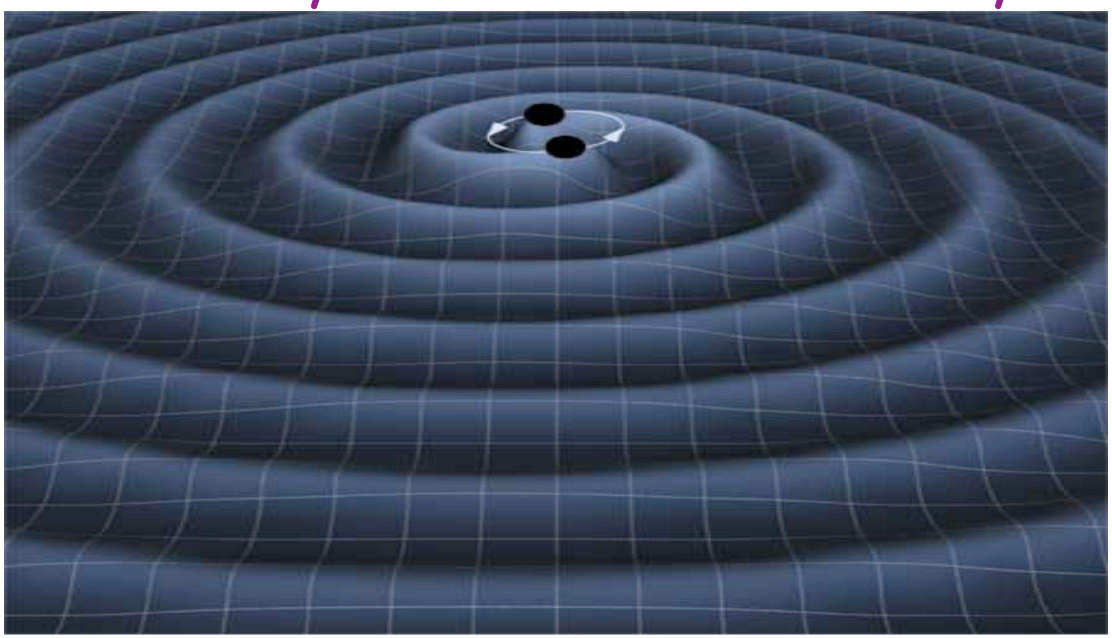
Searches for Gravitational Wave Bursts : Methods and Challenges

Shantanu Desai

Pennsylvania State University



Outline

- Basics of Signal Detection as applied to LIGO
- Similarity with other fields
- “Nuts and Bolts” of LIGO Burst Searches
- Examples of S5 Transient Noise Events
- Aperture synthesis techniques (brief)
- Connection with Dark Matter conundrum

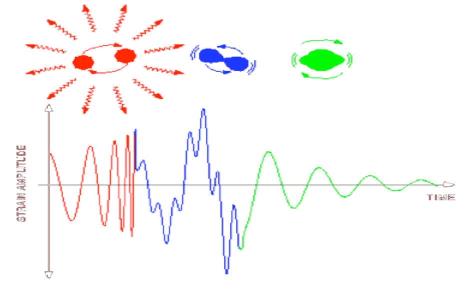
This talk will not present any results from burst searches, but only the methods used.

Jargon used in this talk

- ETG Event Trigger Generator (algorithm for burst searches)
- IFO Interferometer
- H1 4 km LIGO Hanford detector
- H2 2 km LIGO Hanford detector
- L1 4 km LIGO Livingston detector
- Glitch Noise transient

LIGO Science Analysis Efforts

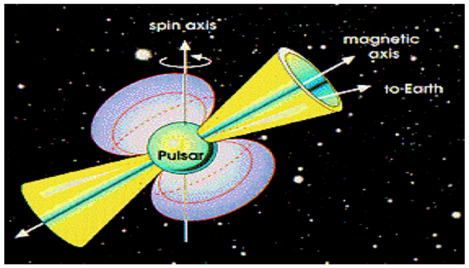
- Compact Binary Inspirals :
  - ➢Template based searches for merger of neutron star/black hole based binaries



- Unmodelled burst sources : ✔
  - ➢Short duration transients(< 1sec) without any knowledge of waveform (core-collapse SN, GRBs etc)

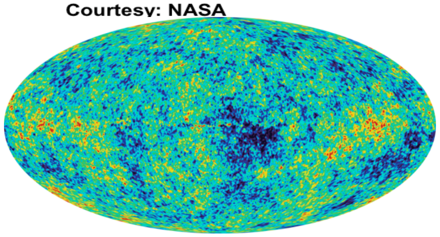

SN1987A

- Periodic sources :
  - ➢Known and unknown pulsars in our galaxy



Courtesy: NASA

- Stochastic Background :
  - ➢Search for cosmological background from a variety of early universe processes.


NASA WMAP

Basics of Signal Detection

A. Estimate number of signal events
B. Calculate the expected background

→ Based on (A) and (B), make a decision on whether there is a detection or if expected signal is consistent with background And there is no detection.

In case of a claimed detection you need to asses the ``statistical significance''

IMPORTANT: Decision on detection/no-detection is not a binary statement . Explicit calculation of the probability of the signal being due to fluctuation of the background must be evaluated.

Similarity to other fields

Issues in LIGO data analysis techniques similar to

- TeV γ-ray astronomy
- Neutrino astronomy

and High-energy physics experiments such as searches for

- Proton decay
- Magnetic monopoles (1982 Cabrera event)
- Higgs boson (2000 LEP results)
- Neutrino-less double-beta decay
- Dark matter detection
- Super-symmetry
- Fractionally charged particles, etc

} No detection so far (some wrong claims of detection)

Important to keep track of how the data analysis in the above searches are done.

Philosophy in LIGO Data Analysis

Surely you are joking Mr. Feynman (1985)

In his speech *Cargo Cult Science* (58), Richard Feynman warns that

> It's a thing that scientists are ashamed of—this history—because it's apparent that people did things like this: When they got a number that was too high above Millikan's, they thought something must be wrong—and they would look for and find a reason why something might be wrong. When they got a number closer to Millikan's value they didn't look so hard. . .
>
> The first principle is that you must not fool yourself—and you are the easiest person to fool.

Blind Analysis done in LIGO (unlike in astronomy) usually done In high energy physics experiments.

Look at the observed signal events ONLY after the background has been tuned and fixed.

Incorrect claims of detection

Dark Matter: *R. Bernabei et al 0804.2741*

The highly radiopure $\simeq$ 250 kg NaI(Tl) DAMA/LIBRA set-up is running at the Gran Sasso National Laboratory of the I.N.F.N.. In this paper the first result obtained by exploiting the model independent annual modulation signature for Dark Matter (DM) particles is presented. It refers to an exposure of 0.53 ton$\times$yr. The collected DAMA/LIBRA data satisfy all the many peculiarities of the DM annual modulation signature. Neither systematic effects nor side reactions can account for the observed modulation amplitude and contemporaneously satisfy all the several requirements of this DM signature. Thus, the presence of Dark Matter particles in the galactic halo is supported also by DAMA/LIBRA and, considering the former DAMA/NaI and the present DAMA/LIBRA data all together (total exposure 0.82 ton$\times$yr), the presence of Dark Matter particles in the galactic halo is supported at 8.2 σ C.L..

Above claim not generally accepted as it is ruled out by other sensitive dark matter experiments even though the claimed significance is ~ 8 σ

Incorrect claims of "excess"

Gravitational Waves *P. Astone et al gr-qc/0301092*

Abstract

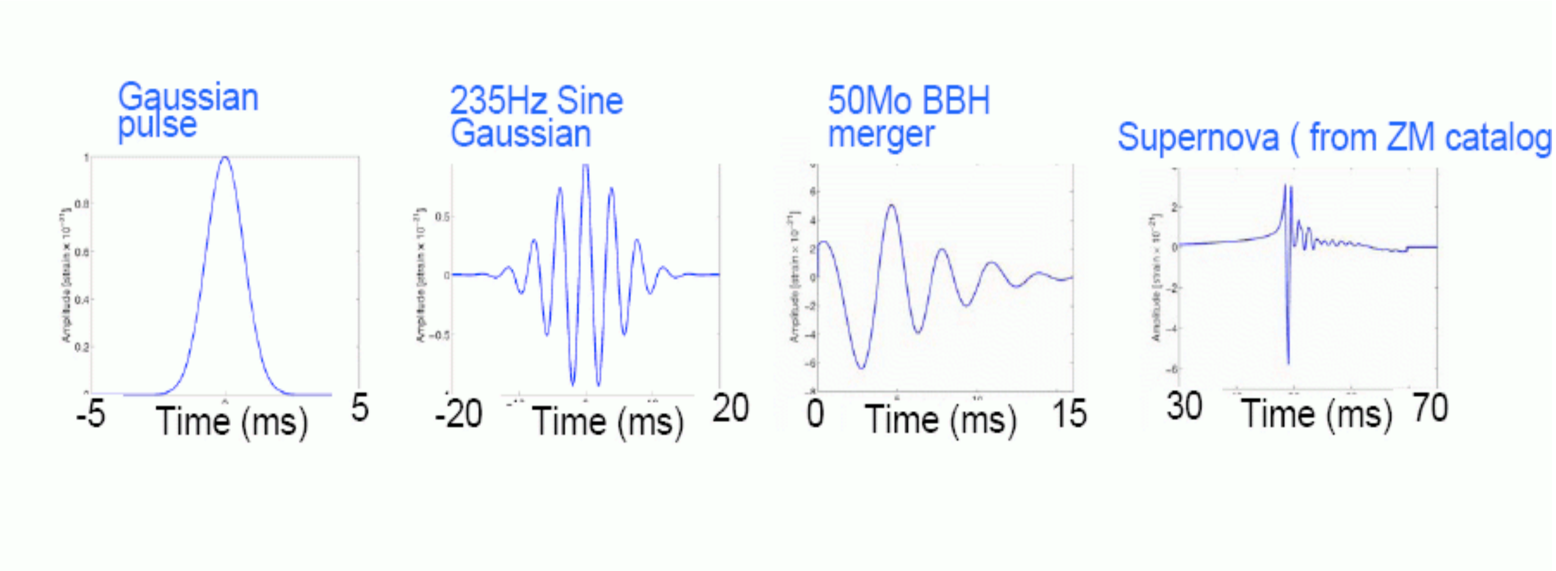
We report the result from a search for bursts of gravitational waves using data collected by the cryogenic resonant detectors EXPLORER and NAUTILUS during the year 2001, for a total measuring time of 90 days. With these data we repeated the coincidence search performed on the 1998 data (which showed a small coincidence excess) applying data analysis algorithms based on known physical characteristics of the detectors. With the 2001 data a new interesting coincidence excess is found when the detectors are favorably oriented with respect to the Galactic Disk.

See L.S. Finn : gr-qc/0301092 for a critique of the above result

→ Important to understand sources of background and
Do various cross-checks in case of something interesting.

LIGO Classification of Burst Searches

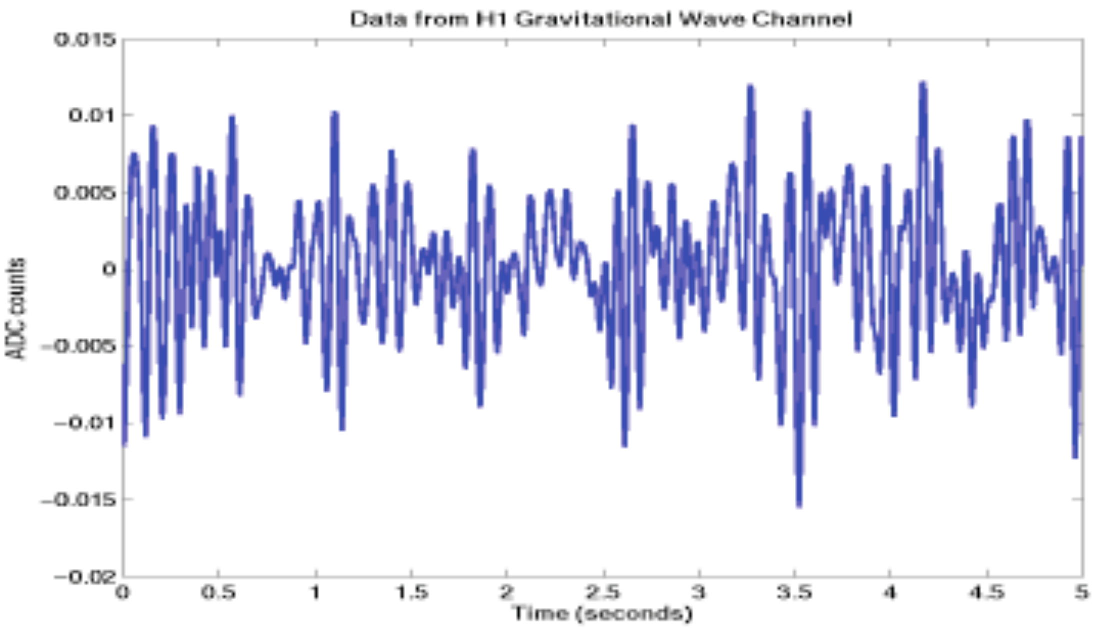
- All-sky all-waveform searches ("untriggered searches") at all times



- Triggered Searches : Look for gravitational wave signals associated with electromagnetic triggers

Rudiments of LIGO Data

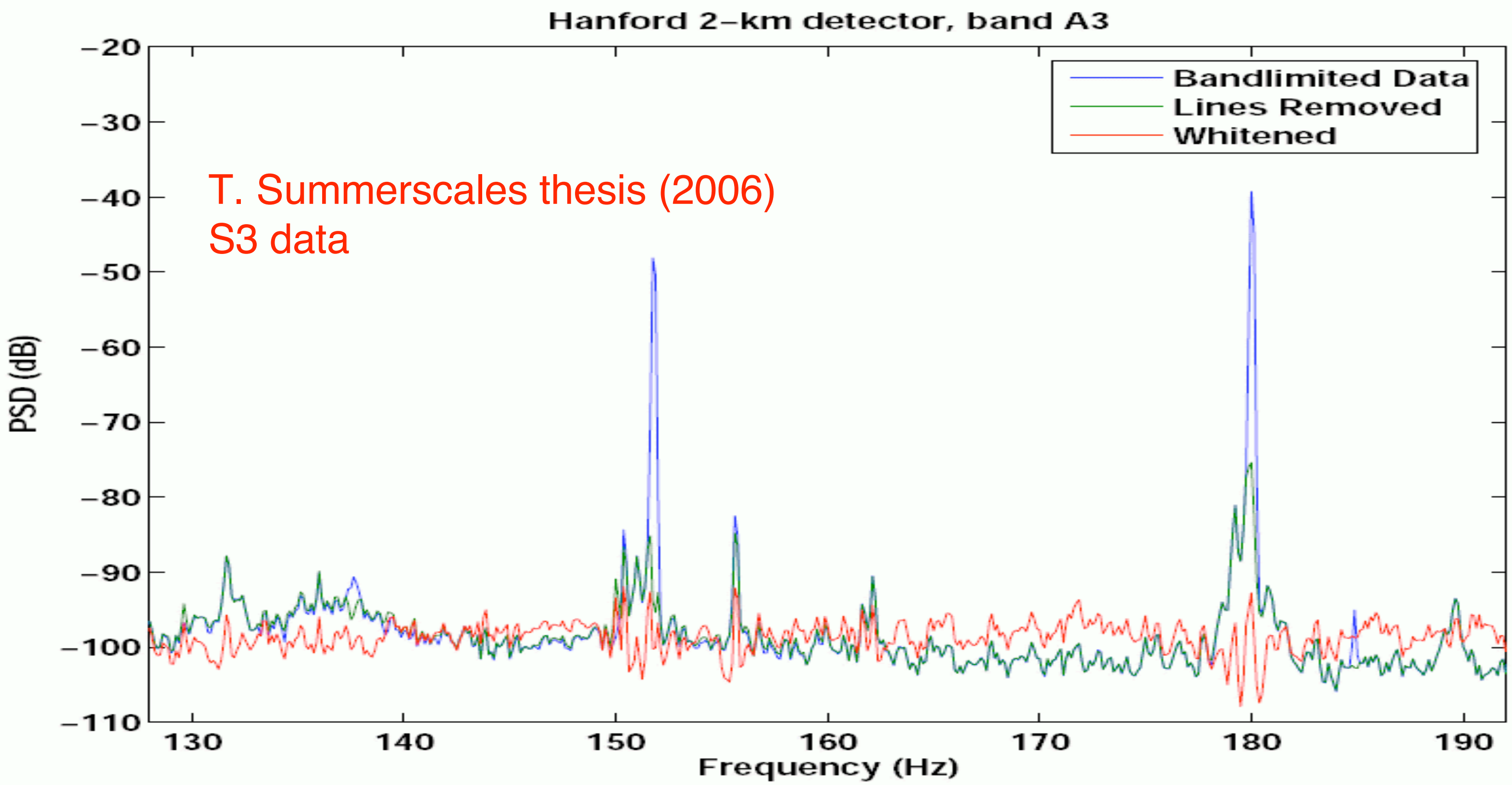
- LIGO data containing possible gravitational wave signal is sampled at 16 KHz and digitized in a data acquisition unit called gravitational wave channel



- Data from auxiliary control channels in the detector and various environmental monitors (eg. seismometers, magnetometers) also stored in similar "channels" for diagnostic and off-line trouble-shooting.

Conditioning of Data

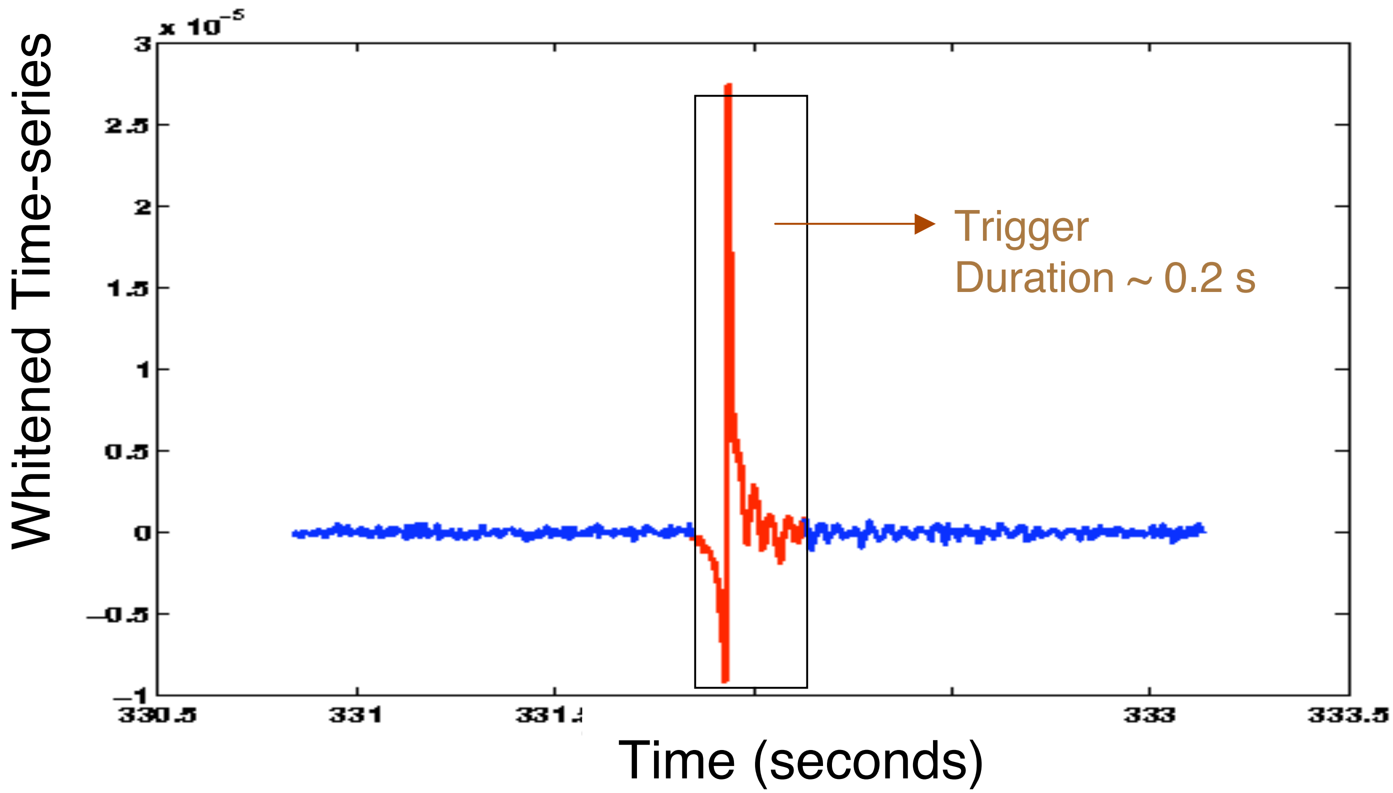
- Raw LIGO data needs to be conditioned and this involves reducing the sampling rate, removal of lines from PSD and whitening the data (make the PSD flat)



- Data conditioning implemented in different ways by various groups.

Basics of Burst Searches

• Various algorithms (time-domain, wavelets , etc) are used to look for transients ("triggers") in the gravity wave channel.



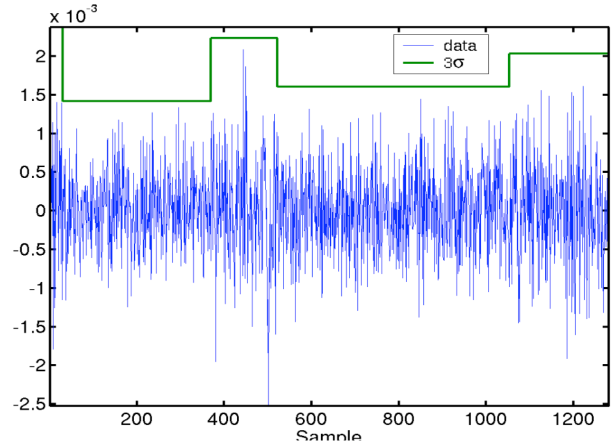
• Same algorithms can also be applied to look for transients in auxiliary channels.

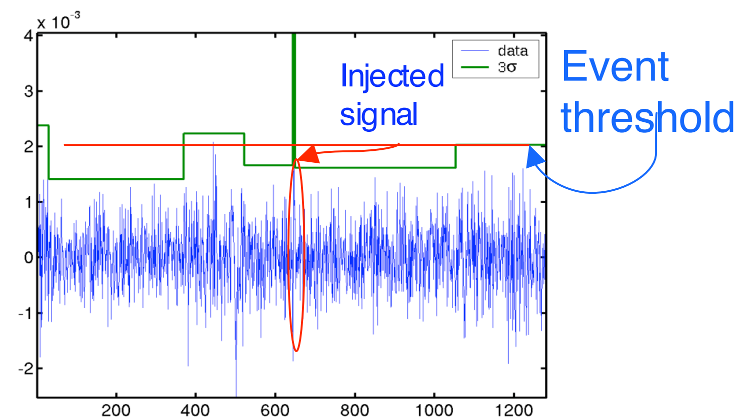
Algorithms used in Burst Searches

LSC Burst group has developed multiple (> 4) algorithms with the SAME science goals ：

- WaveBurst
- Block-Normal (based on Bayesian change point algorithm)
- Kleine Welle
- Q pipeline
- Excess Power
- Slope
- TFClusters
- Hilbert-Huang Transform

and many many more

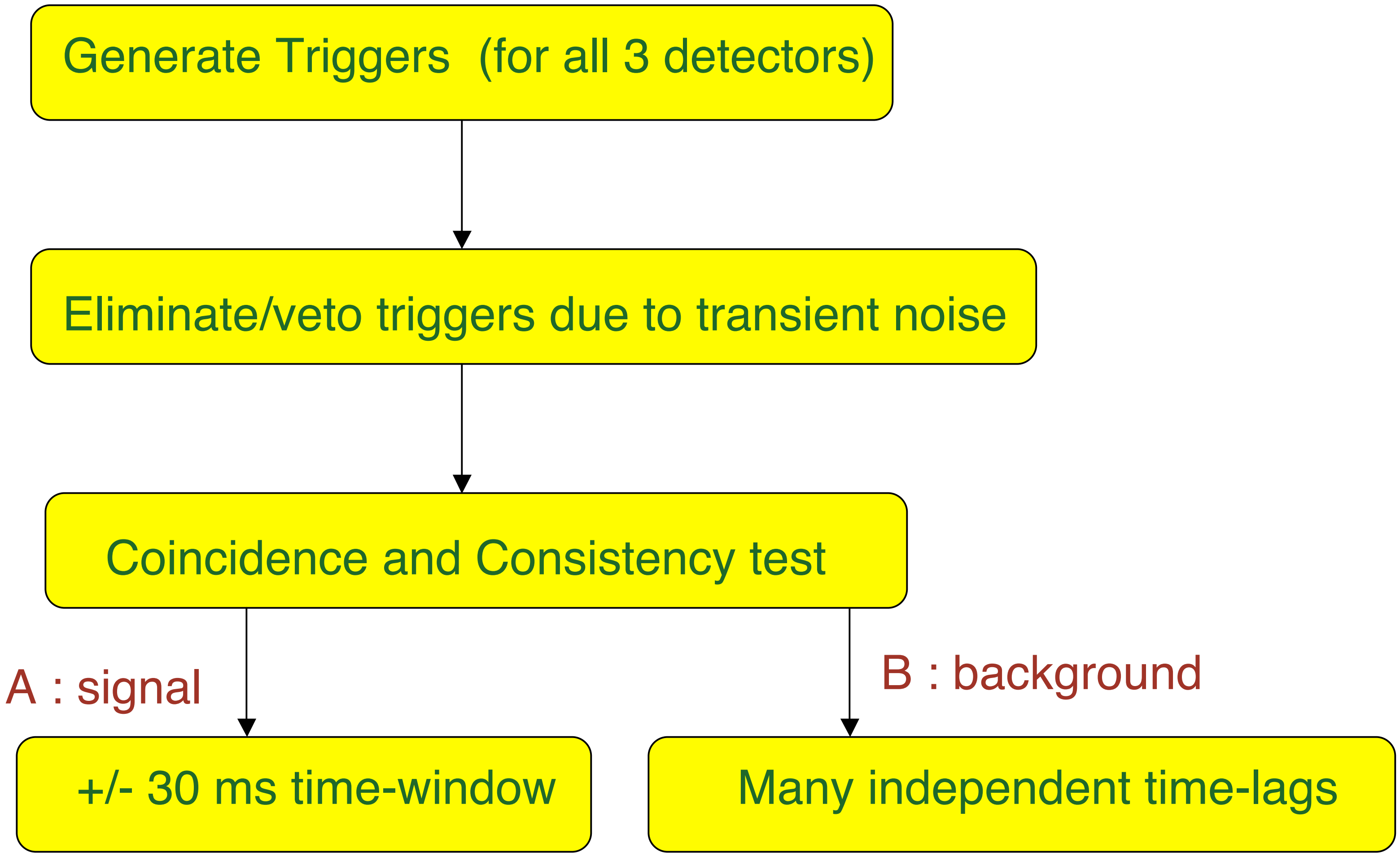




Different burst algorithms see different events.

A. Stuver Ph.D. thesis (2006)

Flowchart of Burst Analysis



Compare (A) to (B) and you are done. Efficiency estimated by injecting various ad-hoc signals in the pipelines.

Transient Noise Identification

Various methods have been used for studying the cause of transient sources of noise lasting few milli-seconds (called “glitches”")

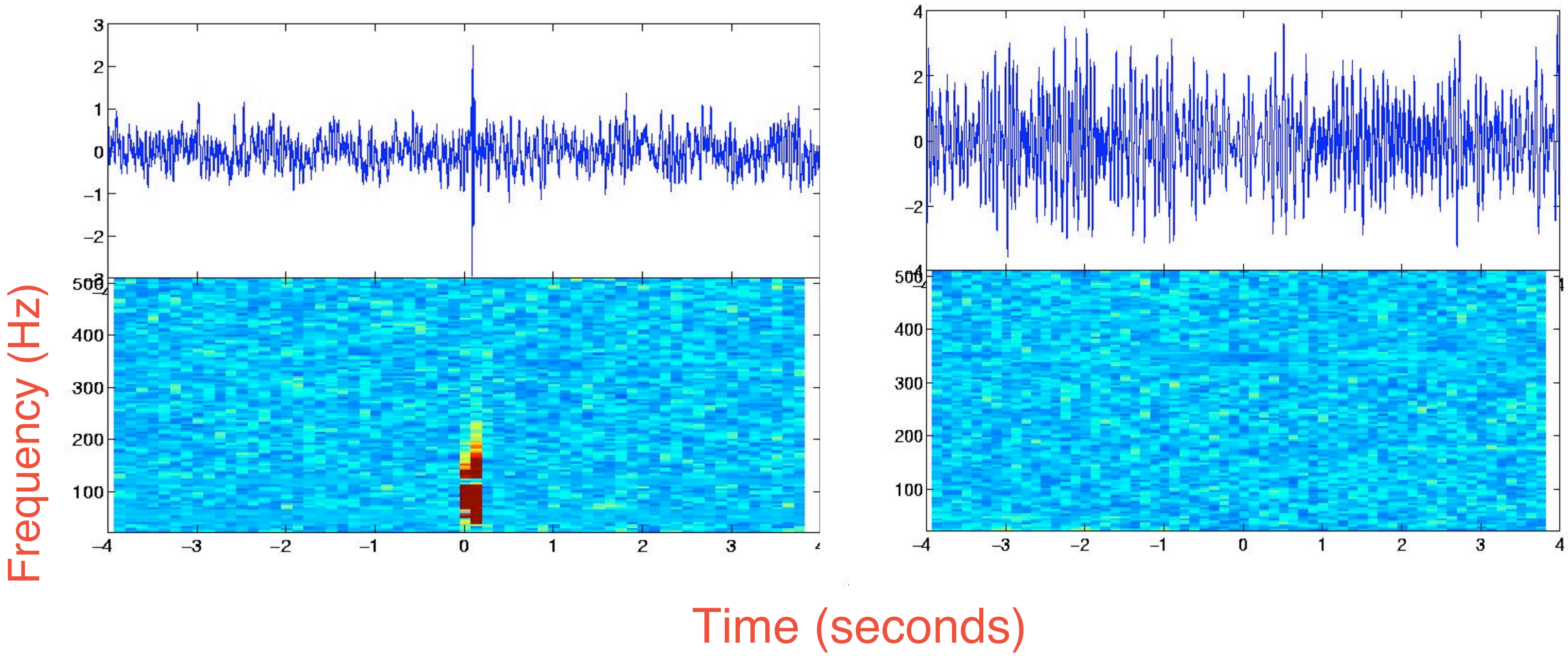
- Event Visualization tools ✔
- Statistical methods (MIT/Syracuse/UMD)
- Measured Transfer Functions (R. Schofield, environmental)
- Expertise of Commissioners
- Listening to Glitches (Syracuse)
- Multi-dimensional classification of noise triggers (UTB)

For more details on methods used see

Blackburn et al : 0804.0800 Gouaty et al : 0805.2412

Event Visualization tool (I)

Filtered Time-Series + Median normalized spectrogram



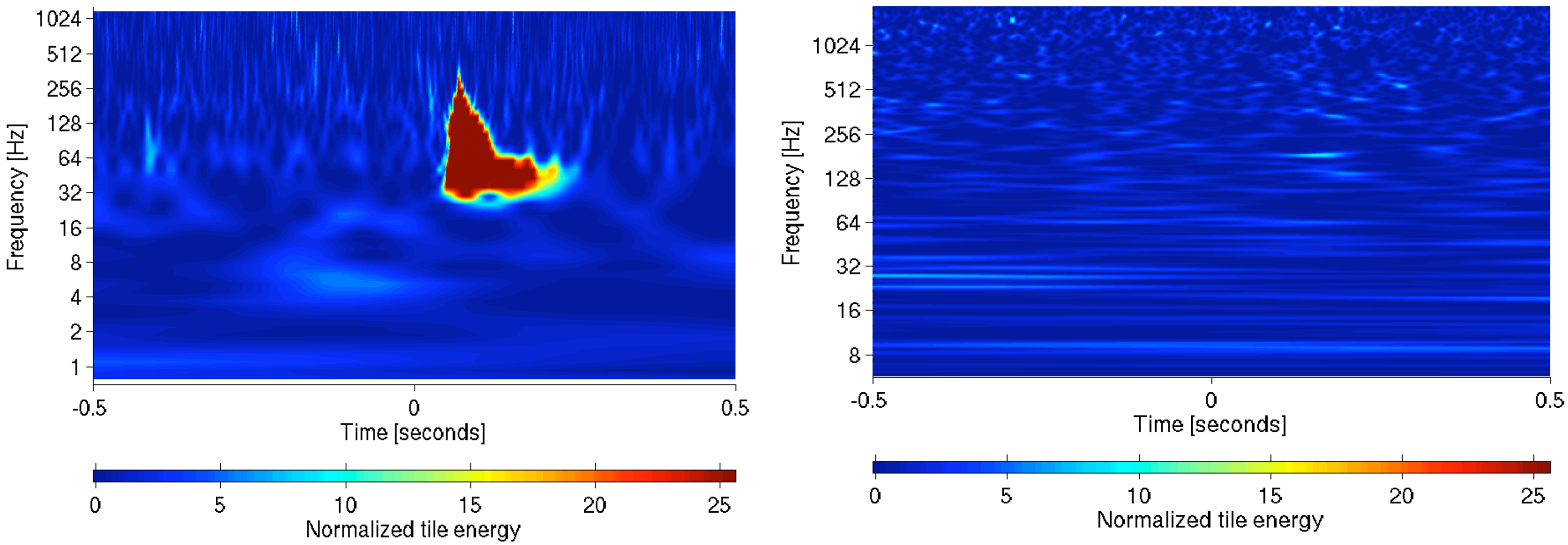
Glitch

No Glitch

K. Rawlins (2005)

Event Visualization tool (II)

Q-Scan   Look at the projected detector data with Q-transform as basis.



Glitch   No Glitch

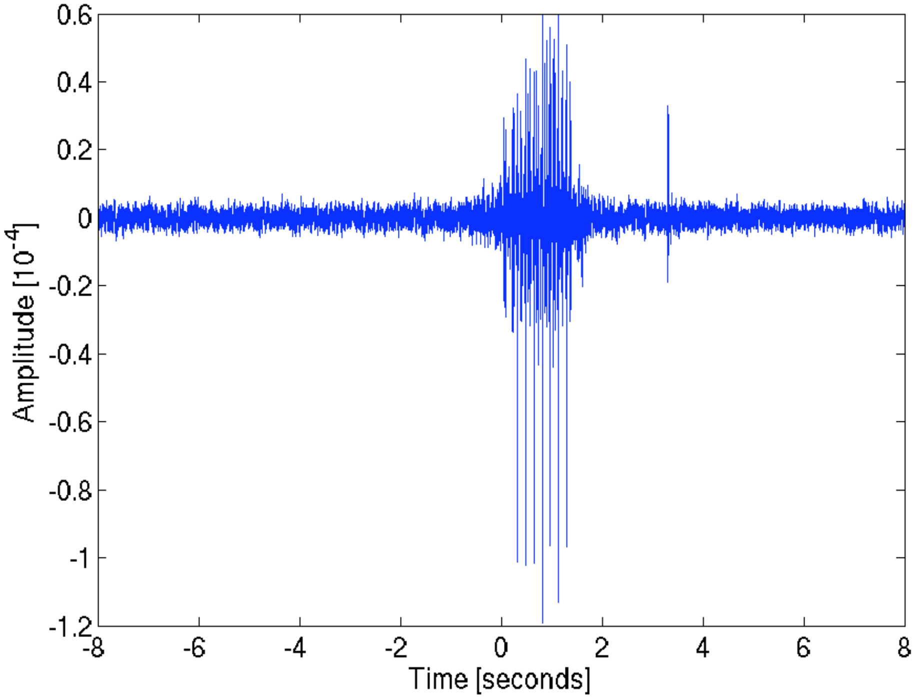
S. Chatterji Ph.D thesis (2005)

This tool also used by operators, detector experts and in GEO and VIRGO

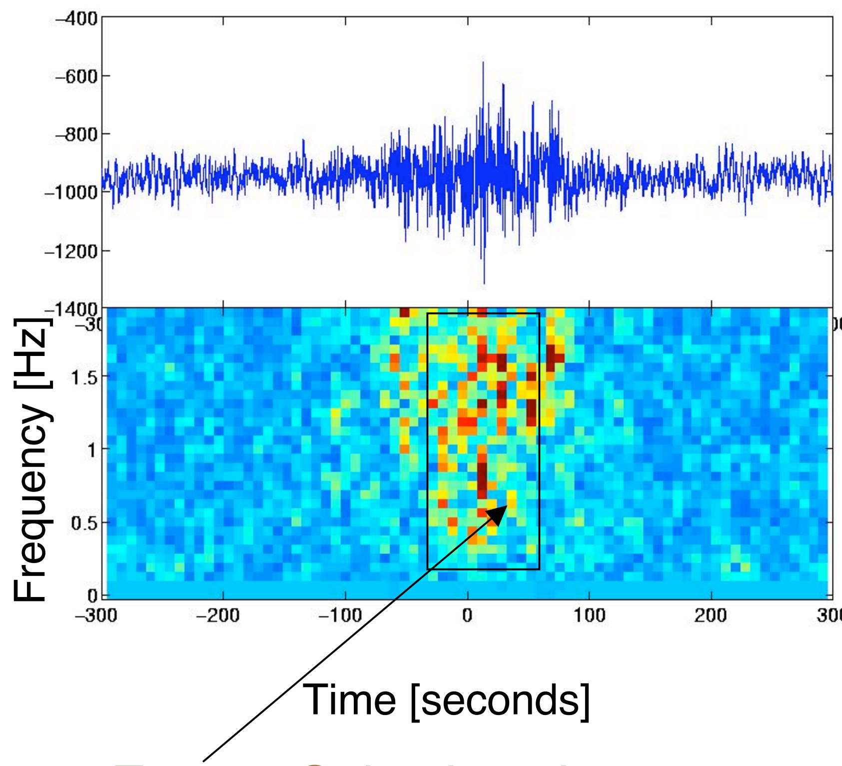
Noise Transient : Seismic Noise

- Transient seismic noise < 10 Hz getting up-converted to ~ 100 Hz in the gravitational wave channel.

Gravity Wave Channel



Hanford Y-end seismometer



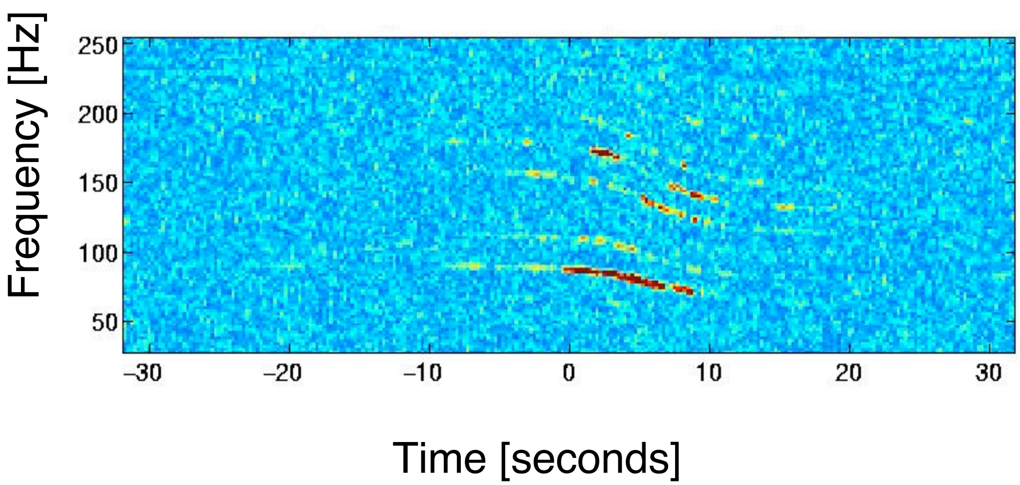
Excess Seismic noise

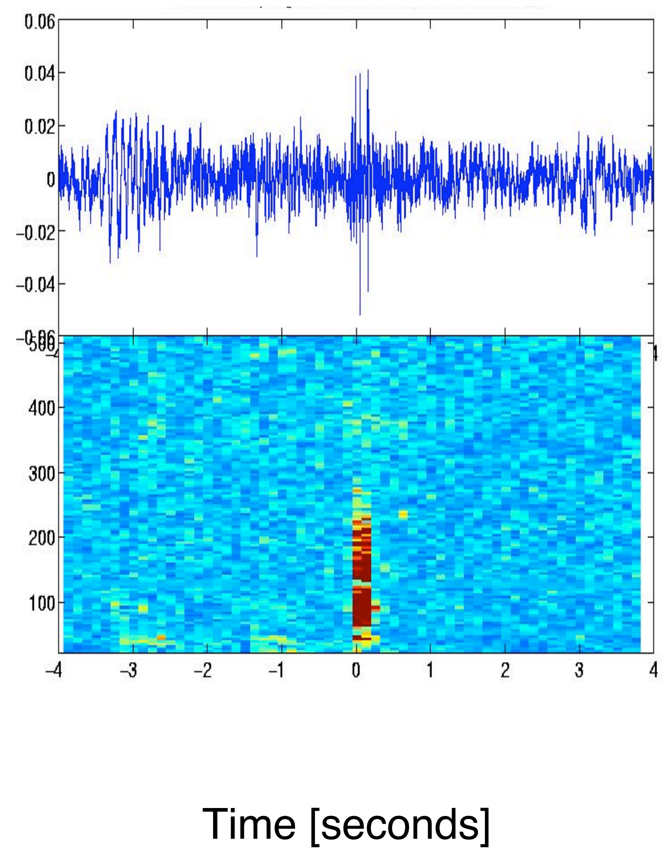
Noise Transient : Acoustic Noise

Gravity Wave channel

Multi-tone features in the microphones

Livingston Y-end microphone



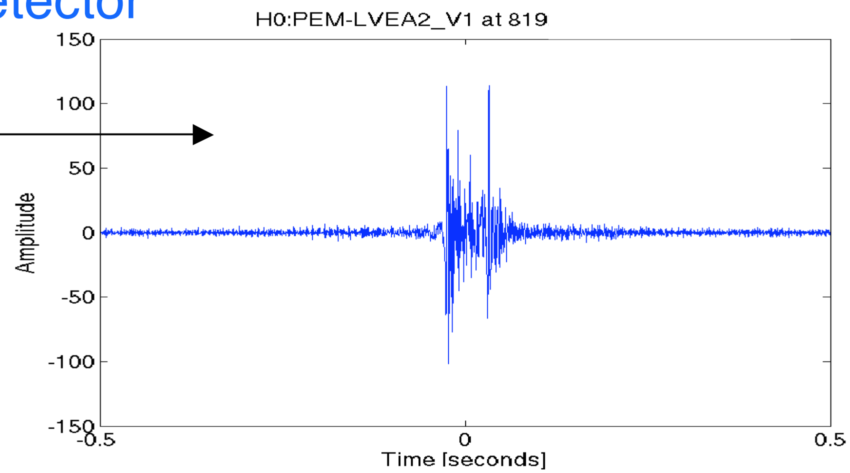


Multi-tone feature most probably caused by an overflying helicopter

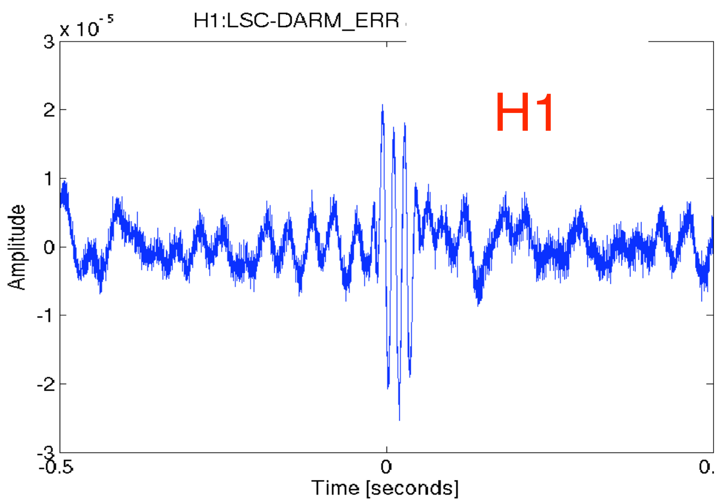
Noise Transient: Power spikes

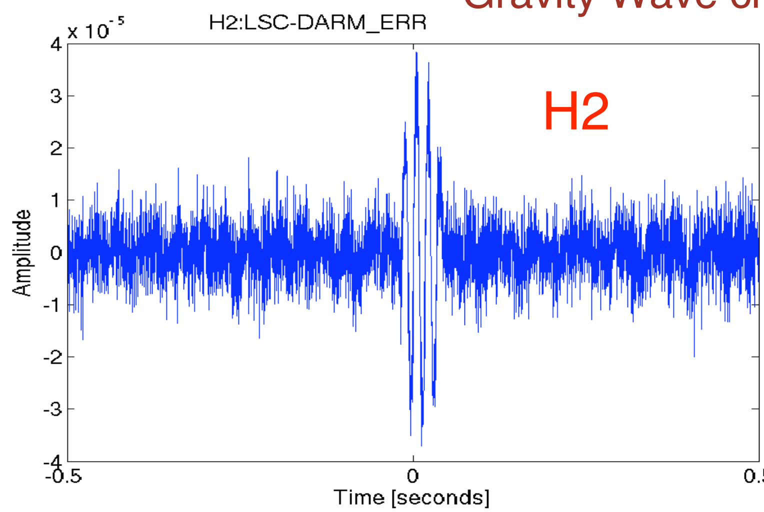
- Disturbances on power mains
  These cause simultaneous coherent noise transients in both LHO 4km and 2 km detector

Mains power voltage monitor

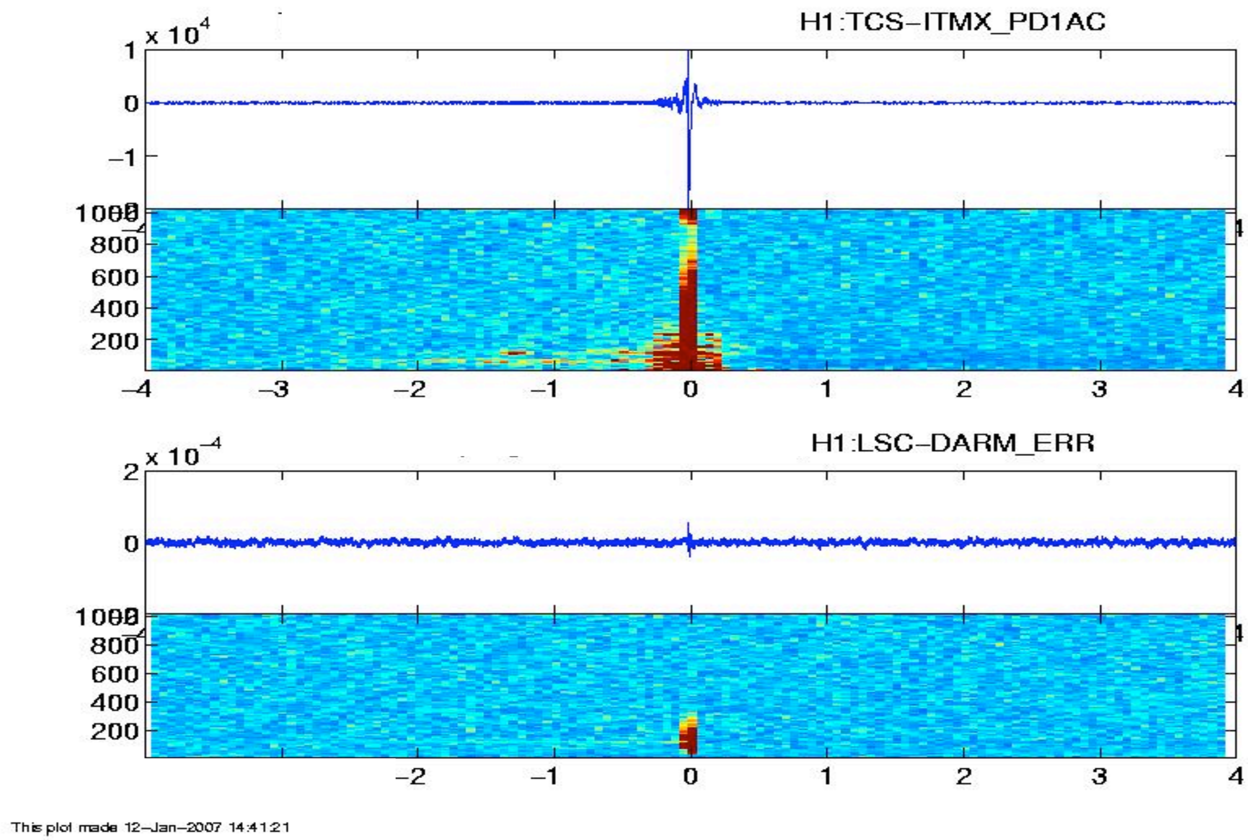


Gravity Wave channel





Noise Transient: TCS

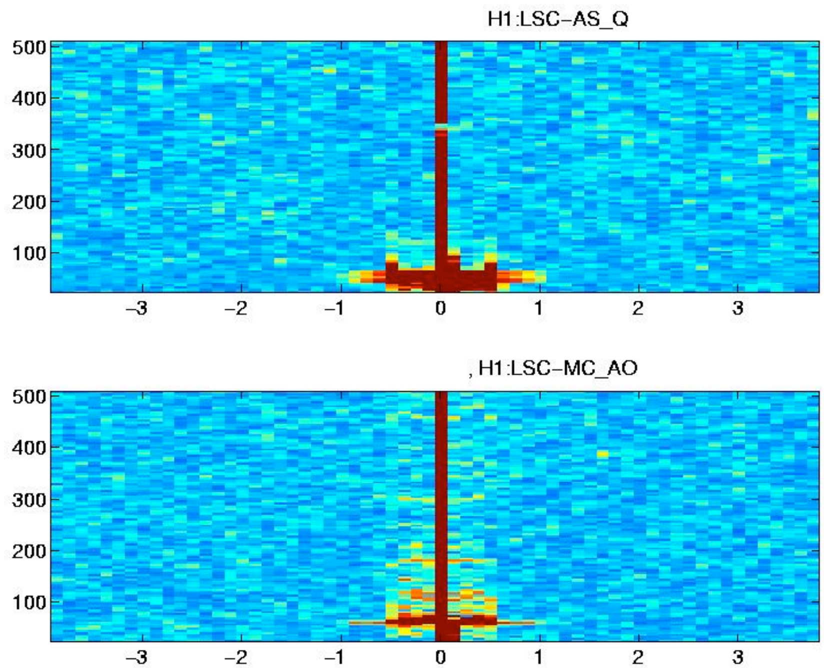


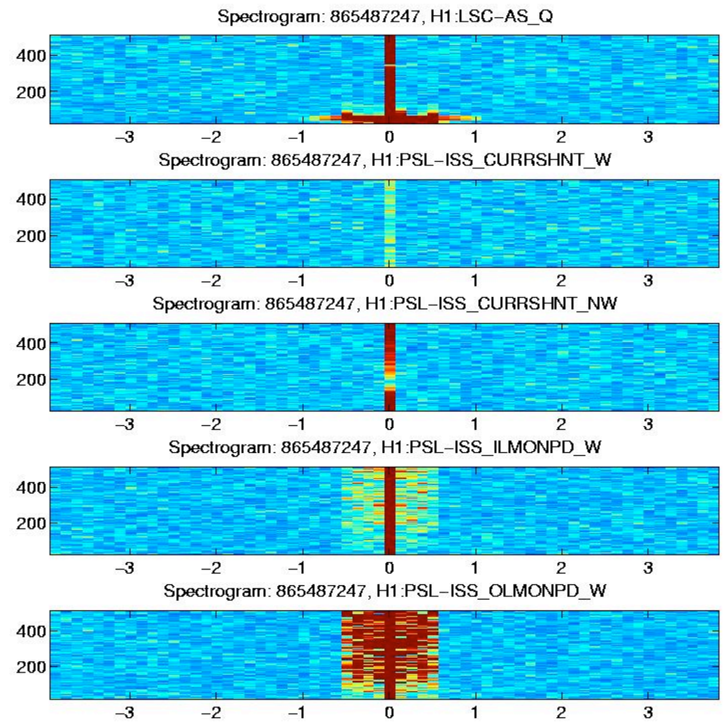
Thermal Compensation System

Gravity wave channel

- TCS glitches caused by mode hops in the TCS laser in which there is a sharp drop in power level incident on the interferometers. Seen in all H1, H2 and L1 during S5. More problematic at LHO

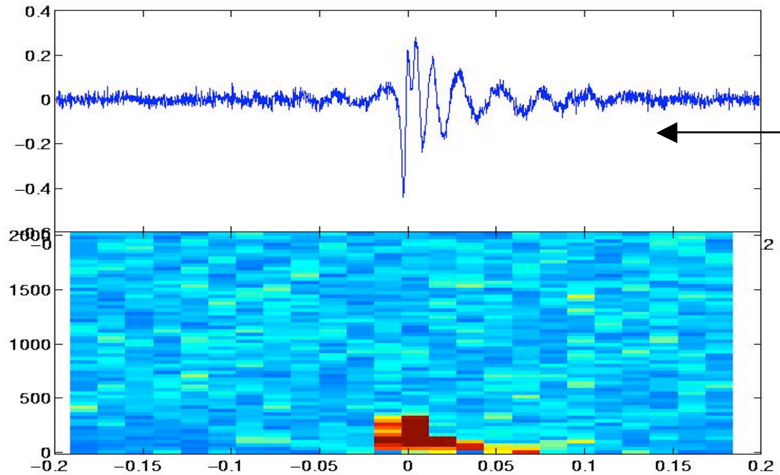
Noise Transient: ISS



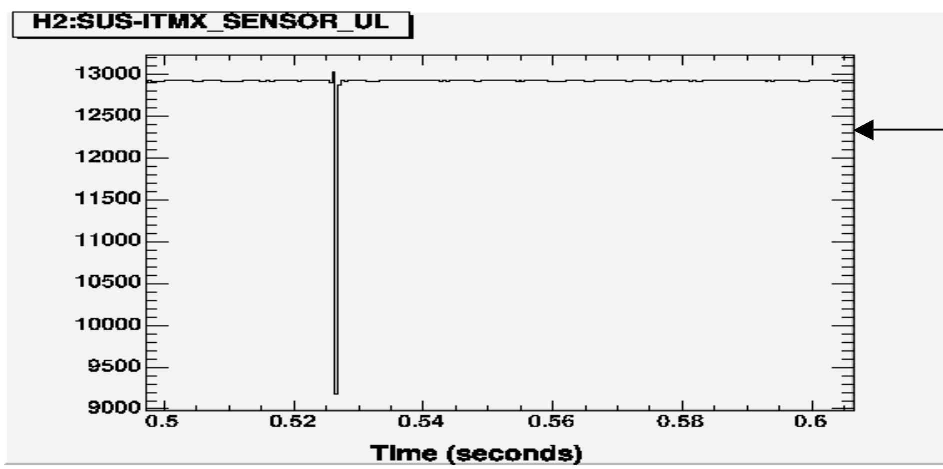


- Causes very loud transients in gravitational wave channel.
- Only seen in H1 during S5.

Noise Transient: OSEM glitches



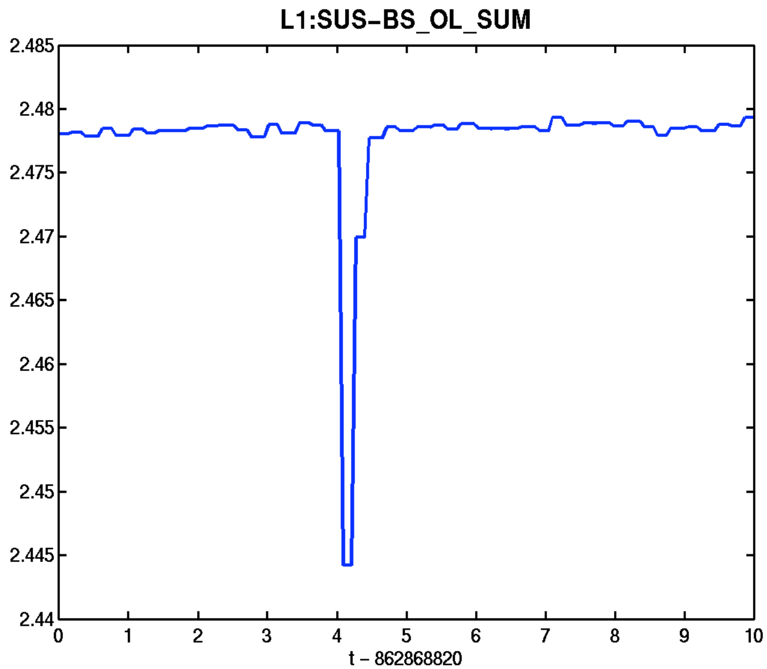
Gravity wave channel



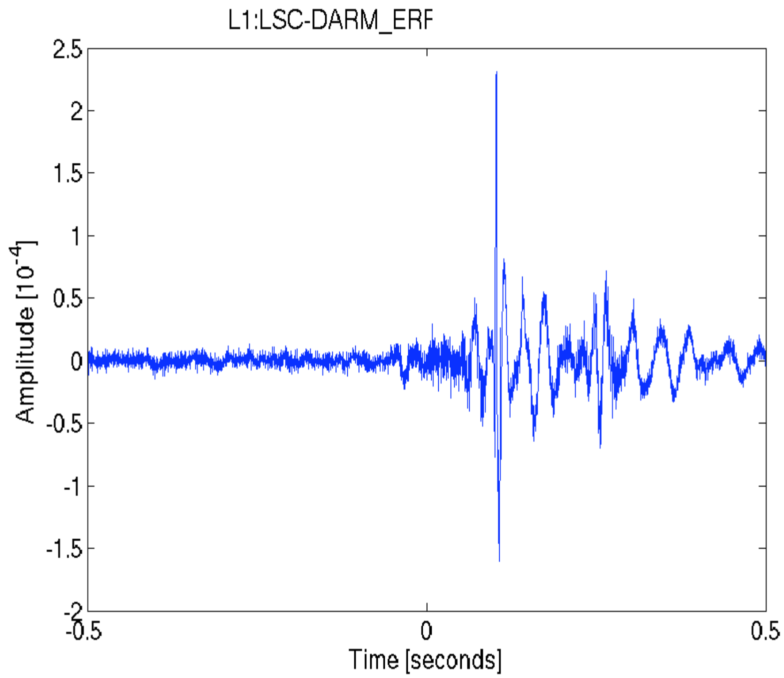
OSEM channel

- Seen in H2 (1st 3-4 months). Fixed by S. Waldman

Noise Transient: Optical Lever



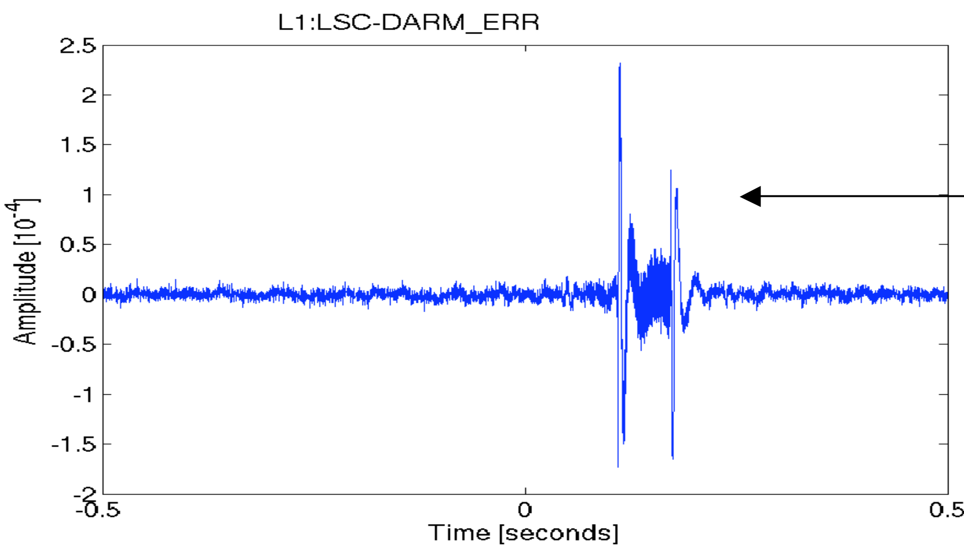
BS optical lever sum



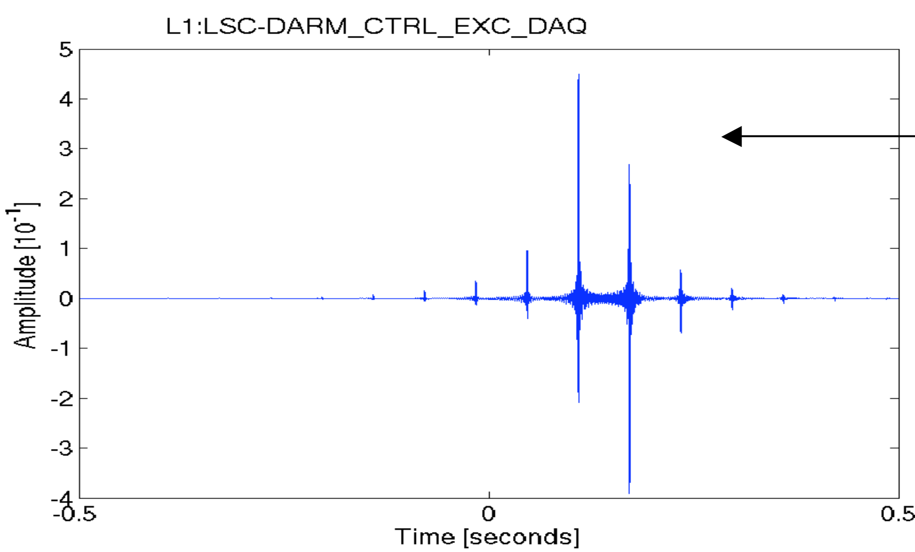
Gravity wave channel

- Such glitches happen when optical lever lasers need to be replaced.

Noise Transient: Calibration Line Glitch

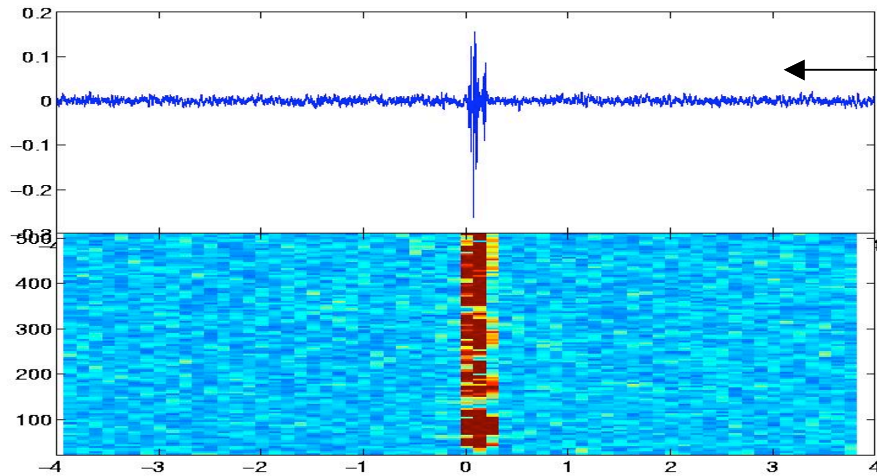


Gravity wave channel

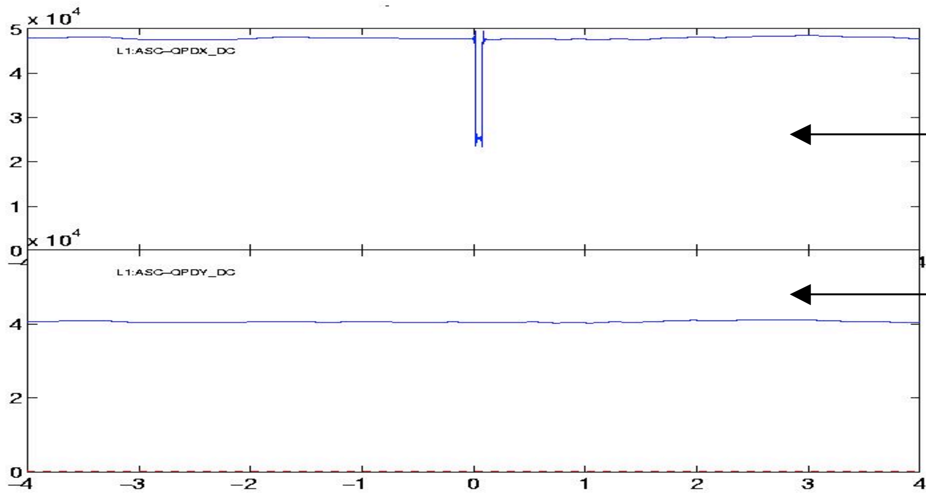


Dropouts in injected Calibration signal

Noise Transient: X-end processor failure



Gravity wave channel

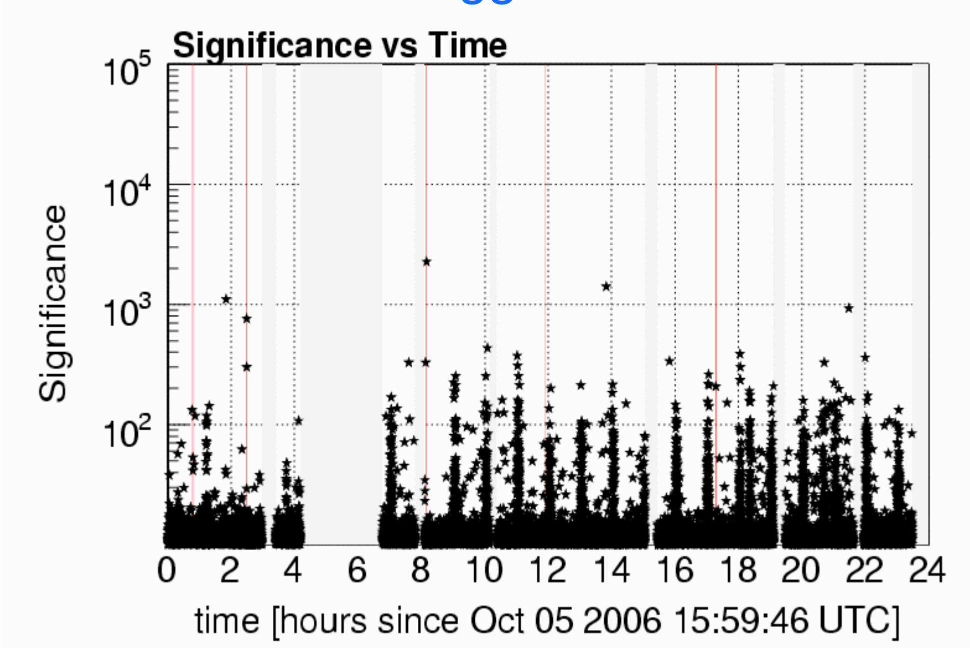


DC light level In X-arm

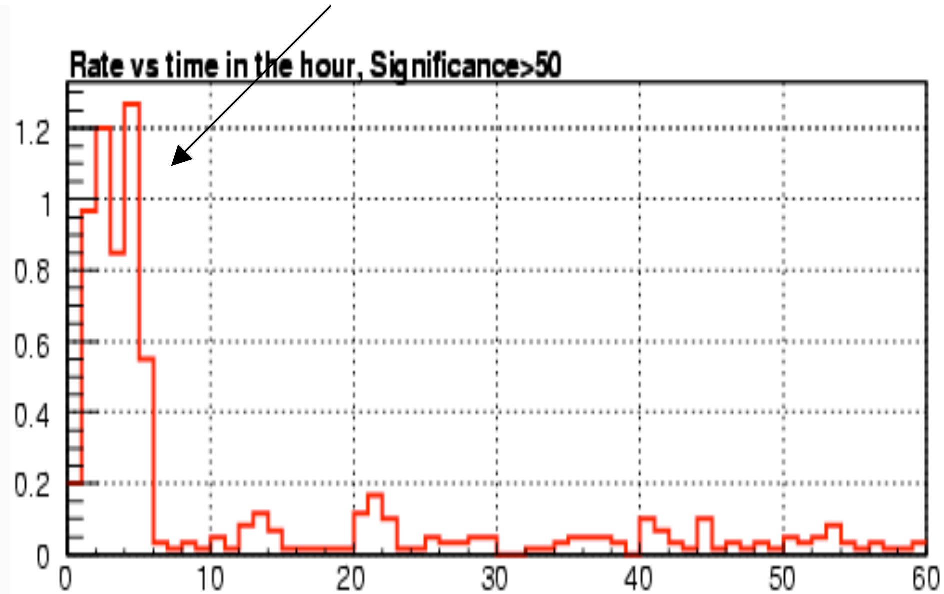
DC light level In Y-arm

Noise Transient: Computer Malfunction

L1 triggers

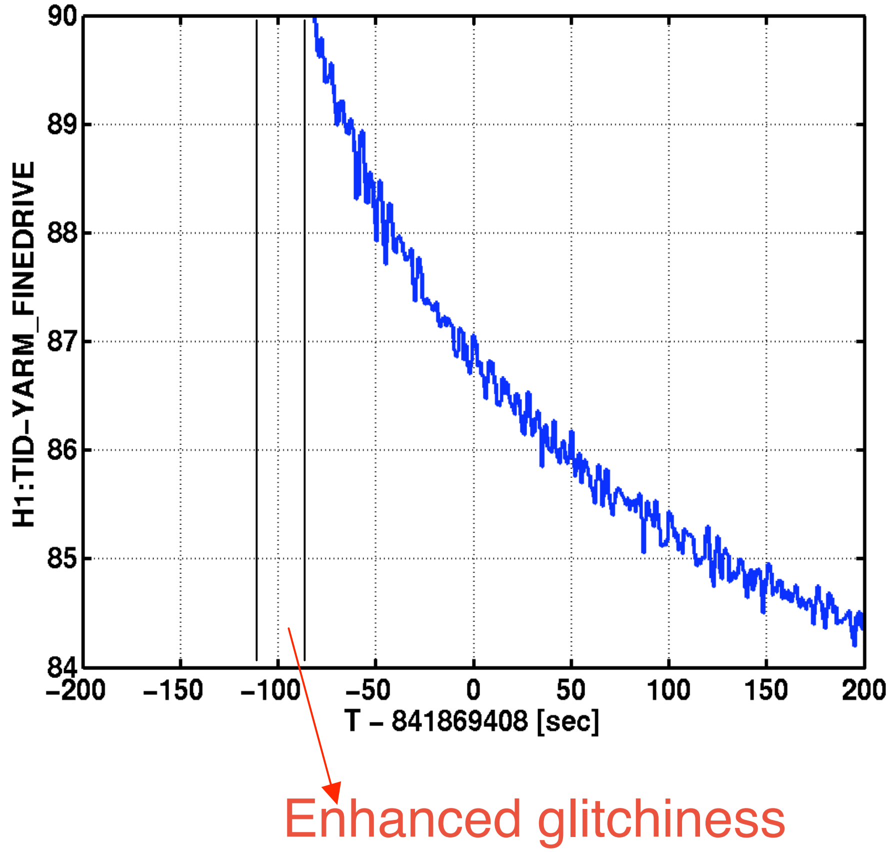


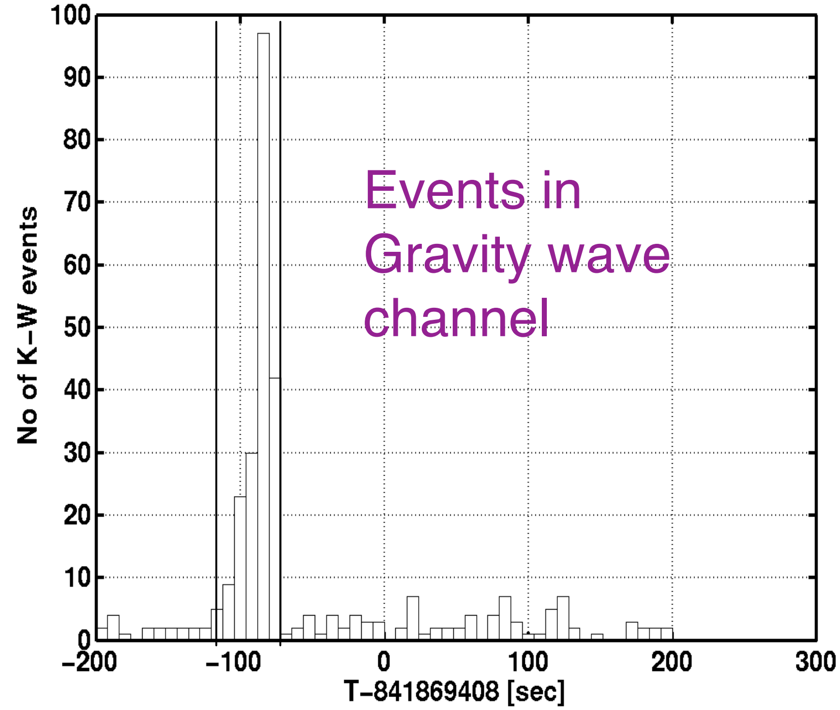
Peak when time (in minutes) ~ 0



- Hourly noise transients first appeared on October 3rd 2006.
- Attributed to snapshot processes performed by the detector DAQ on a periodic basis (every hour in Oct. 2006) called autoburt.

Noise Transient: Tidal Desaturation

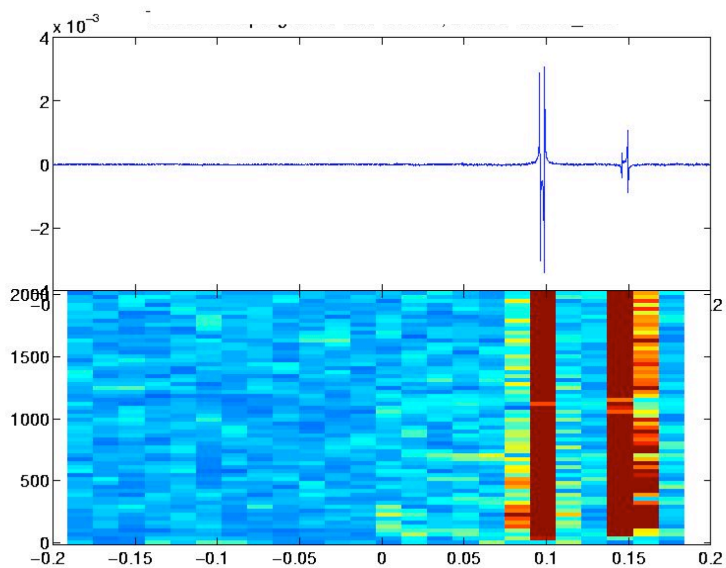




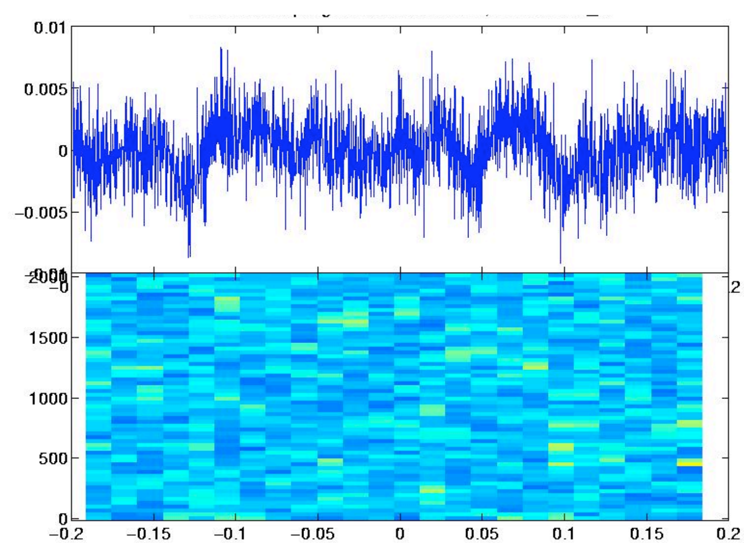
- Interferometer becomes glitchy when the data from the tidal servo comes out/goes into maximum absolute value of 90 counts. Effect mainly seen in H1 during S5

LIGO Noise Transient: Data Acquisition Problem

DARM-ERR

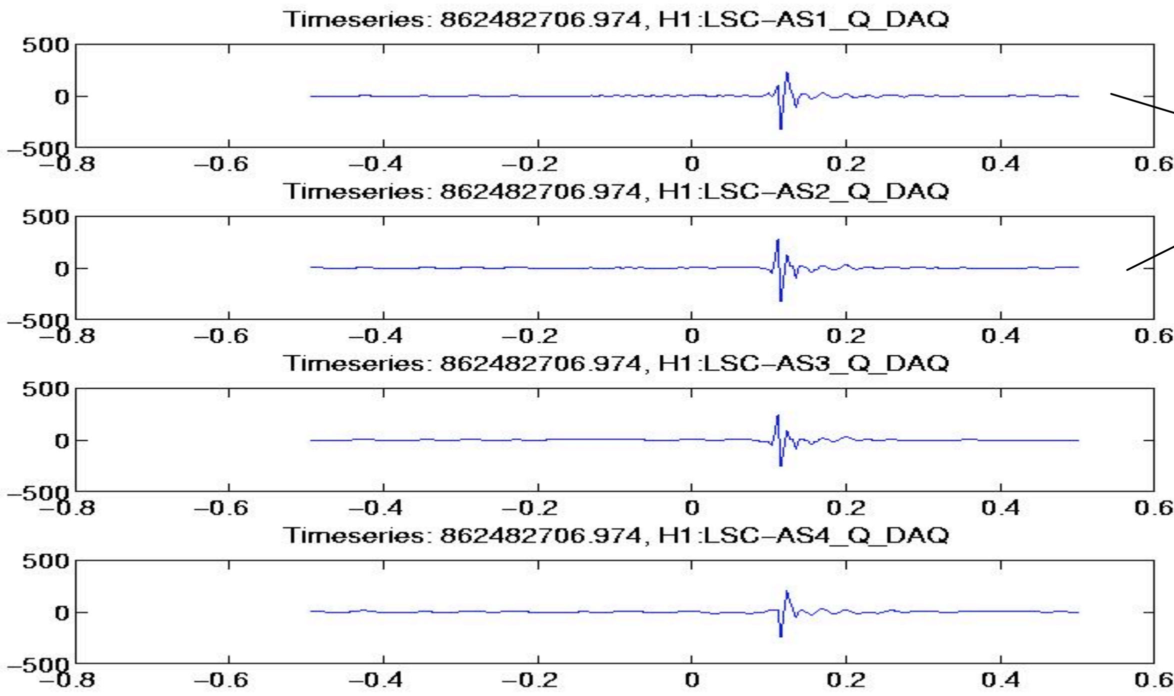


AS-Q



- Probably caused by a timing problem when DAQ is unable to keep up with the data-stream.
- Seen in all 3 interferometers (very low dead-time)

Noise Transient: Dust



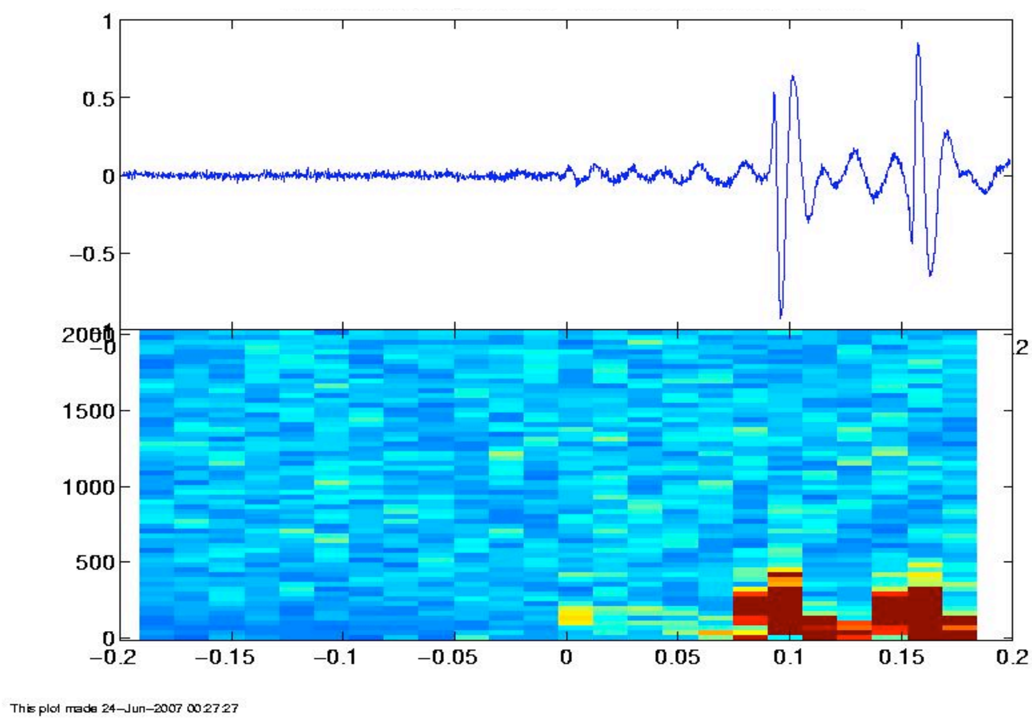
PD1 inverted w.r.t PD2

Event found by Black Hole Ring-down search

- Signals from PD 1 and 4 inverted compared to PD2 and 3
- Possible cause of such glitches is due to dust along the beam path and verified through dust injections (R. Schofield)
- These glitches not seen in any auxiliary channels. Monitor written by for such events. (J. Zweizig)

Noise Transients Recap

• Source of many noise transient events unknown. Lots of work still in progress in hunting down all noise transients in S5.



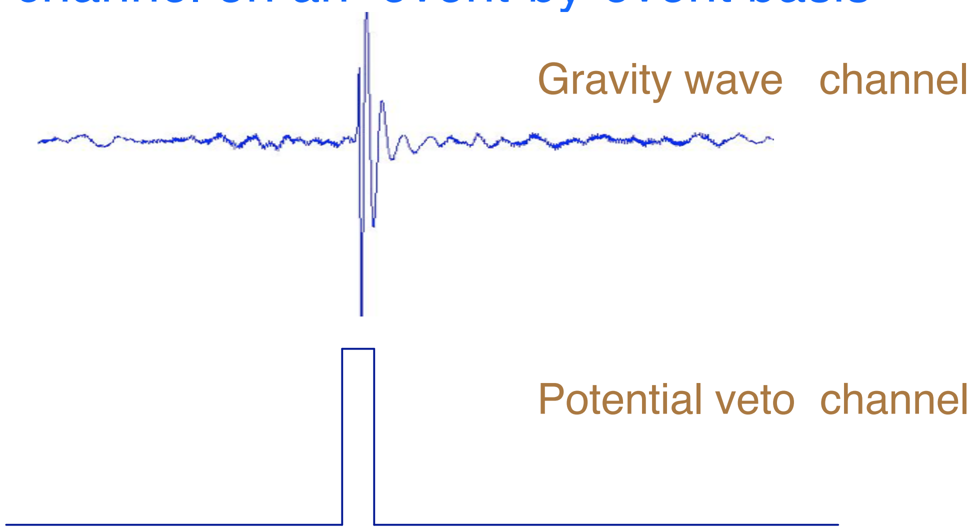
An example of an unknown H2 glitch in June 2007

• A database of noisy intervals maintained by K. Riles :
http://www-mhp.physics.lsa.umich.edu/~keithr/S5DQ/flaginfo.html

Use of Vetoes in Analysis

- Generate Data quality flags for bad intervals with different severity levels.
  - Category 1 - Do not analyze
  - Category 2 - Used in post-processing
  - Category 3 - Advisory for detection confidence and used in upper limit, if no detection
  - Category 4 - Advisory flag used to exert caution in case of a detection candidate

- Use vetoes from auxiliary channel on an event-by-event basis



- Check a real gravitational wave would not couple to veto channels.

Aperture synthesis methods

Network analysis combine data coherently from various detectors

Gravitational-wave signal: $\xi_i(t) = F_{i+}\, h_+(t) + F_{i\times}\, h_\times(t)$

Sky dependence: $F_{i+}, F_{i\times}$ depend on ϕ, θ (2 polarizations)

Likelihood functional: $$L = \sum_{i=1}^{m} \frac{1}{\sigma_i^2} \| x_i(t) - \xi_i(t - \tau_i) \|^2$$

However antenna response matric for near-aligned detectors is ill-conditioned (Condition number >> 1)

Tikhonov regularization: $$L_g = L + g\,\Omega$$

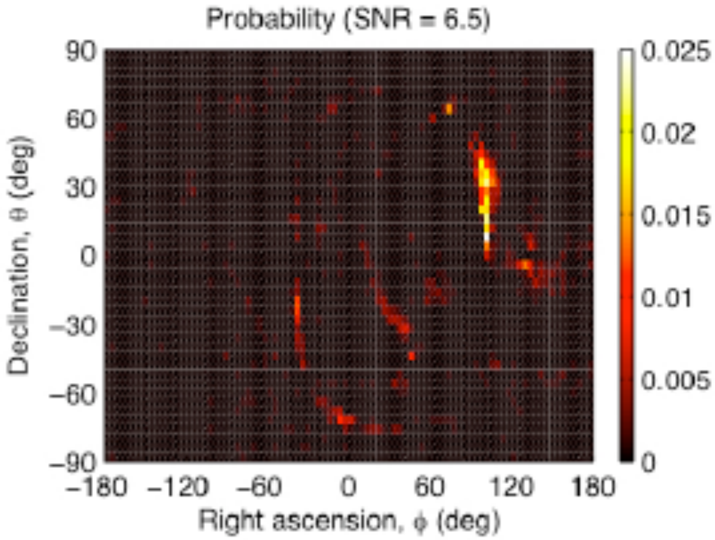
$\Omega \;\alpha\; h^2$

See papers by Ajith, Chatterji, Finn, Hayama, Klimenko, Lazzarini, Mohanty, Rakhmanov, Schutz, Searle, Stein, Summerscales, Sutton, Wen, and many more

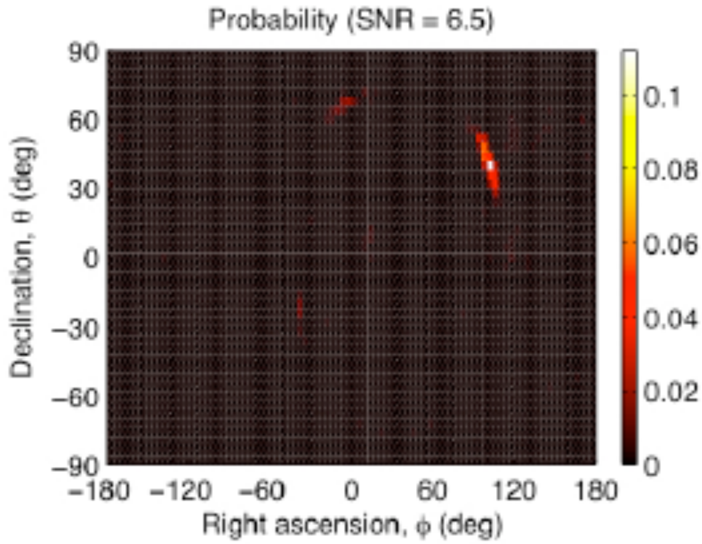
Effect of Regulator

Numerical simulation for LIGO + VIRGO
1000 trials
2 polarization waveforms

True RA = 40°, DEC = 98°

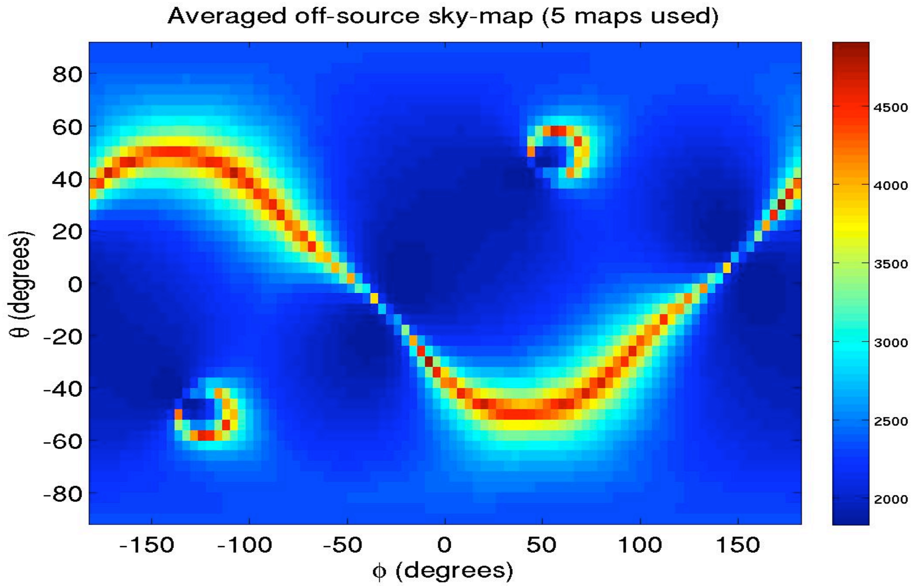


Without regulator

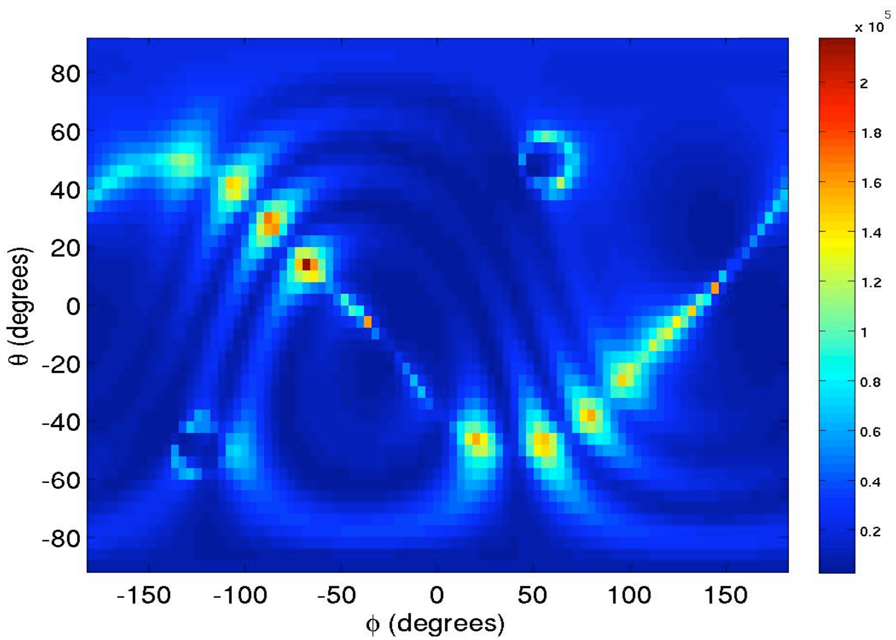


with (Tikhonov) regulator

Skymaps with Simulated Signals and Noise



Averaged noise Skymap for a LIGO only network

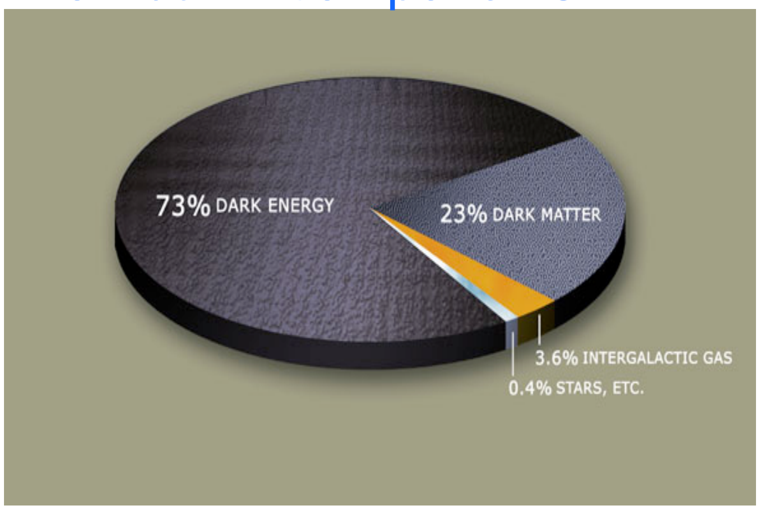


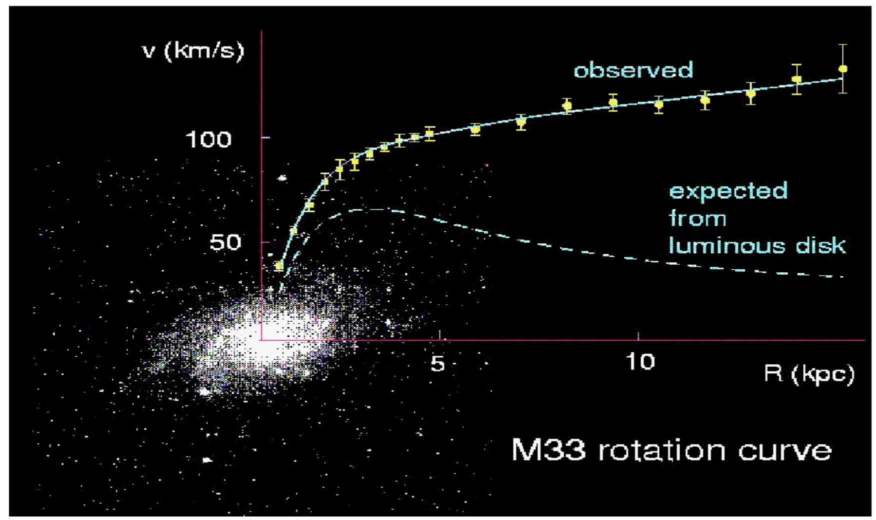
Skymap at location of signal for a LIGO only network

Possible glitch in gravity in ultra-weak field ?

- General relativity agrees very well with observations at solar system and binary pulsar length scales.

- At longer length scales, 95 % of the universe is made up of two ``dark'' components.





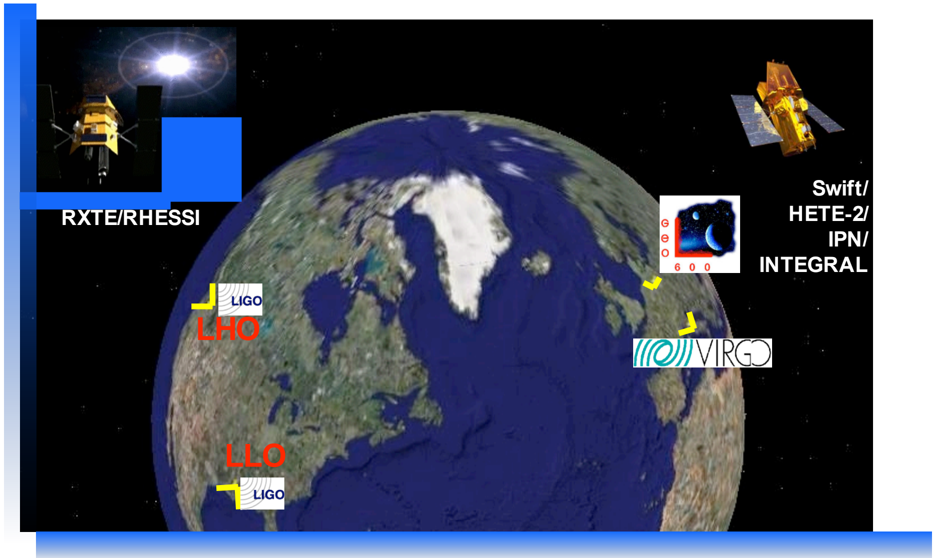
- Evidence for dark matter comes from galactic rotation curves, gravitational lensing, large scale structure, etc. No clue on its identity.

- Could dark matter be a consequence of modified gravity (ala Vulcan)?

Triggered Gravitational wave searches

arXiv : 0802.4320 (Abbott et al)

- Gamma-Ray Bursts
- Soft gamma ray repeaters
- Pulsar glitches
- Low-mass x-ray binaries
- Neutrino triggers
- Optical transients
- Core - collapse supernova
- Blazar flares



Cr: Z.Marka

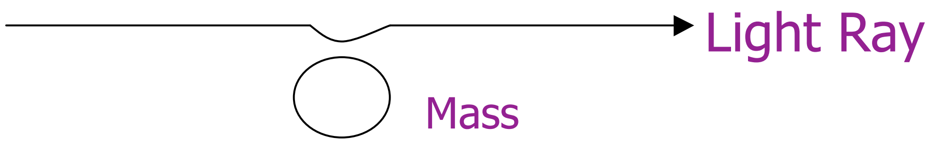
Search is done by looking for gravitational waves in a narrow time window around the trigger (~ 100 seconds)

The *ansatz* assumes that propagation time for GWs is same as light.

One pre-requisite for this assumption is that Dark Matter exists

Shapiro Delay

Time delay of light due to its passage near a massive body first calculated by I. Shapiro (1964). This delay is ubiquitous (radar ranging, binary pulsars etc)



Gravitational waves and neutrinos also experience same Shapiro delay as light in general relativity.

Total (GW/photon/neutrino) travel time for explosive events = light travel time + Shapiro delay from intervening mass.

Shapiro delay for SN1987A (50 kpc) ~ 5 months (M. Longo 1987)

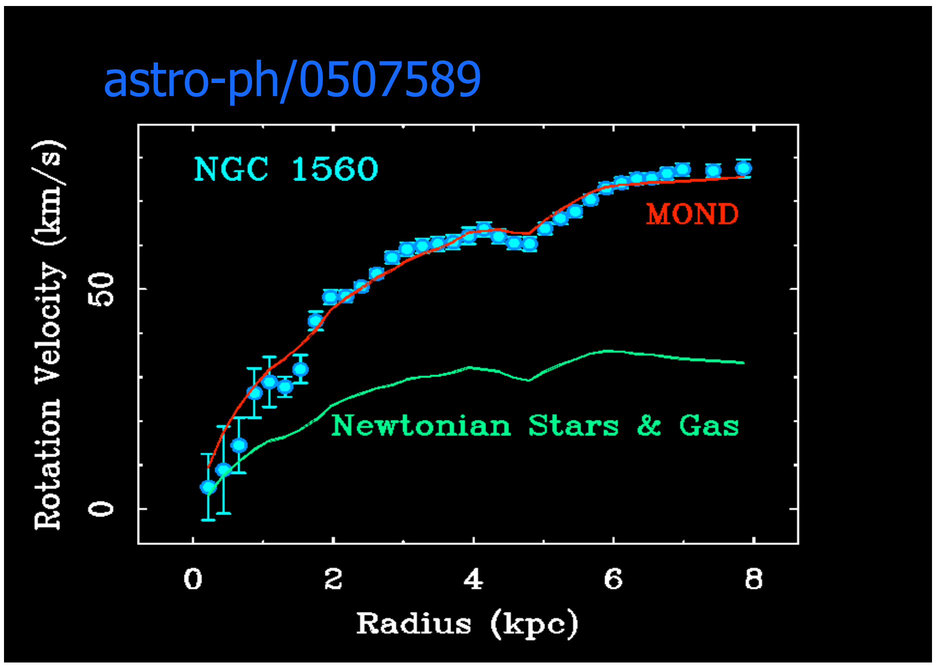
Mass of our galaxy is dominated by dark matter which is dominant contribution to Shapiro delay for any nearby transient sources

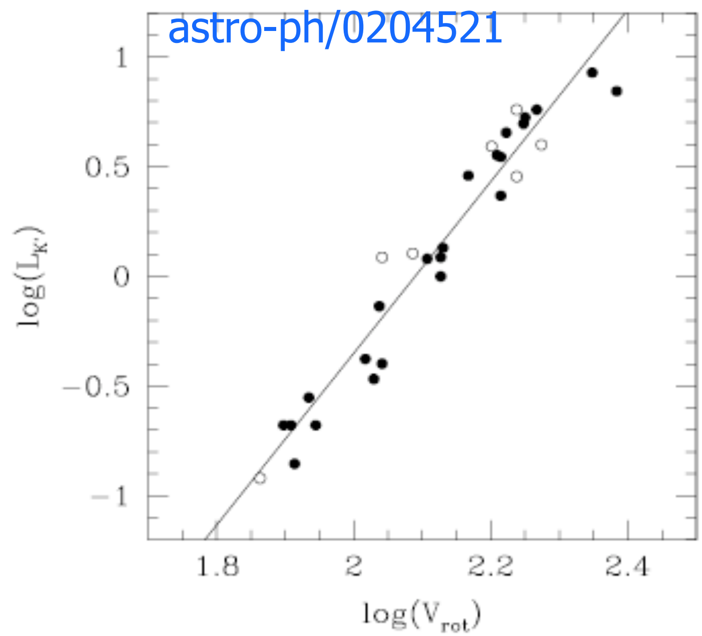
Modification to Newtonian Gravity

- Need for dark matter arises only for $a_o < 10^{-8}$ cm /s^2
- Tully - Fisher relation : $L \propto V^4$

} Milgrom (1983)

$\longrightarrow$ $a = a_{newt} \, (a_{newt}/a_0)^{-1/2}$ for $a < a_0$





Slope = 3.9 ± 0.2

History of modifications to GR for DM

1957 Zwicky

1983 Milgrom (Modified gravity to explain rotation curves & Tully-Fisher relation)

1984 Milgrom and Bekenstein (Non-relativistic generalization)

2003 Soussa and Woodard (No-go theorem)

2004 Bekenstein (Relativistic theory of MOND : TeVeS)

2005 Moffat (Another Relativistic theory to avoid dark matter)

2006 Skordis et al. (Cosmology of TeVeS not so bad)

2007 Kahya and Woodard (Model-independent test with gravitational waves)

Model-Independent Test

arXiv: 0804.3804

For a whole class of modified gravity models which avoid dark matter :

- Shapiro Delay for light/neutrinos = Potential of visible + dark matter.
- Shapiro Delay for gravity waves = Potential of visible matter only.

→ Gravitational waves will earlier compared to light.
Time delay (in days) for 3 sources below

Source	Distance	NFW	Isothermal	Moore
Sco-X1	2.8 kpc	4.88	4.98	4.97
SN1987a	51 kpc	74.8	78.2	74.5
GRB 070201	780 kpc	804	742	811

→ Simultaneous detection of gravitational waves and photons will rule out these models.

Conclusions

- Multiple methods developed for burst searches to look for transients as well as to do coherent network analysis.

- Many new transient sources of noise seen during S5. However cause of many glitches still unknown.

- Gravitational wave observations could resolve the 75 year old dark matter conundrum.

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