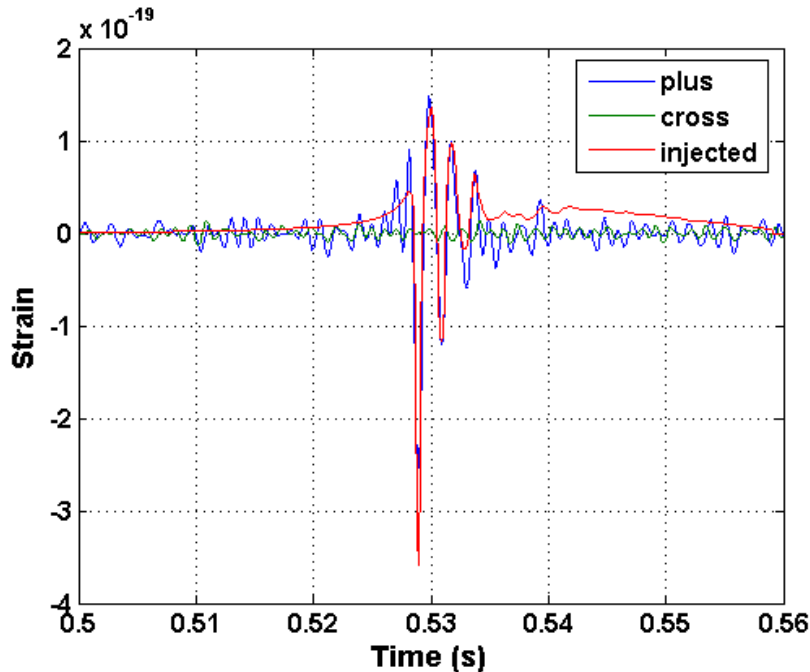
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~10% increase in SNR

consistent with noise

Multi-detector response

- What is the extracted source location and its error?
- What is the best fit waveform?



Simulated (A4B1G4) supernovae from
Dimmelmeier *et al.* A&A 320 (1997) 209

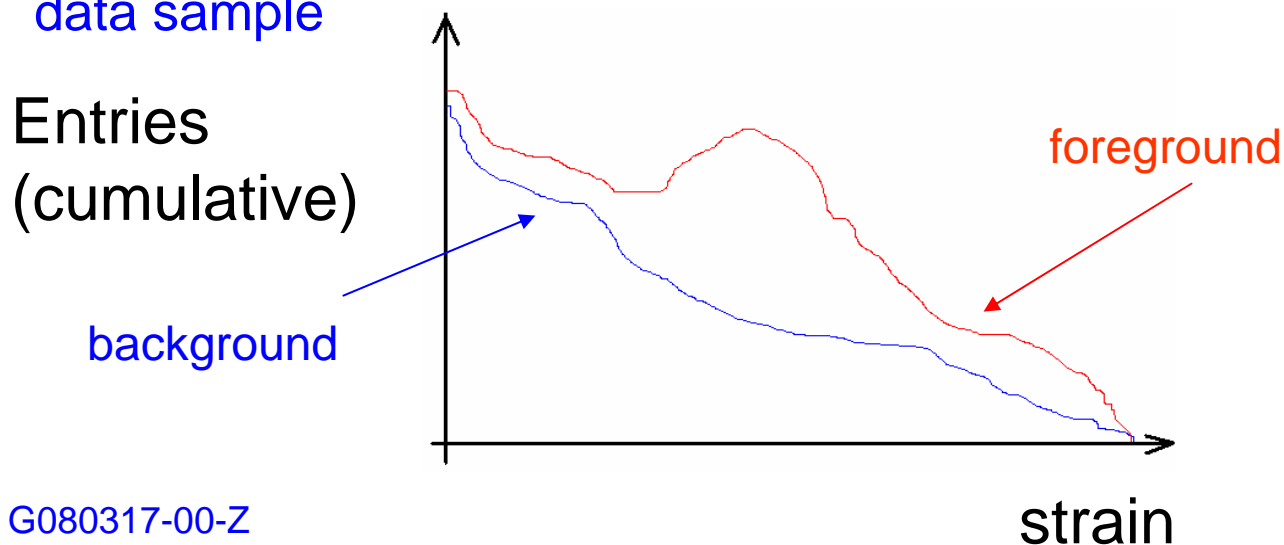
Injected with SNR 40 into simulated H1,
L1, and G1 detector noise

- If it was not registered in one of detectors, is it because it was not collecting data, because it was not sensitive enough and/or was glitchy, or special assumptions about the polarization or the source direction need to be invoked?

- Multiple methods analyzing the same data for the source type of signals can compare notes
 - » How the significance of the candidate event compares?
 - » Extracted signal parameters in agreement?
- They can generally increase our confidence against algorithmic/implementation mistakes, but ... they also increase the false alarm rate (the trials factor...)
- Multiple methods that work synergistically are of paramount importance, like a combining an inspiral, burst and ringdown search → reduced false alarm rate, increased confidence

- Waveform extraction may suggest the candidate source
 - » Reasonably well described for inspirals and ringdowns
 - » Challenging for all the rest
 - » Heavily dependent on SNR
 - » Reanalyze events with refined templates?
 - » Is the GW “in-between” the models we searched for?
 - » Do a targeted search for events matching extracted waveform?
- Electromagnetic counterparts may catalyze the first detection
 - » “prime” E/M triggers are usually prompt and public domain
 - » How about “sub-prime” ones?
- Directional analysis:
 - » are there known sources overlapping the ring/patch on the sky corresponding to the direction of the candidate event?
 - » Identify astrophysical point source locations
 - » Use luminosity data (<http://arxiv.org/pdf/0706.1283>) to plot the cumulative luminosity per solid angle over varying depths, e.g., 0-1Mpc, 1-10Mpc, 10-100Mpc

- Assuming one, “loud” event as detection candidate, this implies there should be many more weaker events corresponding to a fundamental source population behind it– are we able to probe the spectrum of such population?
- A fixed-threshold, counting experiment analysis (and search for the outlier detection event) isn’t (easily) sensitive to this– need multiple analyses of continually decreasing threshold down to “zero” (the loudest event analysis is effectively a no threshold search)
- Compare distribution of foreground and background events of existing data sample



The S5 blind injection challenge

- Blind signal injections were introduced in the second half of S5
- Records of such injections are kept hidden from all but a handful of people
- Goal: test our detection-establishing internal process end-to-end
- “N” burst and inspiral-like signals could have been injected in the LIGO instruments during S5 (N=0 is a possibility)
- Expected to become routine in S6 and beyond (or at least until Nature provides real, astrophysical events routinely)

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17 MAY 1982

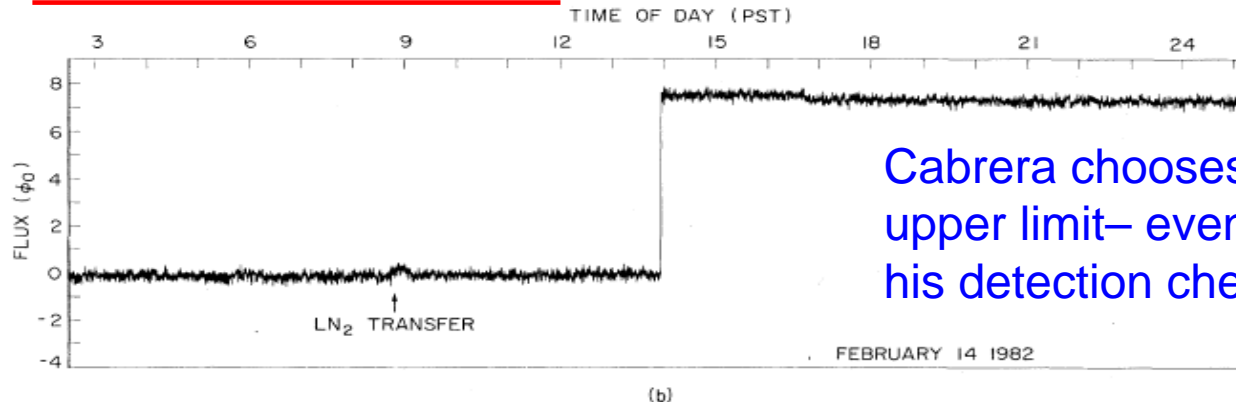
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Cabrera chooses to set an upper limit— event did not pass his detection checklist?

- Luis Alvarez comment on the Price et al. claim on the discovery of a magnetic monopole (1975): ‘My immediate reaction was to say “congratulations”, but, within moment after Buford left my office I started to make some calculations, and I soon convinced myself that the experiment of Price et al. was in serious conflict with several others, including our own search in moon rocks’
 - Andrew Pickering, *Social Studies of Science* (1981) ;11;63
- Confidence in a detection can come from its consistency with all past results (e.g., one will be skeptical if LIGO sees in S5 events with strength and rate that should had been detected in S4)
- The ultimate juror of a detection is the next generation, improved detector

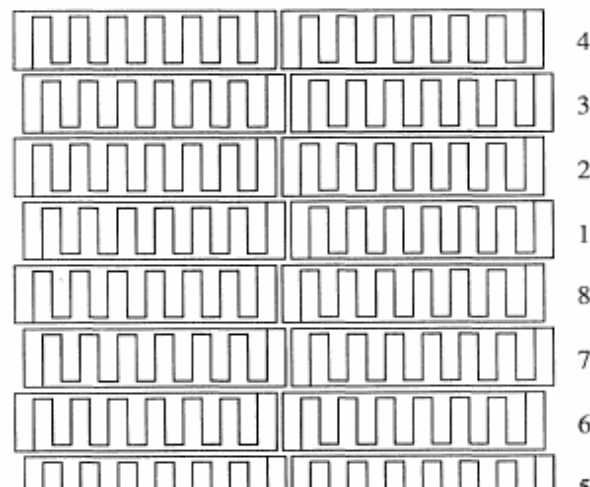
Search for a flux of cosmic-ray magnetic monopoles with an eight-channel superconducting detector

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A superconducting detector for cosmic-ray magnetic monopoles originally designed with a cross section of 1.5 m^2 (averaged over 4π solid angle) for double-coincident events was active from 5 May 1987 to 5 August 1988. The detector consists of eight independent inductive gradiometers located on the surface of an octagonal prism. The conductor is niobium-titanium foil and the current sensors are rf SQUID's. The signal-to-noise ratio for a single Dirac charge is greater than 50 in a 0.05-Hz bandwidth, and low-noise data was obtained over 547 days of continuous cryogenic operation. Of this time, we obtained $\sim 50\%$ live time. Open circuits in portions of two gradiometers and occasional coupling of disturbances in adjacent gradiometers reduce the active sensing area to 1.1 m^2 . A closed-cycle helium liquefier eliminates helium transfers and increases the stability of the data. Anticoincidence instrumentation includes strain gauges, a flux-gate magnetometer, an ultrasonic motion detector, and a wideband rms rf voltmeter. The exposure to date represents a limit on the flux of cosmic-ray magnetic monopoles of $7.2 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ at a 90% confidence level, eliminating most of the phase space for monopole plasma oscillation theories.

VII. CONCLUSIONS

With no candidate events observed, these data set an upper limit of $7.2 \times 10^{-13} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$ at 90% confidence level ($2.3 / \int dA d\Omega dt$) on any uniform flux of magnetic monopoles passing through the Earth's surface at any velocity (Fig. 19). This limit is a factor of 2000 below the flux suggested by the single-candidate event seen with the prototype detector [2] in 1982. Based on this large factor and based on the noncoincident nature of the prototype detector, we conclude that the entire data set from the prototype detector which contains the single event should be discarded when quoting particle-flux limits for cosmic-ray magnetic monopoles. In addition, this new and lower flux limit is below the lev-



- Debate on the confidence of the first detection may be never-ending for certain type of events¹ as arguments challenging their particularities may be brought up both from the instrument and interpretation perspective
- For this, the ultimate detection confidence for the first detection may have to be provided by the second detection

“... as of this writing (early 1984) , it is not certain that nobody has ever seen one (monopole). What seems certain is that nobody has ever seen two.”

– John Preskill, Ann. Rev. Nucl. Part. Sci., 34 (1984) 461-530

¹ the no-brainer detections are excluded here

- The LIGO Scientific Collaboration is making constant progress towards methods and criteria for the first detection and its interpretation.
- Joint analysis with Virgo (present and future) improve our ability to make detections.
- “Detection checklists” help organize our thoughts, our work. Totally blind (or self-imposed) injections and follow up of search outliers hone our procedures, mature our thinking, test our sociology.
- Establishing confidence for the first detection candidate will be an exciting moment for the collaboration but it won’t necessarily be automatic or straightforward (e.g., first detection right at the “threshold”, “without a source” and “without a waveform”).
- While the first detection is a milestone, it is not our goal: it is only the beginning of the road to gravitational wave astronomy
- Good time to be optimistic:
 - » S5 data analysis are well underway
 - » enhanced detectors in 2009+ will increase science reach $\times O(10)$
 - » advanced LIGO will bring detections with near certainty
- Please let us know of any other tests you think our detection checklist should encompass and please stay tuned!