First Detections

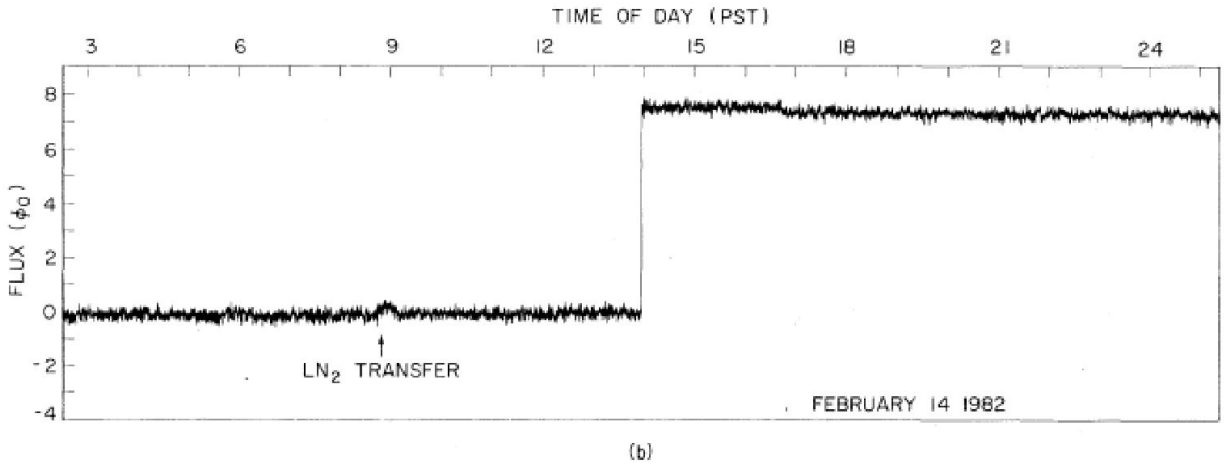
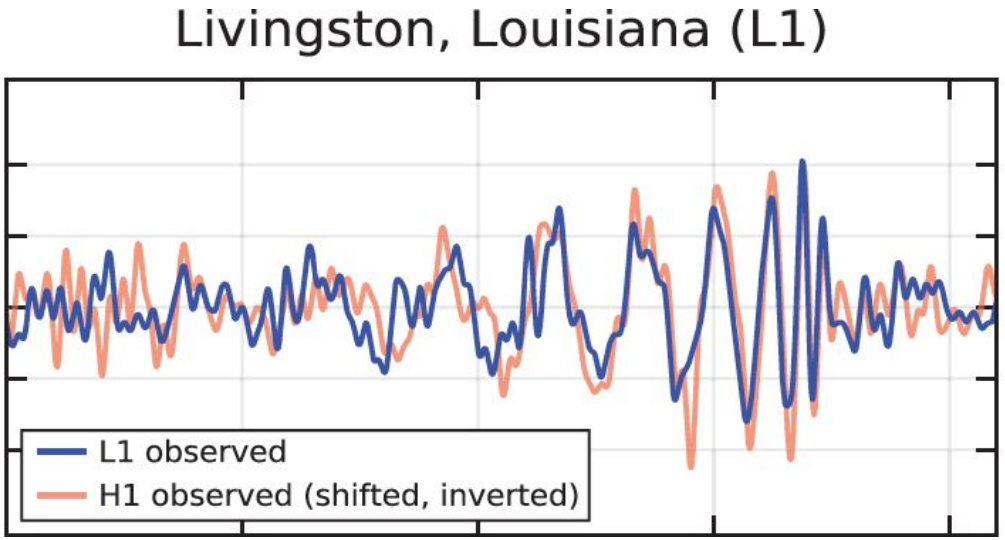


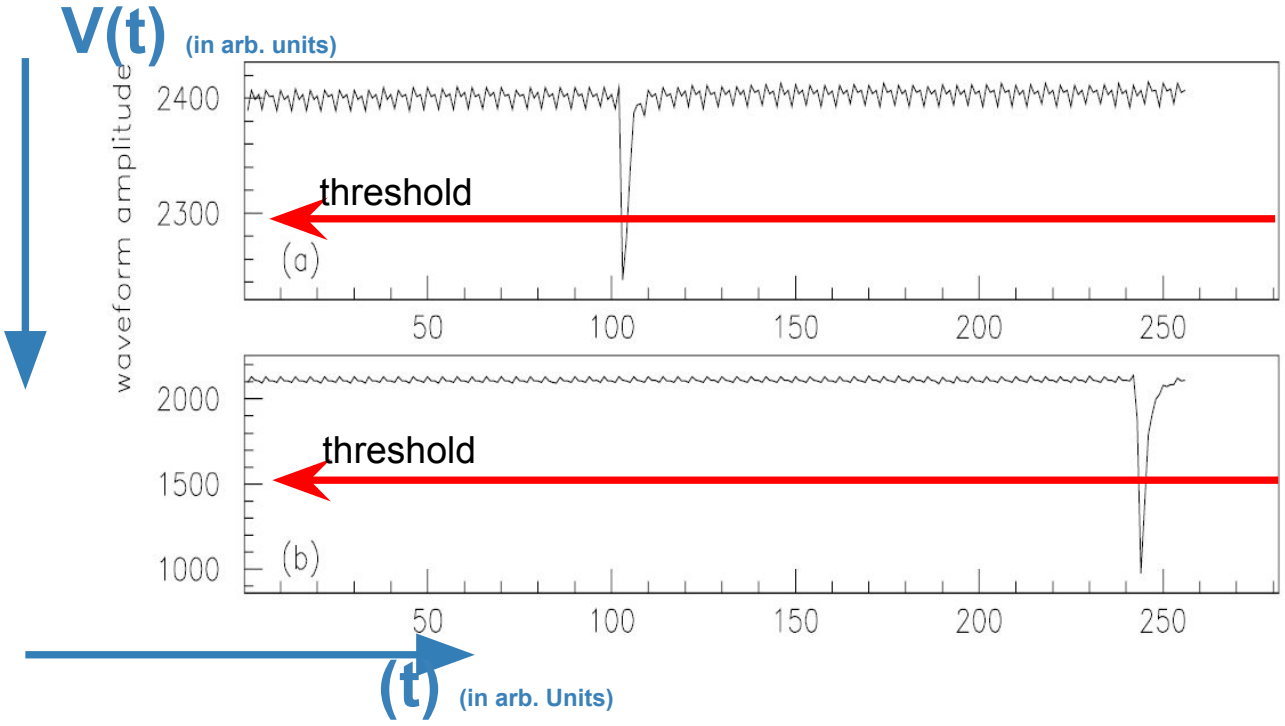
FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

Erik Katsavounidis
MIT



September 14, 2015, 09:50:45 UTC

Time series *x(t), x(n)*



Time domain analysis: little information in the frequency content; count particles, integrate charge etc.

Time-frequency information

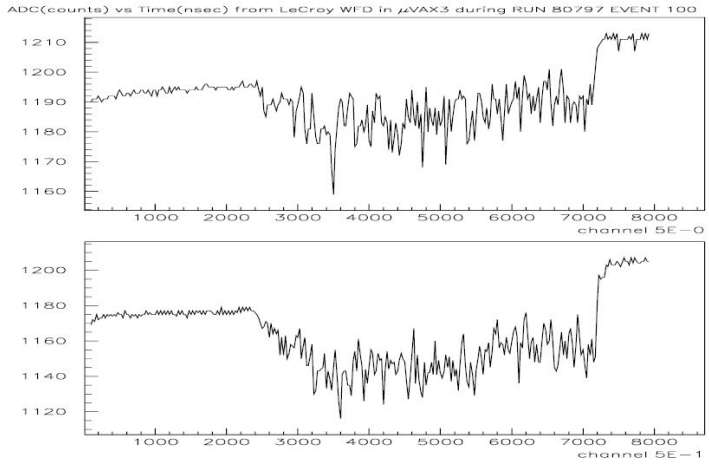


Figure 5.1: Typical LED-induced event as recorded by the WFDs during RUN 80797. The pulse width driving the LEDs was approximately $5\mu s$. The recorded waveforms show the typical LED risetime. A few thousand photoelectrons are included in each of the waveforms.

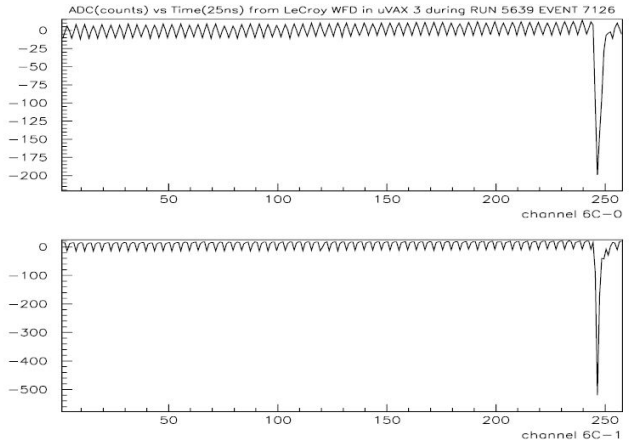
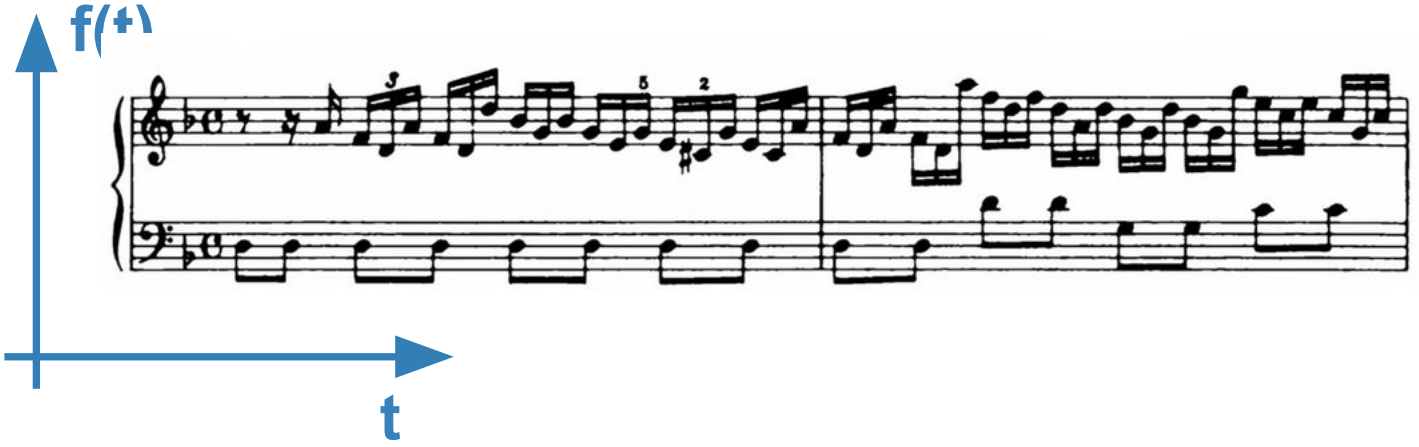


Figure D.3: Both of the above waveforms have been identified by means of the Haar transform as sharp ones. Although their apparent pulse height and pulse integral (number of photoelectrons) should have been enough to trigger the ERP in both ends of the tank, the ERP failed to fire.

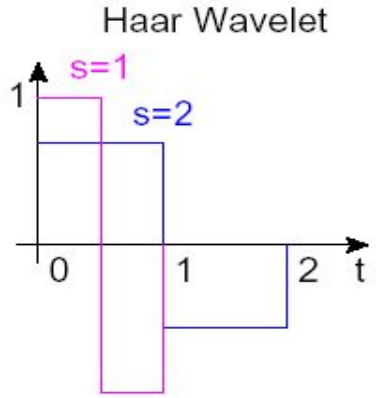
Time-frequency localization

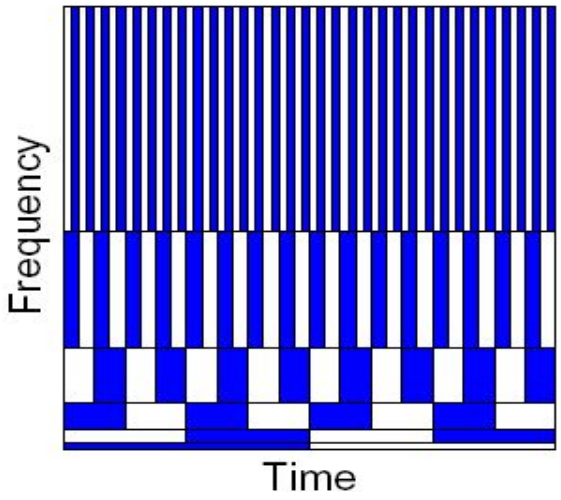


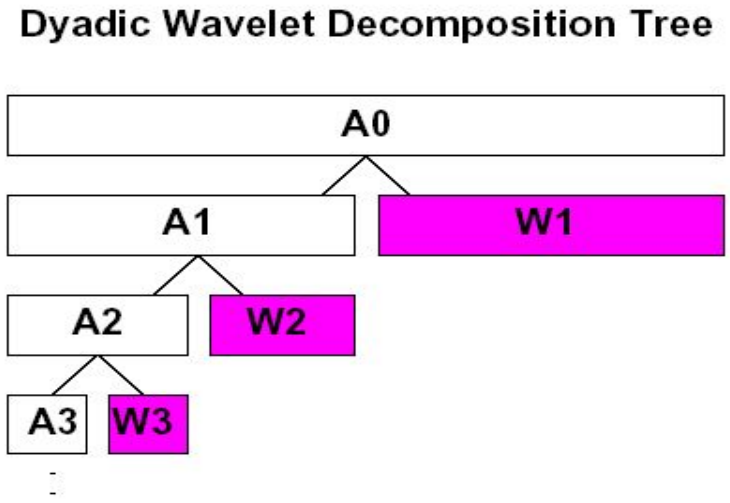
Multiresolution techniques

Project $x[n]$ onto time-shifted and scaled wavelets.

$$X_W[m,s] = \sum_{n=0}^{N-1} x[n] \frac{1}{\sqrt{2^s}} \psi\left(\frac{(n-m)T}{2^s}\right)$$







Gravitational-wave detector data

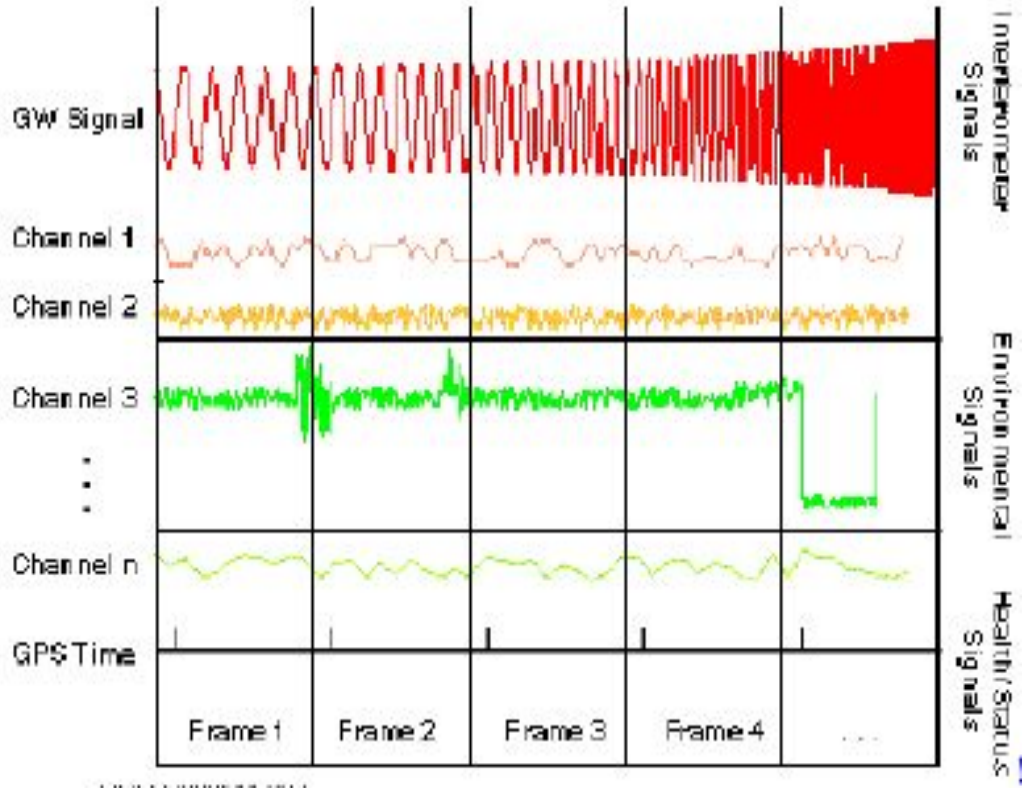
Continuous **time series** (1Hz, 128Hz … 16kHz)

Gravitational Wave channel:
~20GB/day (per instrument)

Physical Environment Monitors (seismometers, accelerometers, magnetometers, microphones etc)

Internal Engineering Monitors (sensing, housekeeping, status etc)

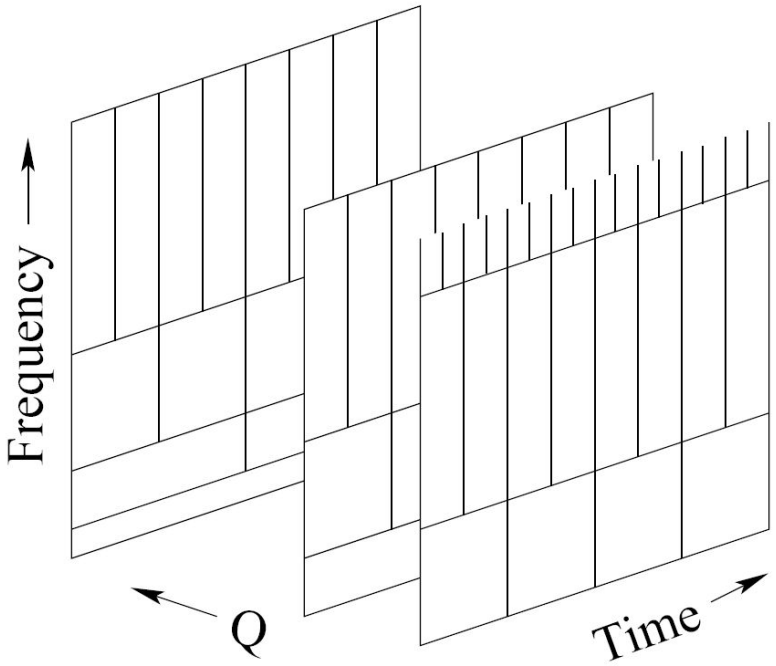
Together with various intermediate data products >2TB/day (per instrument)

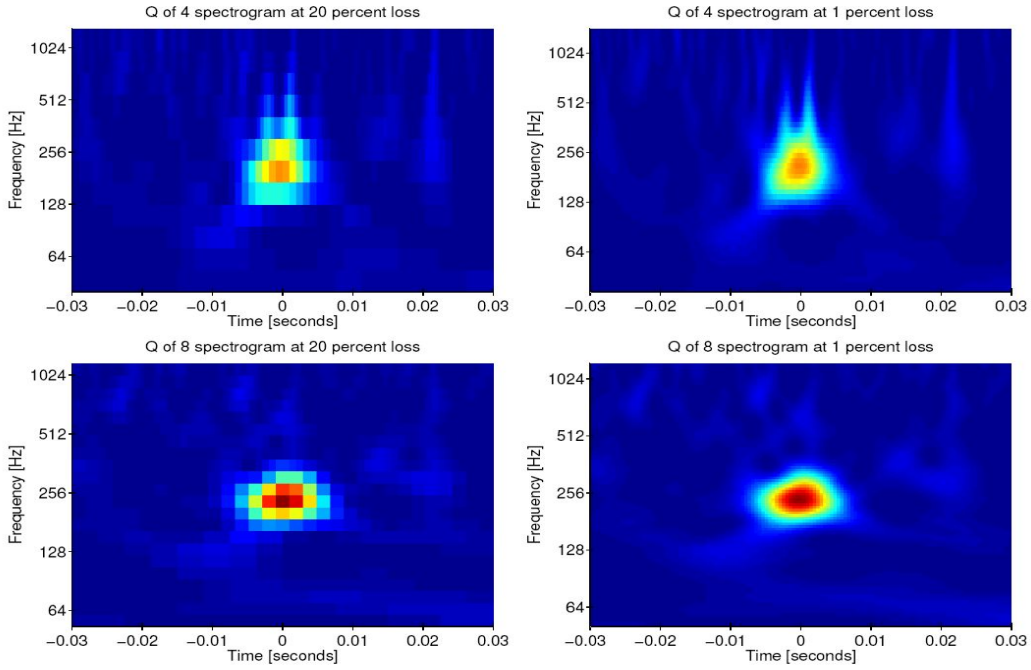


The Q transform

Project whitened data onto multiresolution basis of minimum uncertainty waveforms

$$X(\tau, \phi, Q) = \int_{-\infty}^{+\infty} x(t)\, w(t-\tau, \phi, Q)\, e^{-i2\pi\phi t}\, dt$$





S. Chatterji, MIT thesis 2005

INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **21** (2004) S1809–S1818 PII: S0264-9381(04)80352-6

Multiresolution techniques for the detection of gravitational-wave bursts

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Received 5 May 2004, in final form 5 August 2004
Published 30 September 2004
Online at stacks.iop.org/CQG/21/S1809
doi:10.1088/0264-9381/21/20/024

Abstract

We present two search algorithms that implement logarithmic tiling of the time–frequency plane in order to efficiently detect astrophysically unmodelled bursts of gravitational radiation. The first is a straightforward application of the dyadic wavelet transform. The second is a modification of the windowed Fourier transform which tiles the time–frequency plane for a specific Q. In addition, we also demonstrate adaptive whitening by linear prediction, which greatly simplifies our statistical analysis. This is a methodology paper that aims to describe the techniques for identifying significant events as well as the necessary pre-processing that is required in order to improve their performance. For this reason we use simulated LIGO noise in order to illustrate the methods and to present their preliminary performance.

PACS numbers: 04.80.Nn, 07.05.Kf, 02.70.Hm, 95.55.Ym

Performance of the WaveBurst algorithm on LIGO data

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† Department of Physics, University of Florida, Gainesville, FL 32611, USA
‡ LIGO Livingston Observatory, Livingston, LA 70754, USA

Abstract. In this paper we describe the performance of the WaveBurst algorithm which was designed for detection of gravitational wave bursts in interferometric data. The performance of the algorithm was evaluated on the test data set collected during the second LIGO Scientific run. We have measured the false alarm rate of the algorithm as a function of the threshold and estimated its detection efficiency for simulated burst waveforms.

How can one claim a first detection in rare event searches?

Can one claim a first detection based on a single event?

Can one run an experiment with zero background?

The magnetic monopole paradigm

Pollock, Phys. Rev. A 24, 1544 (1981).
[3]F. 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).
[4]L. Spitzer, Jr., *Physics of Fully Ionized Gases* (Interscience, New York, 1956).
[5]L. P. Kadanoff and P. C. Martin, Ann. Phys. (N.Y.) 24, 419 (1963).
[6]P. V. Giaquinta, M. Parrinello, and M. P. Tosi, Phys. Chem. Liq. 5, 305 (1976); B. Bernu, to be published.
[7]B. Bernu and P. Vieillefosse, Phys. Rev. A 18, 2345 (1978).
[8]H. Minoo, M. M. Gombert, and C. Deutsch, Phys. Rev. A 23, 924 (1981).
[9]R. J. Bearman and J. G. Kirwood, J. Chem. Phys. 28, 136 (1958).

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-cm^2-area superconducting loop. A single candidate event, consistent with one Dirac unit of magnetic charge, has been detected during five runs totaling 151 days.

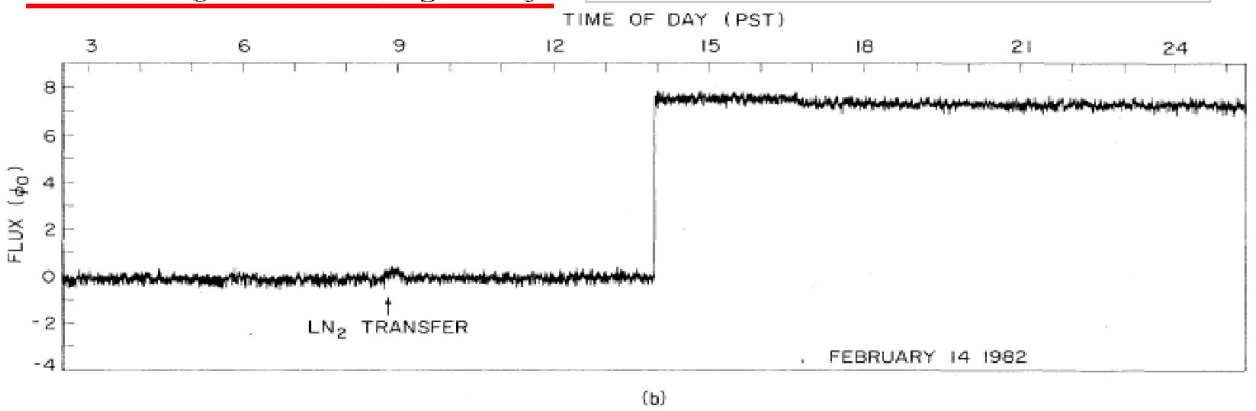


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

Cabrera's "detection checklist" from PRL 48, 20 (1982)

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

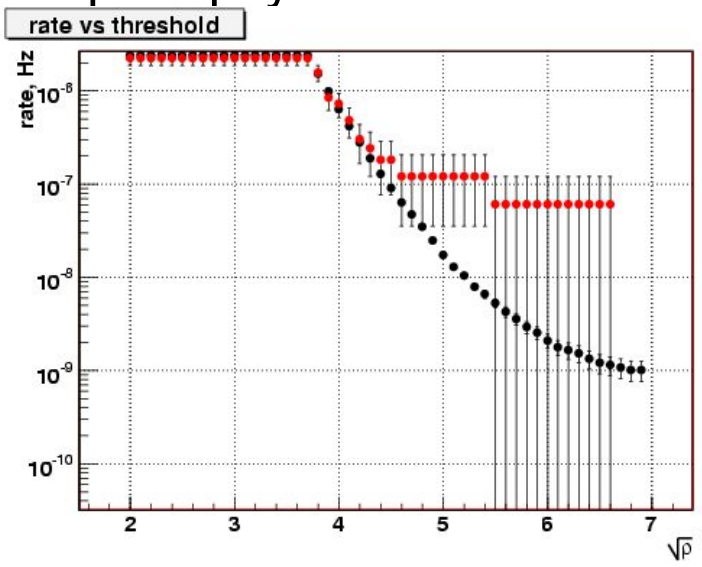
- Flux consistent with one Dirac unit of magnetic charge
- Local missing mass density: 0.05 M_solar/pc^3 made up of monopole of mass 10^{16}GeV at 300km/sec would result in 1.5 events per year through his detector

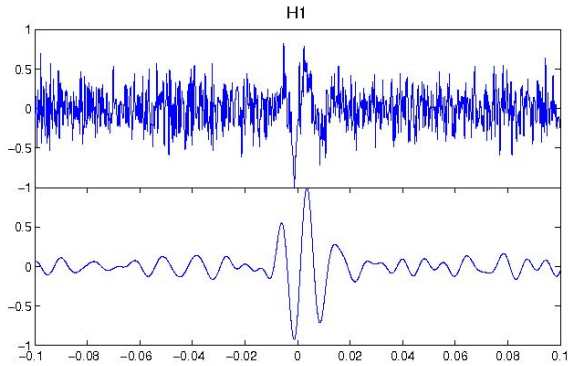
Blind injection challenges in GW detection

Two blind injections in the 2007 run and one blind injection in 2009

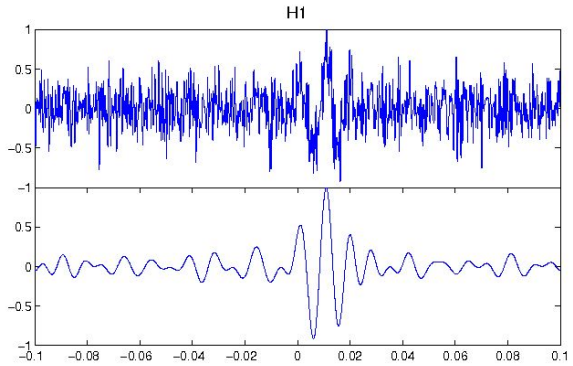
Extremely valuable in honing the ability to understand what it means to vet a gravitational-wave transient event to a level to call it astrophysical.

Many lessons learned in terms of the importance to look at the data promptly and in establishing detection follow-up criteria





Equinox event



Equal mass, no spin, 70+70 solar mass black hole merger

Detection checklist

https://wiki.ligo.org/Bursts/DetectionChecklist_S6_968654557 80%

Checklist

Please notice that some of the suggested checks may conflict with the notion of keeping ourselves blind from the possible blind injection. Do not undertake any such checks until after the blind injection challenge has been declared over.

Status: X (Complete), I (Incomplete), O (Open, Critical), NA (Not Applicable)

Contributors: Generally, if the contributor name appears in parentheses () that individual or group was largely responsible for covering the item, but the item was linked and summarized in this wiki by a third party. Names not in parentheses are generally the people who directly entered the item in the wiki.

ID	Category	Check Description	Status	Contributors	Link
1	Zero-level sanity	Convert GPS times to calendar times and check for suspiciousness. **Sep 16 2010 06:42:22.95 UTC. Other than happening within a day of the return of 3-detector data, not suspicious**	X	Brennan	
2	Zero-level sanity	Read e-logs for the times/days in question. Was there anything anomalous going on? **Nothing stands out in H1, L1 or V1 logs**	X	Brennan, Nicolas	H1 L1 V1
3	Zero-level sanity	S6 update: Check the data quality flags active around the event time for each instrument. Are there active flags? Any potential vetoes among active flags? **LUMIN DQ check shows only active cat 5 Virgo flags and no undefined flags. Confirmed by rerunning ligo_lw_dq_active_cats 12 hours after event on both 968654558 and 968654557 with S6D online burst definer file and S6_CBC_LOWMASS_CURRENT_ONLINE definer file. (Obviously will need to re-run once offline flags are finalized)** **Detchar analysis determines all active flags (including those not in online cat definer files) to not impact any detection statement**	X	Brennan,(DetChar)	LUMIN DQ DetChar page Virgo page
4	Zero-level sanity	Identify inspiral range of the instruments in order to set the scale of sensitivity. Is this typical/low/high? **SenseMon for both H1 and L1 reports 18-19Mpc. This is typical for this part of the run and time of day. Virgo was a steady ~4.5Mpc.**	X	Dan Hoak, Nicolas Josh (spectra)	H1 FOMs L1 FOMs V1 inspiral range

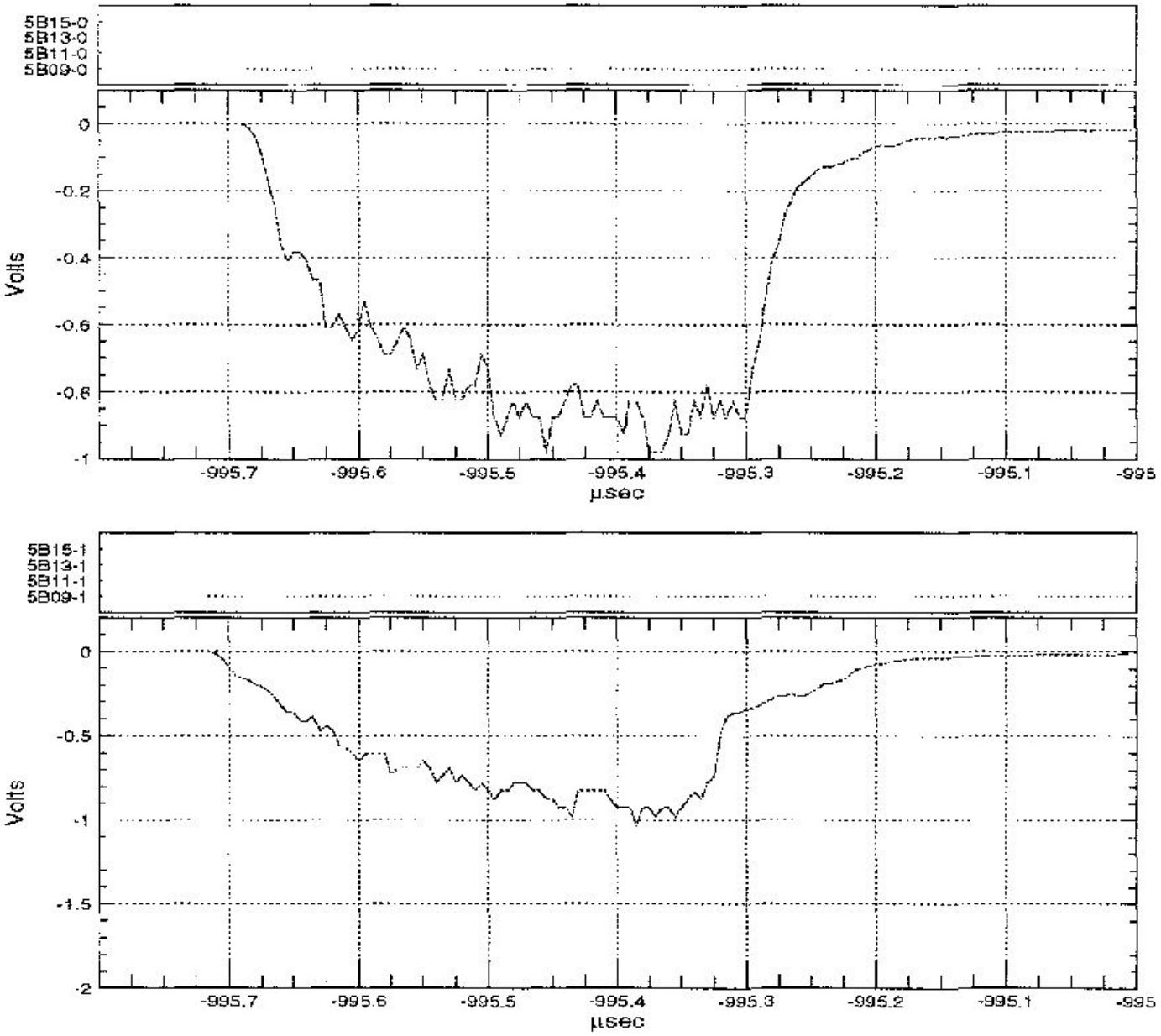
		Checked skyalert.org, nothing obviously happening at time of event. No nearby Swift GRBs, one Fermi GRB ~12 hours later. Significant transient from Catalina Real-time Transient Survey also hours after the event			
76	non-GW detectors	Was a LIGO-Virgo trigger sent out for EM follow-ups? Any interesting results? **Follow-ups were performed with several terrestrial telescopes and Swift. Preliminary X-ray data from Swift indicates no X-ray sources in 2 observed fields, optical telescope results require further analysis.**	I	(Christian, Jonah, LUMIN team),Brennan	Initial LUMIN report Follow-up info for Big Dog
77	Astrophysics	Any known sources overlapping the ring/patch on the sky corresponding to the direction of the candidate event? **The top 5 pixels within the cWB error area that intersect known galaxies within 50Mpc include objects from ~9 to 47 Mpc.**	X	Erik	GEM galaxies for Swift followup (use standard LVC passwd)
78	Astrophysics	Examine events (other than the candidate) reconstructed at the same direction. Perform a directional search; if a point source is behind this, more, lower SNR events might be in our data.	NA		Link
79	Astrophysics	How the extracted waveforms compare to astrophysical waveforms? What is the energy scale going into GW, assuming galactic distances? **The waveforms are very consistent with what we would expect from a binary black hole inspiral/merger.**	I	All	Link
80	Other methods	Take the extracted waveform per IFO and run matched filtered search in order to establish how often the specific morphologies appear in the data.	O		Link
81	the event	SNR as color in Omega scans	X	Satya	SNR vs Normalized Energy as color in Omega scans
82	the event	cWB sensitivity for BBH around the sept16th event params	X	Satya	Extrapolation of cwbSensitivity
83	the event	time-frequency animation 3 s before and after the event	X	Satya	Omega scan animation +/- 3 s of the event
84	the event	residual time-frequency morphology after MCMC best fit waveform is subtracted	X	Satya	MCMC best fit waveform subtracted Omega scans

Were we capable to detect magnetic monopoles in MACRO?

A blind monopole signal injection

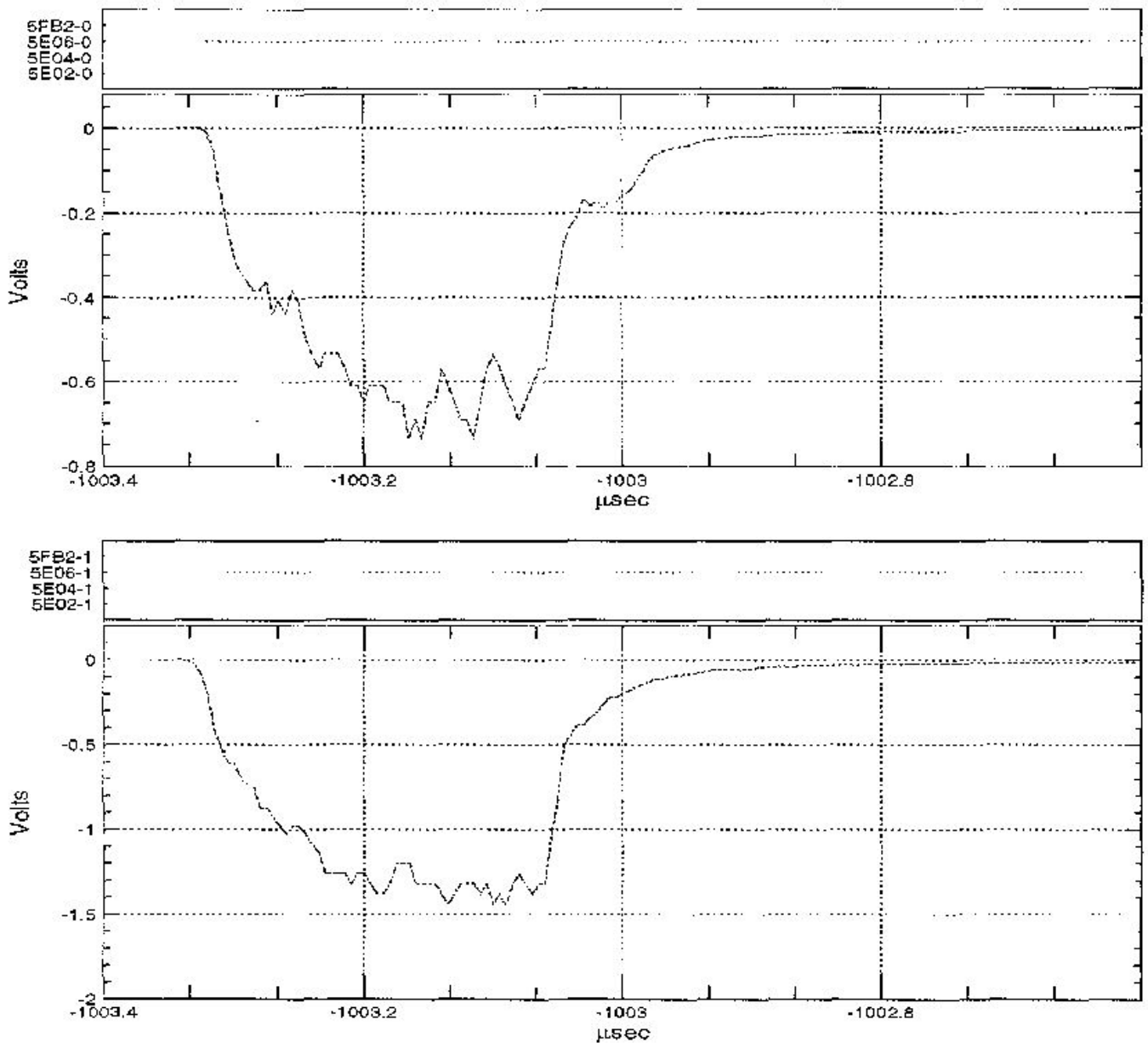
```
^@Dear Barry, dear Giorgio,?^@The fake monopole event I talked to you about w
as just inserted<^@in the data stream at 22 April 2000 15:58:00 Universal Tim
e,@^@MACRO RUN # 19441. As soon as this RUN is closed I'll e-mail youB^@the f
ull event details. The test seemed to be successfull; however@^@it will take
a full RUN analysis to verify it. I'll let you know^X^@later today or tomorro
w.^F^@--Erik

 ^@Return-Path: <GIACOMELLI@axpbo.bo.infn.it>D^@Received: from gsnet0.lngs.inf
n.it by axpgs0.lngs.infn.it with SMTP;(^@          Tue, 25 Apr 2000 9:49:47 +
0200D^@Received: from axpbo3.bo.infn.it (axpbo3.bo.infn.it [131.154.10.68])<^
@         by gsnet0.lngs.infn.it (8.9.3/8.9.3) with ESMTP id JAA02065Q^@  for
<Erik.Katsavounidis@lngs.infn.it>; Tue, 25 Apr 2000 09:49:46 +0200 (MET DST)A
^@Received: from axpbo.bo.infn.it (axpbo.bo.infn.it [131.154.11.4])9^@ by axp
bo3.bo.infn.it (8.9.3/8.9.3) with SMTP id JAA15685Q^@     for <Erik.Katsavoun
idis@lngs.infn.it>; Tue, 25 Apr 2000 09:49:54 +0200 (MET DST)B^@Received: by
axpbo.bo.infn.it for Erik.Katsavounidis@lngs.infn.it;(^@          Tue, 25 Apr
 2000 9:50:07 +0200$^@Date: Tue, 25 Apr 2000 9:50:07 +02008^@From: GIORGIO GI
ACOMELLI <Giorgio.Giacomelli@bo.infn.it>#^@To: Erik.Katsavounidis@lngs.infn.i
t.^@Message-Id: <000425095007.2c02858e@bo.infn.it>R^@Subject: RE: MACRO 'test
' monopole: http://cithe502.cithep.caltech.edu/~kats/evnt/^@^@N^@
                                          Bologna, 25-APR-2000^@^@^N^@
 dear Erik,^@thanks for the informations about the fake monopole: let us hope
 that*^@everybodi has a good efficiency to see it!   ^@greetings^@^@5^@
                            Giorgio Giacomelli
```

```
>>> RUN:    19441 EVENT:       2560 LENGTH:  13212
>>> AT 22-APR-2000 15:59:18.37
>>> VAX TIME:   0- 4-22 15:59:18.370001 UT:   0- 4-22 14:57:59.978302
>> uVax 1 had  0 triggers!
>> uVax 2 had  2 triggers!
>triggers  > 13:SPAM_MU 15:2/3_EVNT
>> uVax 3 had  4 triggers!
>triggers  >  2:ERP_MUON 7:CIT_MONO12:SPAM_FMT16:2/3_EVNT
>eqp32(SP)w1> 1:FMT56    3:TOHM5    7:ERP5
>eqp32(SP)w2>
>eqp32(SP)w3> 2:ERP MU   7:TOHM    12:FMT
WFSTPSM5/F3A0  /TRGPAT>  1:CITm  2:ERPM  4:FMTm
WFSTPSM5/F2A0:7/TRGTIM> 1(CITm):   44 2(ERPM):    0 3(STmn):10016 4(FMTm):   79
WFSTPSM5/F2A0:7/TRGTIM> 5(SPAM):10016 6(LIPT):10016 7(xSTP):10016 8(HIPT):10016
WFSTPSM5/F5A0  /CITPAT>  1:x2Fc  3:BOTT  5:EAST 12:i2Fc 14:EMPT
WFSTPSM5/F4A0:7/CITTIM> 1(CENT): 9760 2(BOTT):   69 3(WEST): 9760 4(EAST):    0
WFSTPSM5/F4A0:7/CITTIM> 5(NorS): 9760 6(TOP ): 9760 7(SM-1): 9760 8(SM+1): 9760
>eqp22     (ERP Muon) registered      2 hits in SM 5 :
5B09 ADC&TDC(1A/2A/1B/2B) 2126 1675  721  233 & 4095 4095 4095 4095 E/P   0   0
5E06 ADC&TDC(1A/2A/1B/2B) 1493 3139  243  367 & 2454 2507 2447 2533 E/P   0   0
Box -mTIME(sec,NoAt/At) PhotoElectrons(0/1) Energy(MeV, T/PE) Position(cm,T/PE)
5B09   680.06    682.44    1446.7    1039.1     63.2     62.1  -132.01  -188.33
5E06   417.75    419.88    6991.3   15108.9    137.4    117.9    88.60   459.78
>eqp30(CSPM-uV):(LOW )  5bH1 5bH0 5eL1 5eL0
>eqp30(CSPM-xV):(LOW )  5bH1 5bH0 5eL1 5eL0
>eqp30(CSPM-uV):(HIGH)  5EL1
>eqp30(CSPM-xV):(HIGH)  5EL1
>eqp27(CIT-LOWtrg): 5B09 5E06
>eqp27(CIT-LOWact): 5B09 5E06
```



Sophia Kyriazopoulou
PhD Thesis

Figure 6.14: Run 19441, Event 2560. The segment of the waveforms for tank 5B09 that fires the PR algorithm. The time axis is in units of μs before the WFD stop.



Sophia Kyriazopoulou
PhD Thesis

Figure 6.13: Run 19441, Event 2560. Segment of the waveforms of tank 5E06. The time axis is in units of μs before the WFD stop.

GW150914: A binary black hole merger

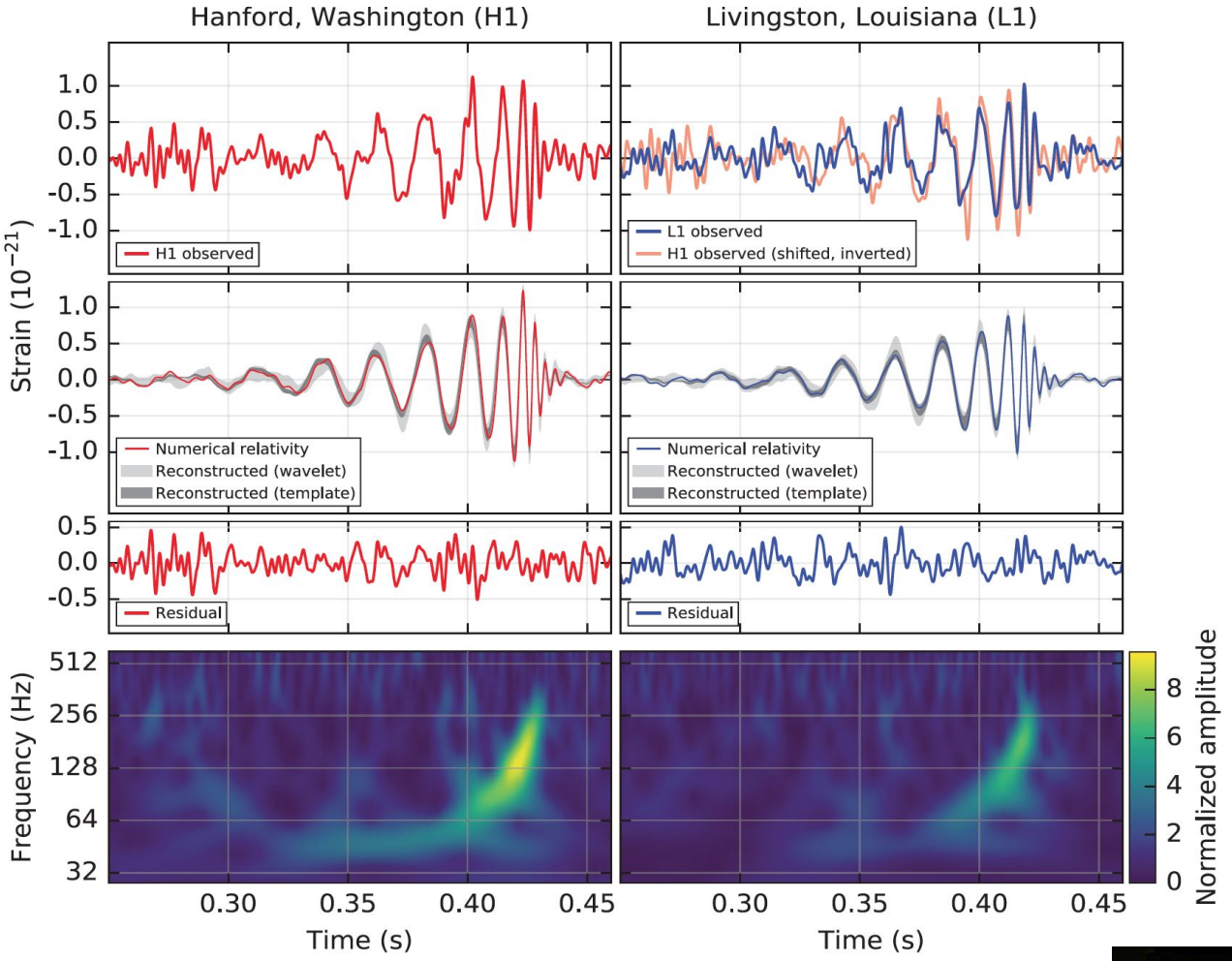
LIGO and Virgo Collaborations Phys. Rev. Lett. 116, 061102 –11 February 2016

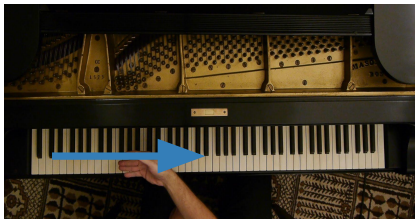
Time series from detectors bandpassed 35-350Hz

Best fit waveforms/NR

Time series minus best fit

Spectrogram

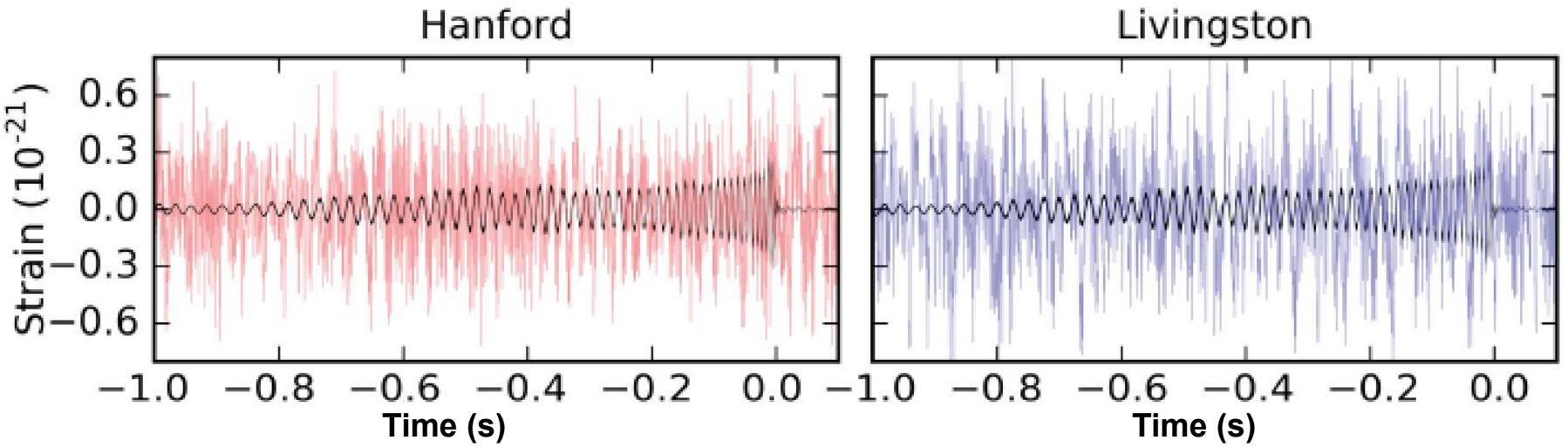




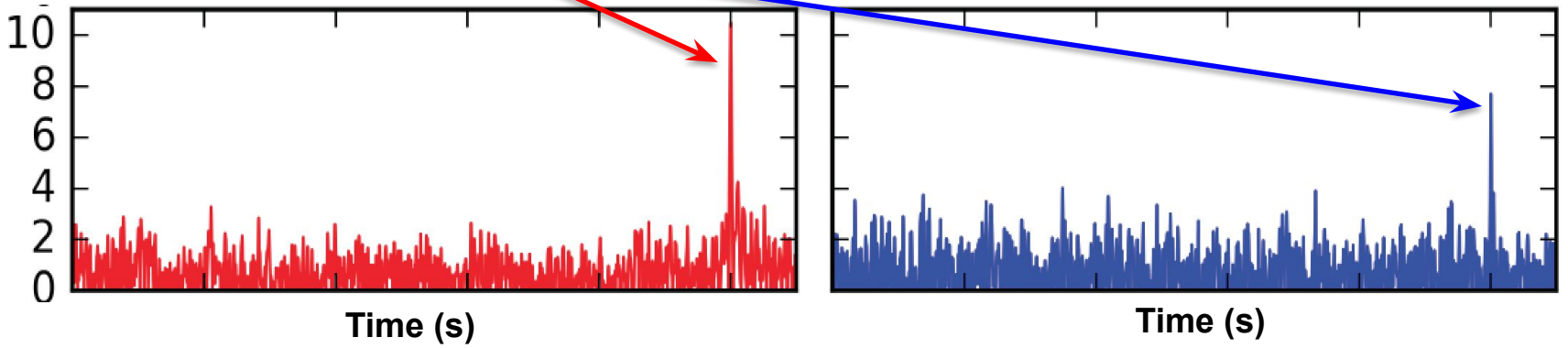
«*Lasciate ogni speranza, voi ch’entrate»*

The second detection: GW151226

LIGO and Virgo Collaborations, Phys. Rev. Lett. **116**, 241103 (2016) (June 15, 2016)



Signal-to-noise (SNR) when best template matches at coalescence time



A Binary Black Hole system with 14+8 solar masses (false-alarm-rate <1/Myr)

The ultimate detection confidence

"… 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

CAN A GRAVITATIONAL WAVE AND A MAGNETIC MONOPOLE COEXIST?

Re: MPLA/358/97

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Abstract

We investigate the behavior of small perturbations around the Kaluza-Klein monopole in the five dimensional space-time. We find that the even parity gravitational wave does not propagate in the five dimensional space-time with Kaluza-Klein monopole pro-