LIGO's continuing search for gravitational waves

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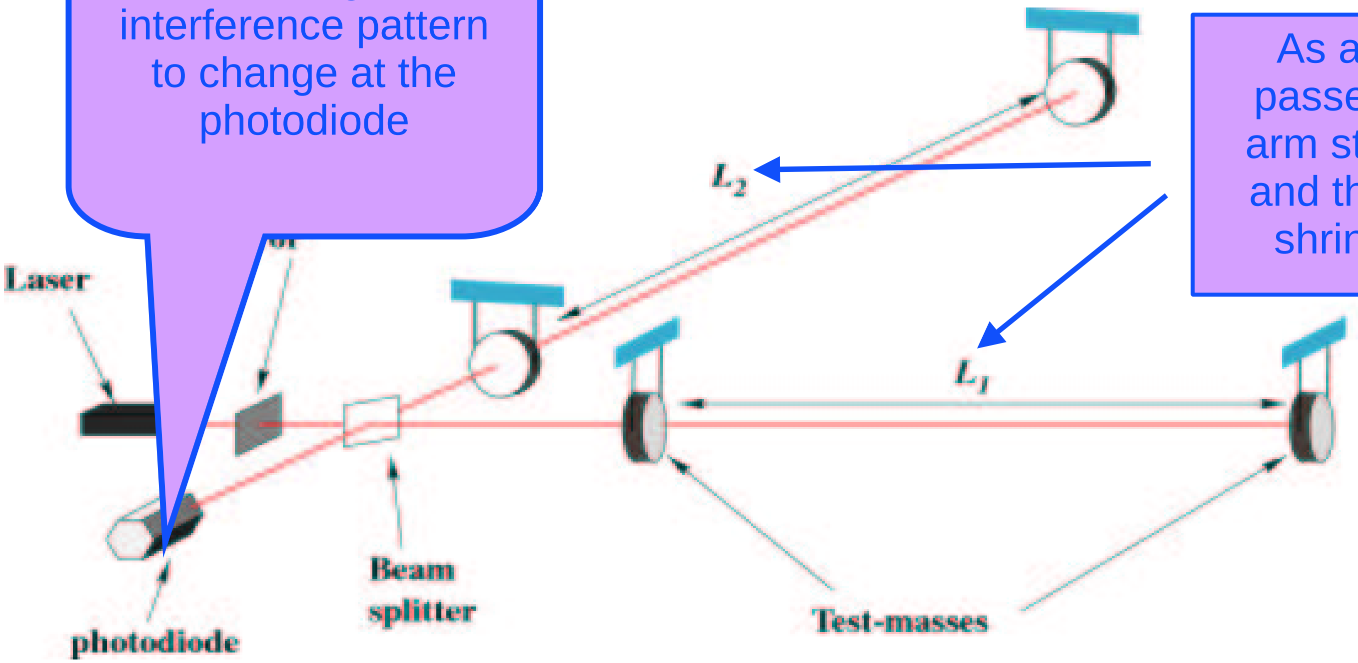
LIGO Scientific Collaboration

G040018-00-Z

LIGO Interferometers

- LIGO is an interferometric detector
    - » A laser is used to measure the relative lengths of two orthogonal cavities (or arms)
- Measure fractional change in arm length h = δL/L



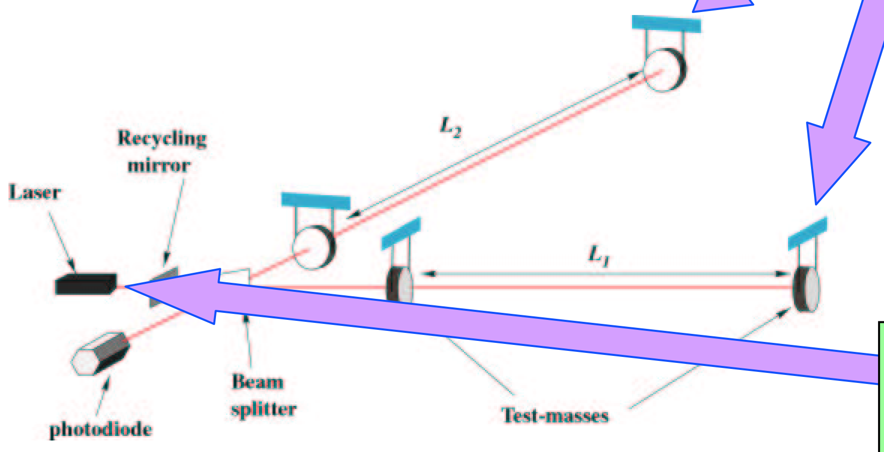
…causing the interference pattern to change at the photodiode

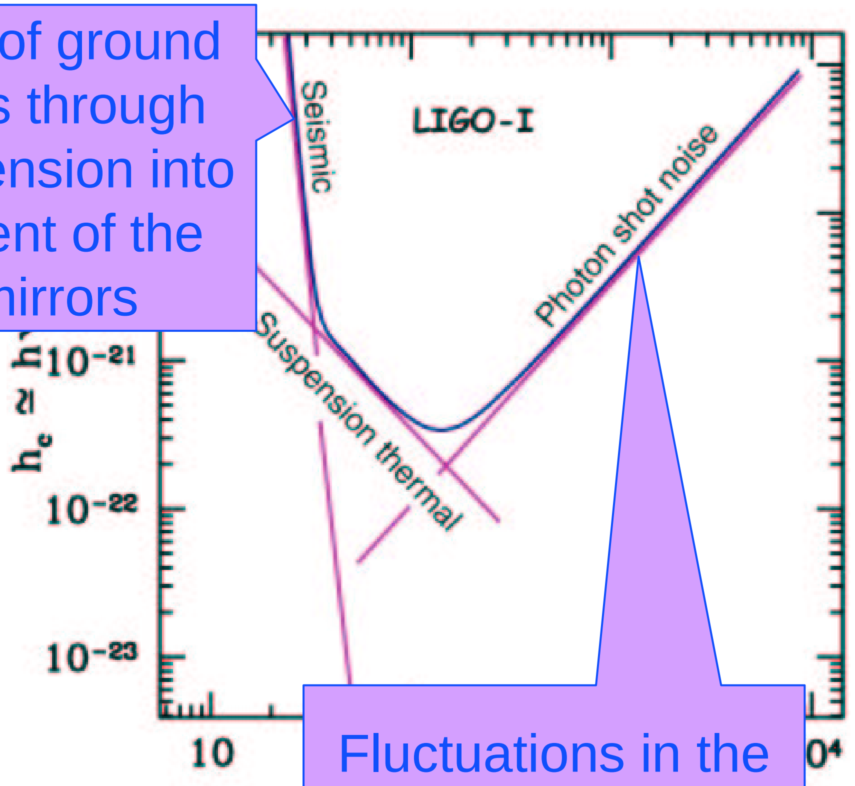
As a wave passes, one arm stretches and the other shrinks ….

LIGO noise budget

- Three fundamental noise processes frame the frequenc window of LIGO detectors – these are continuous random processes (almost Gaussian!)

Shaking of ground transfers through the suspension into movement of the test mirrors



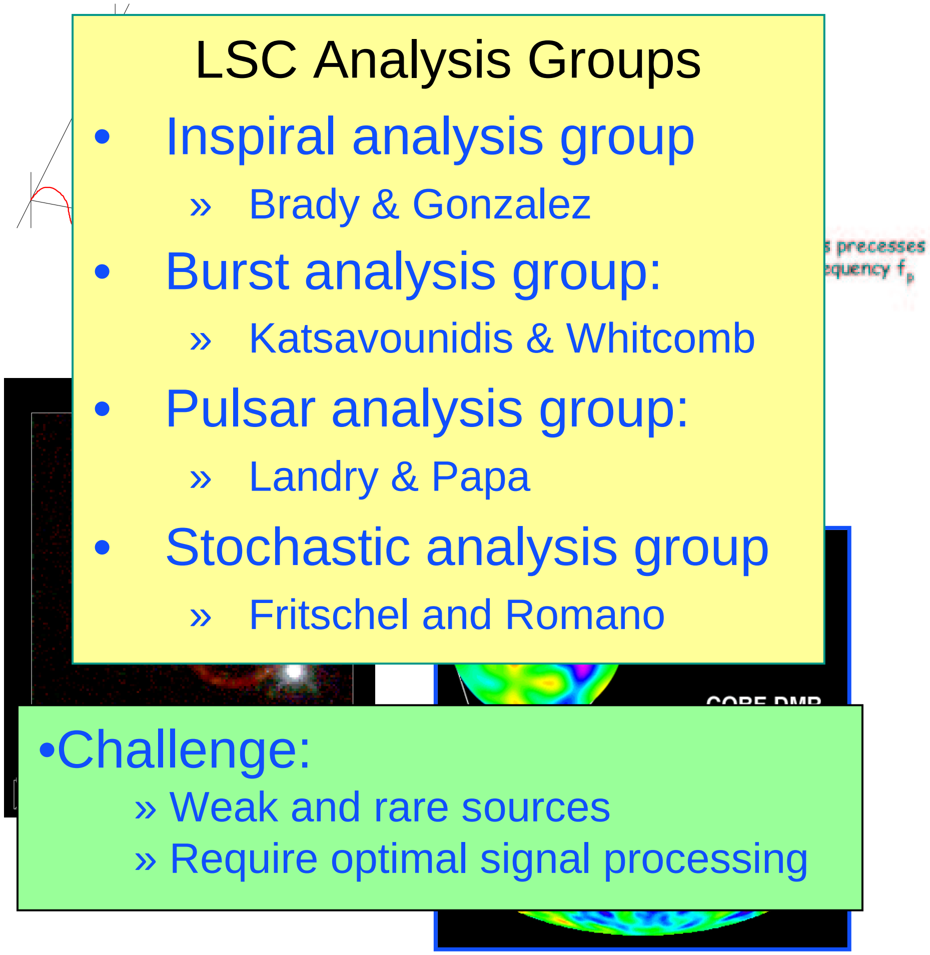


Fluctuations in the

- Challenge of real LIGO data:
  - » Strong line resonances
  - » Non-gaussian noise bursts
  - » Dynamic calibration due to complicated control systems

Sources and our analysis strategy

- Compact binary systems
  - » Neutron star inspiral
  - » LIGO range =20Mpc, N< 1/(4yr)
  - » Black hole inspiral/merger
  - » LIGO range=105Mpc, N<1/(2yr)
- Spinning neutron stars
  - » LMXBs, known & unknown pulsars in our Galaxy
  - » Need months of integration time
- Neutron star birth
  - » Tumbling bar could be detectable to ~5Mpc (~1/3yr)
  - » Convection within Galaxy (~1/30yr)
- Stochastic background
  - » Big bang & other early universe
  - » Background of GW bursts



LSC Analysis Groups

- Inspiral analysis group
  - » Brady & Gonzalez
- Burst analysis group:
  - » Katsavounidis & Whitcomb
- Pulsar analysis group:
  - » Landry & Papa
- Stochastic analysis group
  - » Fritschel and Romano

•Challenge:
  - » Weak and rare sources
  - » Require optimal signal processing

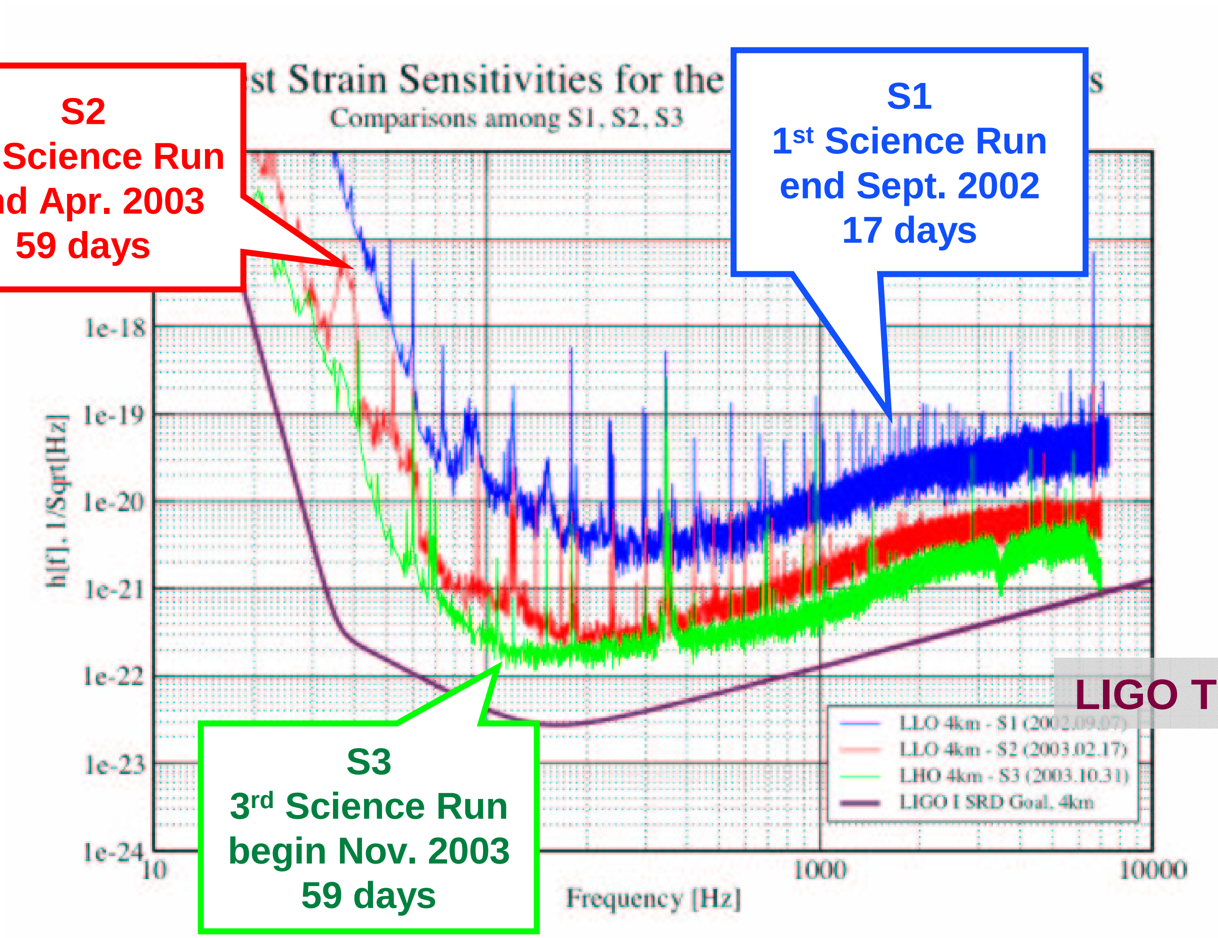
Computational challenge of optimal signal processing

- Optimal signal processing:
  - » Use filters which are tuned to the particular type of signal/source
- Rule of thumb:
  - » As signal complexity increases, number of different filters increases
  - » Attempt to analyze data in equivalent time to acquire it
- Examples:
  - » Compact binary inspiral depends on masses, spins, eccentricity, orientation: ~100,000 different filters for masses only, giving ~100 GFlop computing problem
  - » Phenomenological waveform from spinning neutron stars depends on sky location (Doppler shifts) and orientation: 1000's TFlop computing problem

•Challenge:

» Design *and* implement computationally efficient algorithms for filtering

Experience gained to date



S2
2nd Science Run
end Apr. 2003
59 days

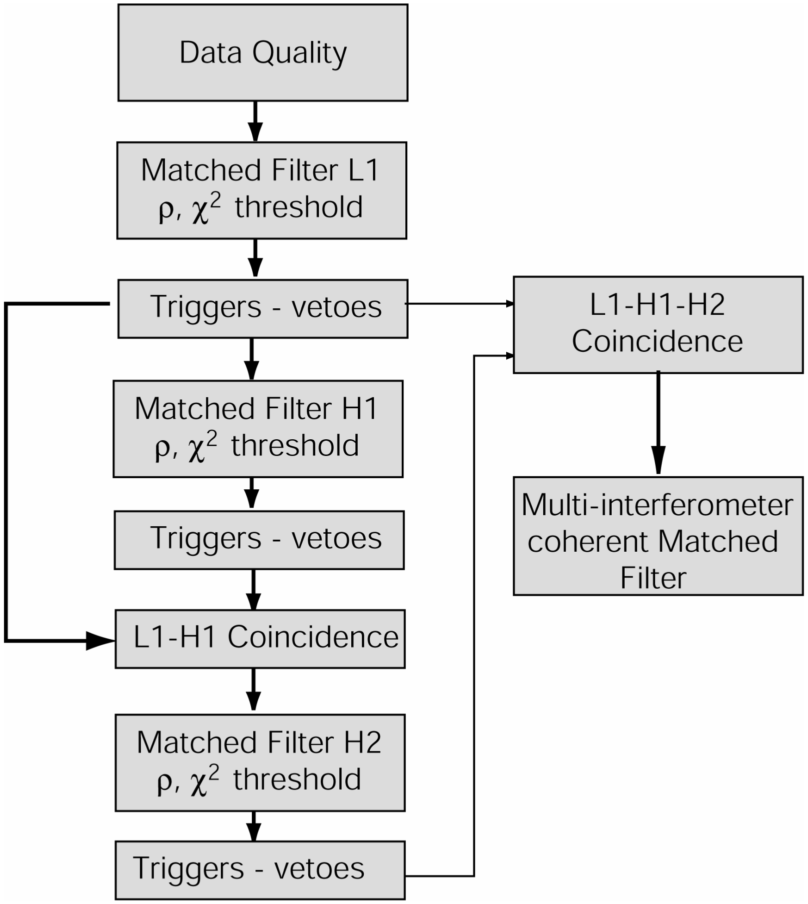
S1
1st Science Run
end Sept. 2002
17 days

LIGO Target Sensitivity

S3
3rd Science Run
begin Nov. 2003
59 days

Inspiral search pipeline: a case study in LIGO data analysis

- LIGO is sensitive to:
    - » Gravitational waves from binary systems containing neutron stars & stellar mass black holes
    - » Last several minutes of inspiral driven by GW emission
- Neutron Star Binaries
    - » Known to exist (Hulse-Taylor)
    - » Waveform accurately modeled
    - » LIGO range =20Mpc, N< 1/(4yr)
- NS/BH, BH/BH
    - » New science: rates, dynamics of gravitational field, merger waves
    - » LIGO range=105Mpc, N<1/(2yr)



Data Quality

Matched Filter L1
ρ, χ^2 threshold

Triggers - vetoes

L1-H1-H2
Coincidence

Matched Filter H1
ρ, χ^2 threshold

Multi-interferometer coherent Matched Filter

Triggers - vetoes

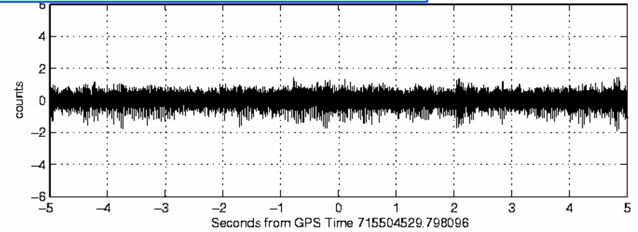
L1-H1 Coincidence

Matched Filter H2
ρ, χ^2 threshold

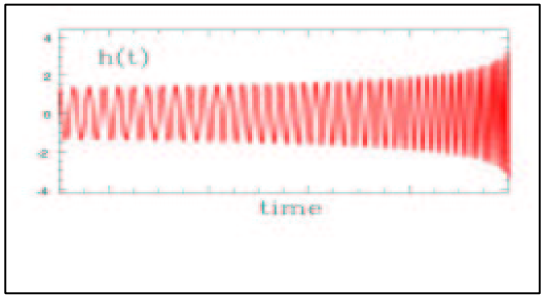
Triggers - vetoes

Optimal signal processing using a matched filter

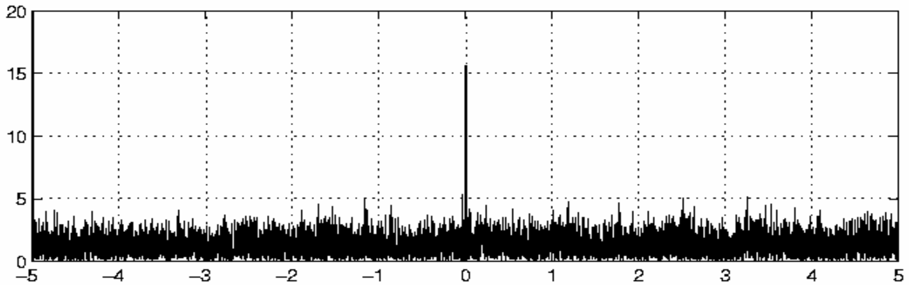
GW Channel
+ simulated inspiral



Filter to suppress
high/low freq



SNR



Coalescence Time

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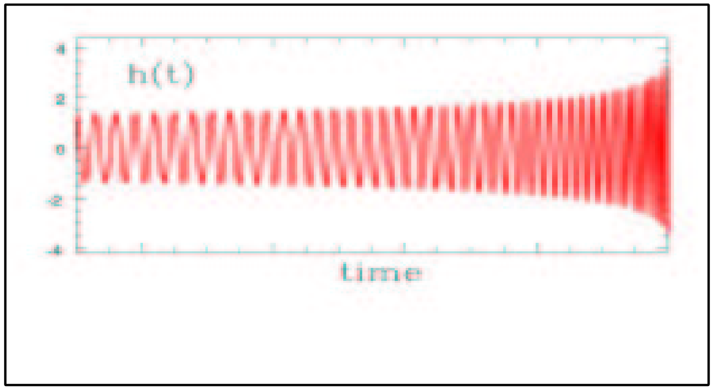
Template filters for inspiral waves

- Use template based matched filtering algorithm
- Search for non-spinning binaries
    - » 2.0 post-Newtonian waveforms

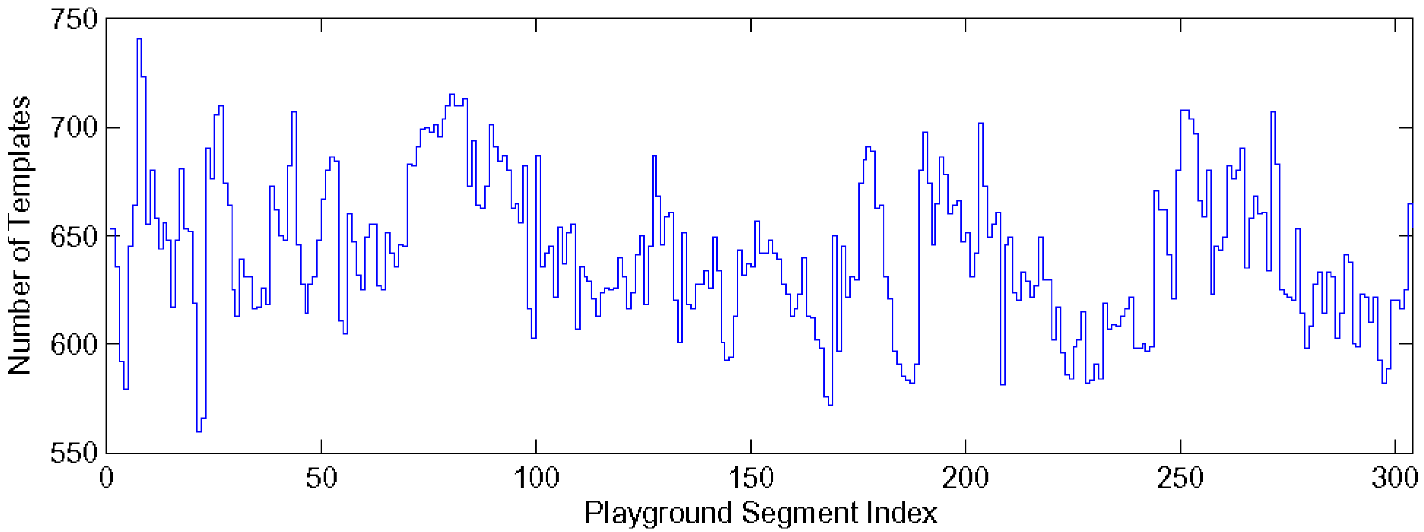


$$h(t) = (1\mathrm{Mpc}/D) \times [\, \sin(a)\, h^{I}_{s}\,(t-t0) + \cos(a)\, h^{I}_{c}\,(t-t0)]$$

- D: effective distance
- a: unknown phase
- Discrete set of templates labeled by I=(m1, m2)

Templates for S2 playground data set

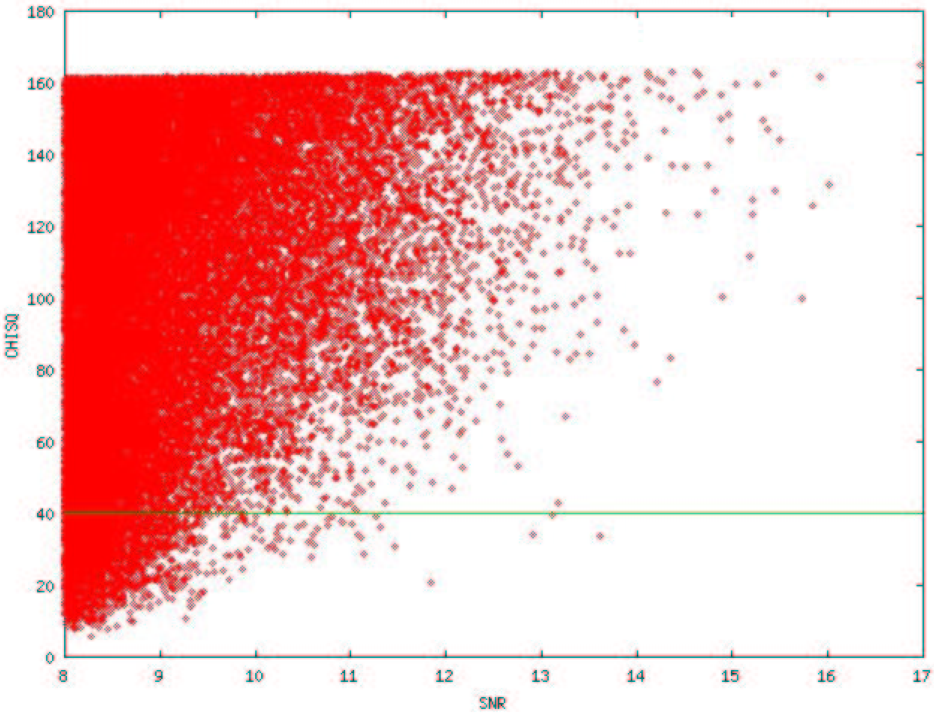
- Search for inspiral signals with matched filtering
  - » Templates: 2 pN stationary phase waveforms $1.0 < (m_1, m_2) < 3.0\ M_{sun}$
  - » Generate bank for each chunk with maximum 3% loss in signal-to-noise
  - » Apply a low frequency cutoff of 100 Hz to data
  - » 15 x 256 sec data segments overlapped by 128 sec
  - » Median power spectral estimate using 15 segments



G0

Generation of inspiral triggers

- Resample data to 4096 Hz and high pass at 90 Hz
- Compute median PSD for 15 segments of length 256 sec
- Matched filter templates to obtain signal-to-noise ρ
- If SNR $\rho > \rho_*$ compute template based veto, χ^2
  - » Small values of χ^2 indicate that ρ was accumulated in a manner consistent with an inspiral signal: If $\chi^2 < \chi^2_*$ then record trigger at maximum ρ
- Triggers are clustered within duration of each template
- Multiple templates can trigger at same time



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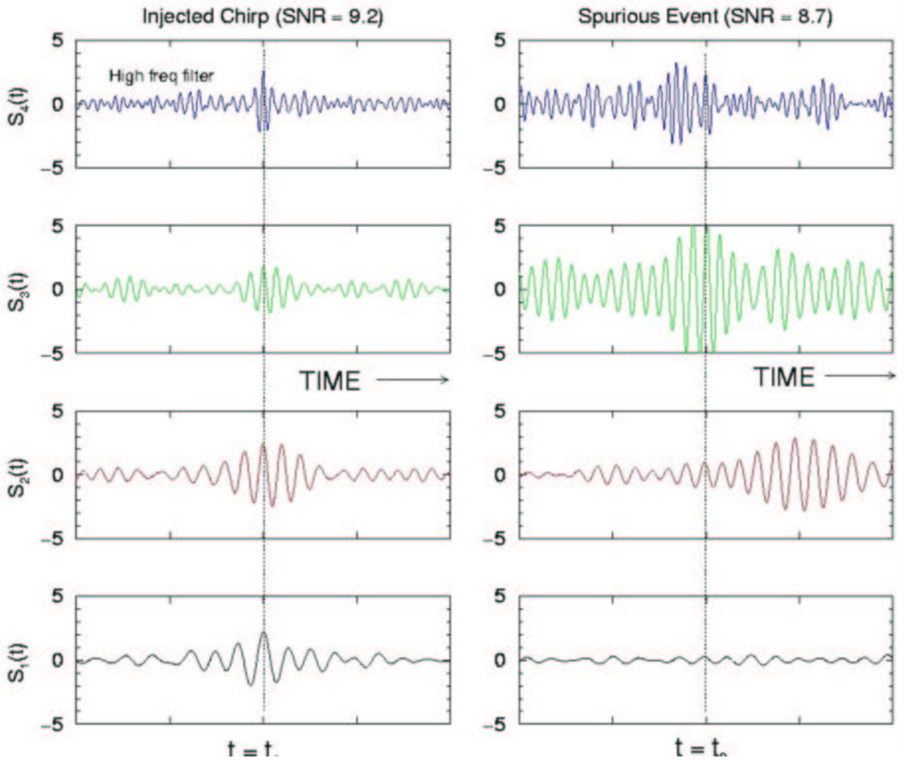
Template based χ^2 test

- Break inspiral template into p pieces each of which should accumulate 1/p of the total SNR
- Construct

$$\chi^2 \propto \sum_{i=1}^{8} (\rho_i - \rho/8)^2$$

- In Gaussian noise, this is distributed Chi squared (2p-2) degrees of freedom



Effectiveness of χ^2 veto

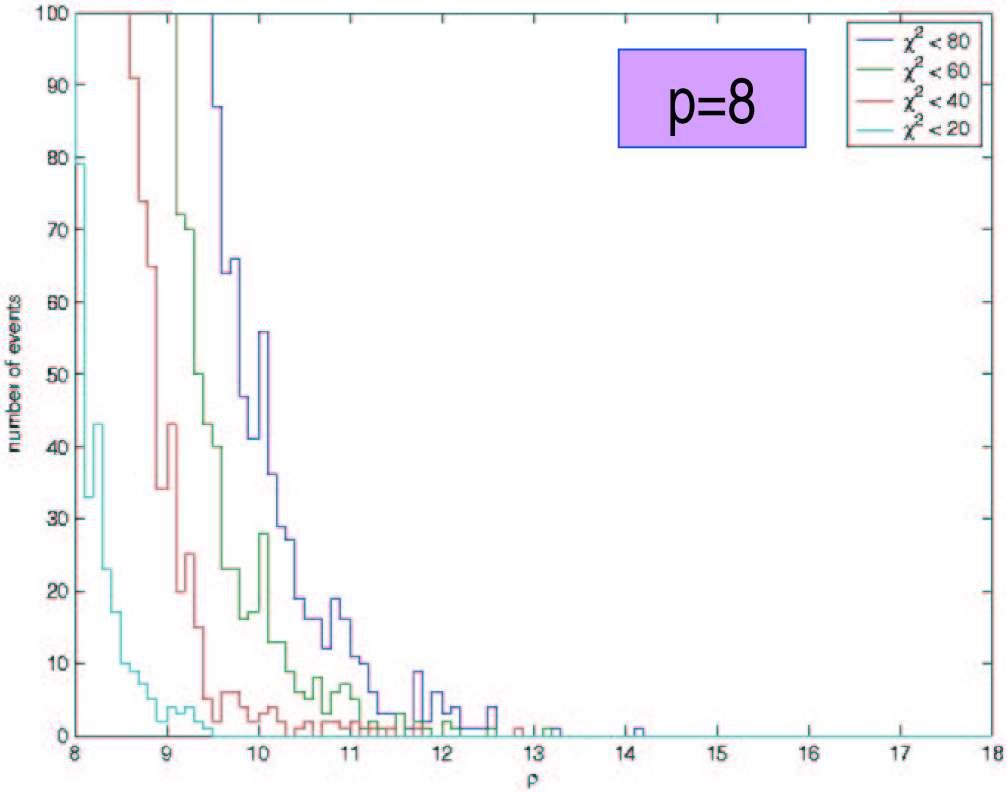
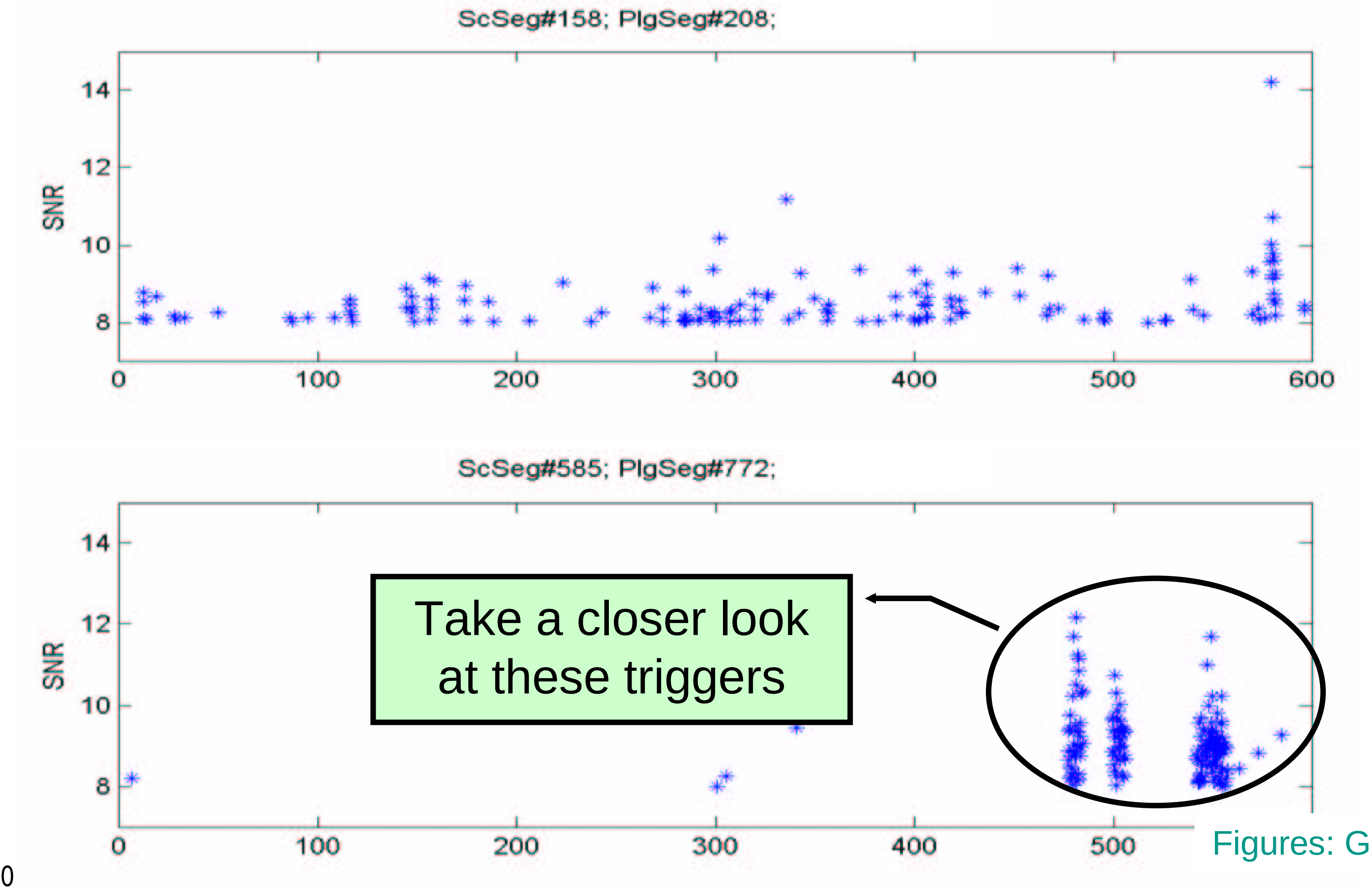


Figure: D. Brown

Nature and origin of inspiral triggers



Take a closer look at these triggers

Figures: G. Gonzalez

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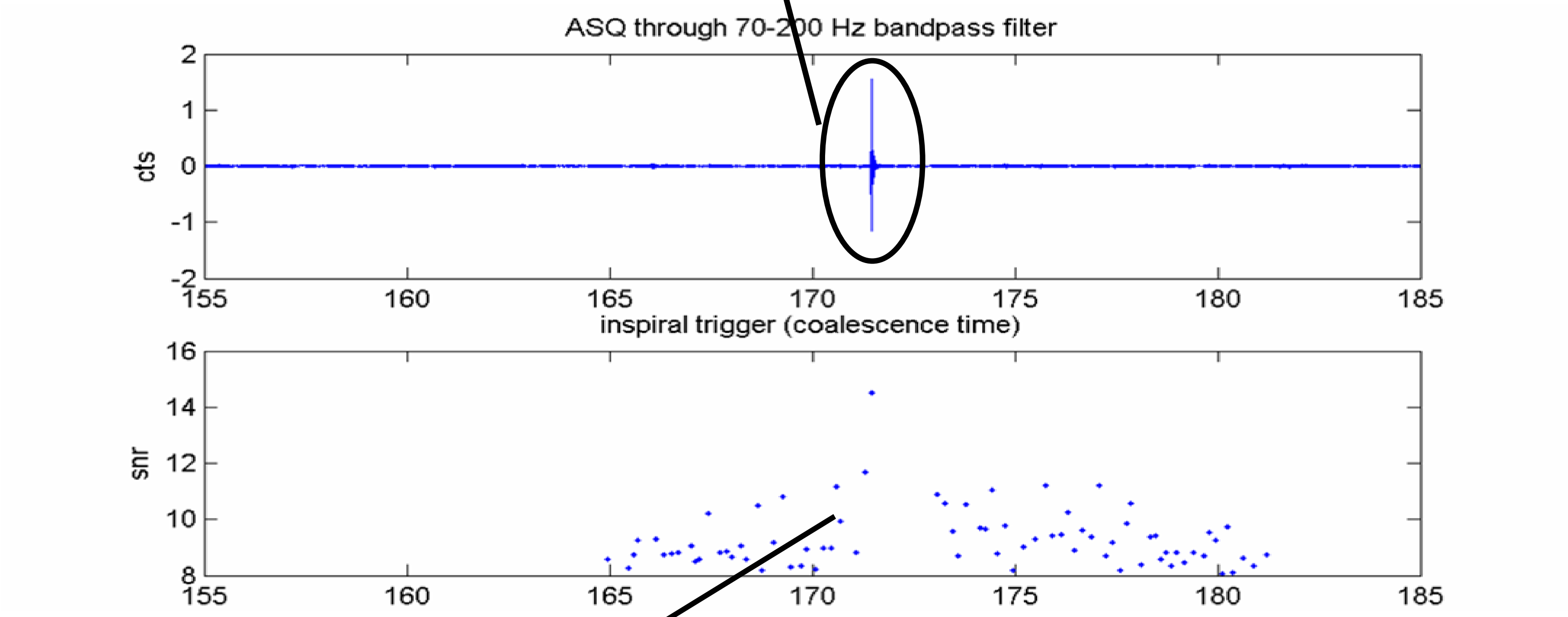
Origin of striped triggers

Non-Gaussian noise burst



Coalescence time of trigger does not agree with non-Gaussian burst

Figure: G. Gonzalez

Response of inspiral filters to glitch

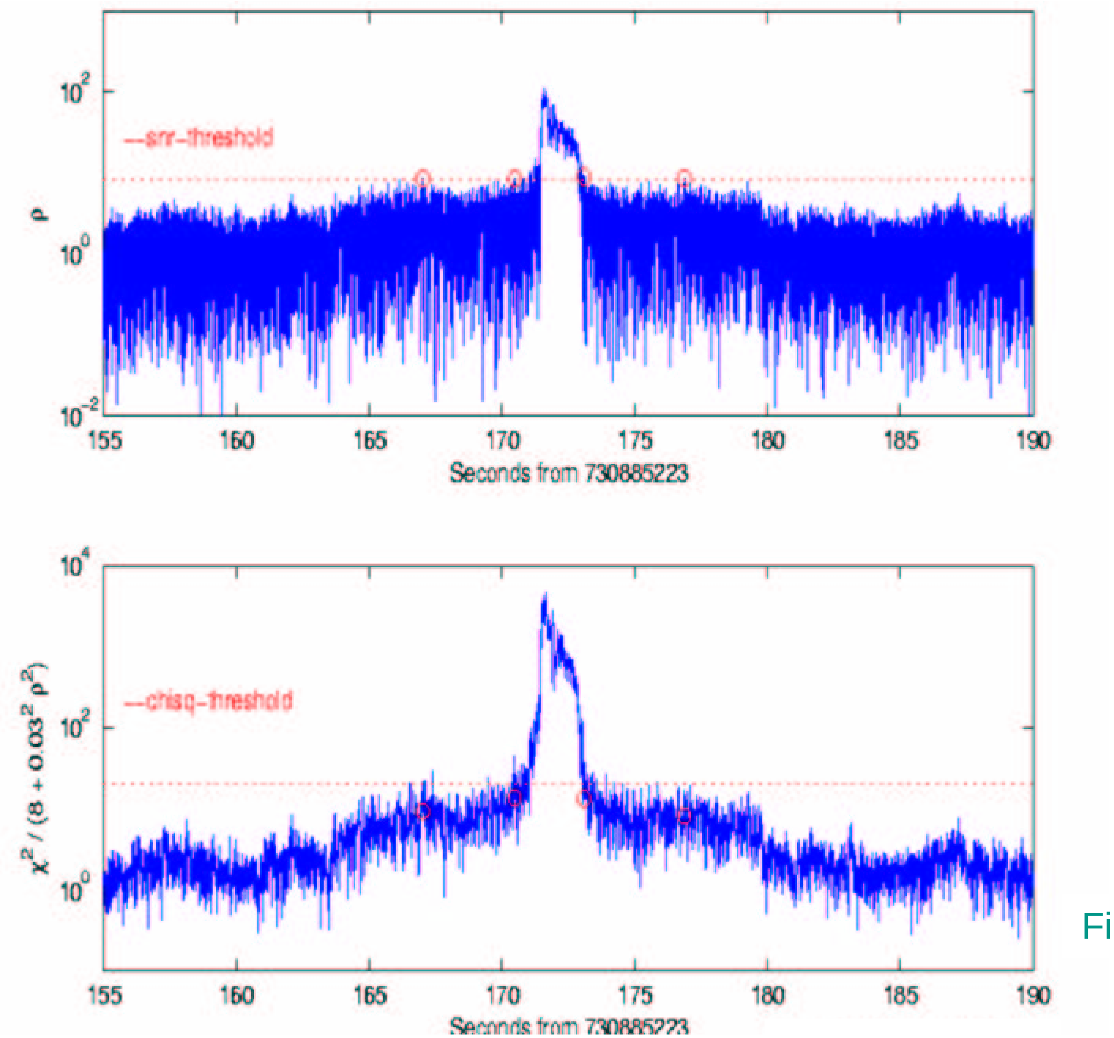
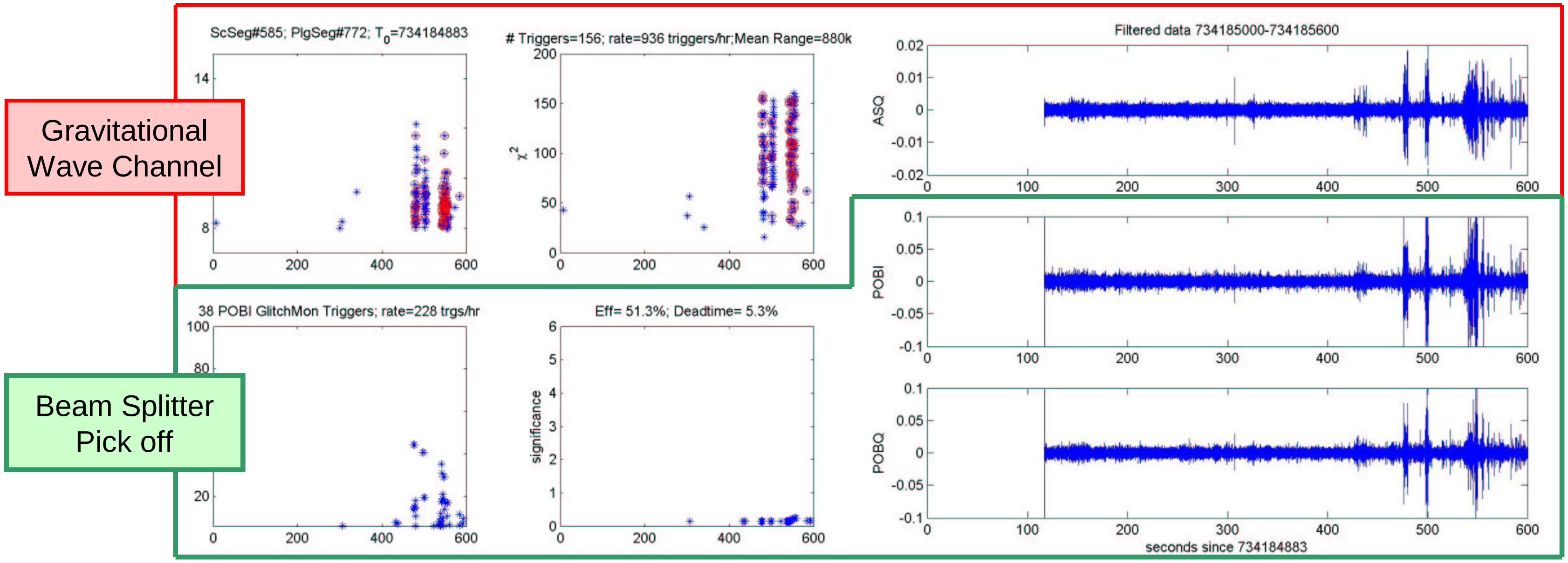


Figure: D. Brown

Vetoing non-Gaussian noise bursts

- Construct vetoes to remove spurious inspiral triggers
  - Some inspiral triggers are due to “obvious” instrumental glitches
  - Look for explanation of spurious inspiral triggers in other channels
    - Glitch monitors on auxiliary interferometer channels
    - Physical environment monitoring channels



- Tune vetoes on playground then apply to inspiral triggers full data set

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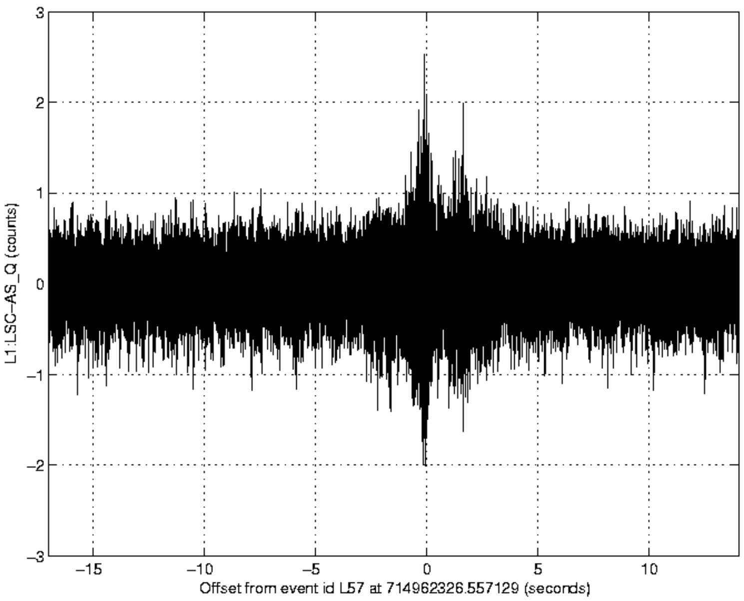
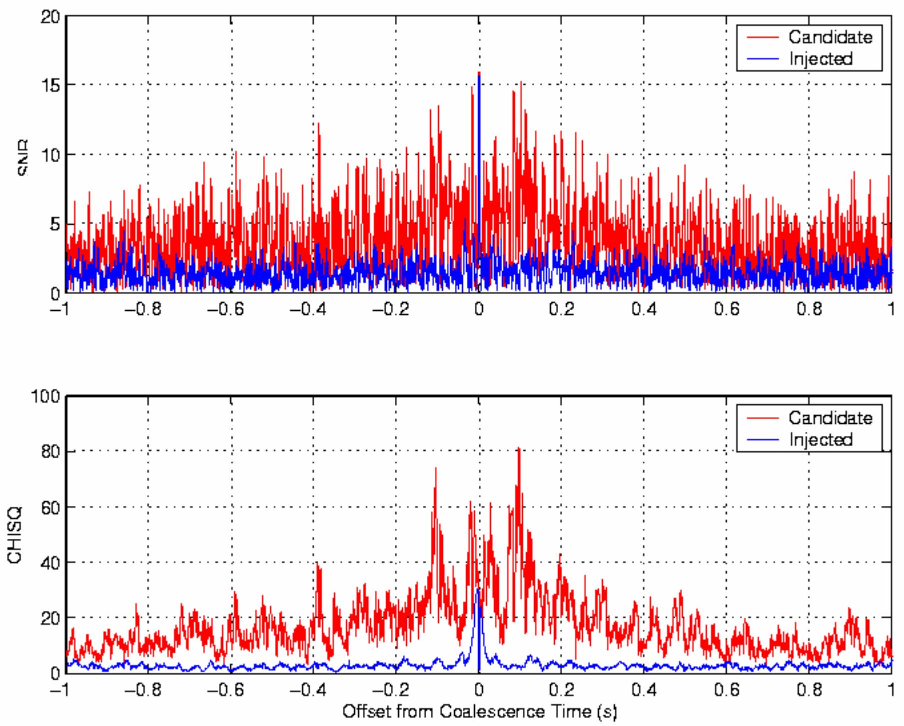
Important lesson from S1 analysis

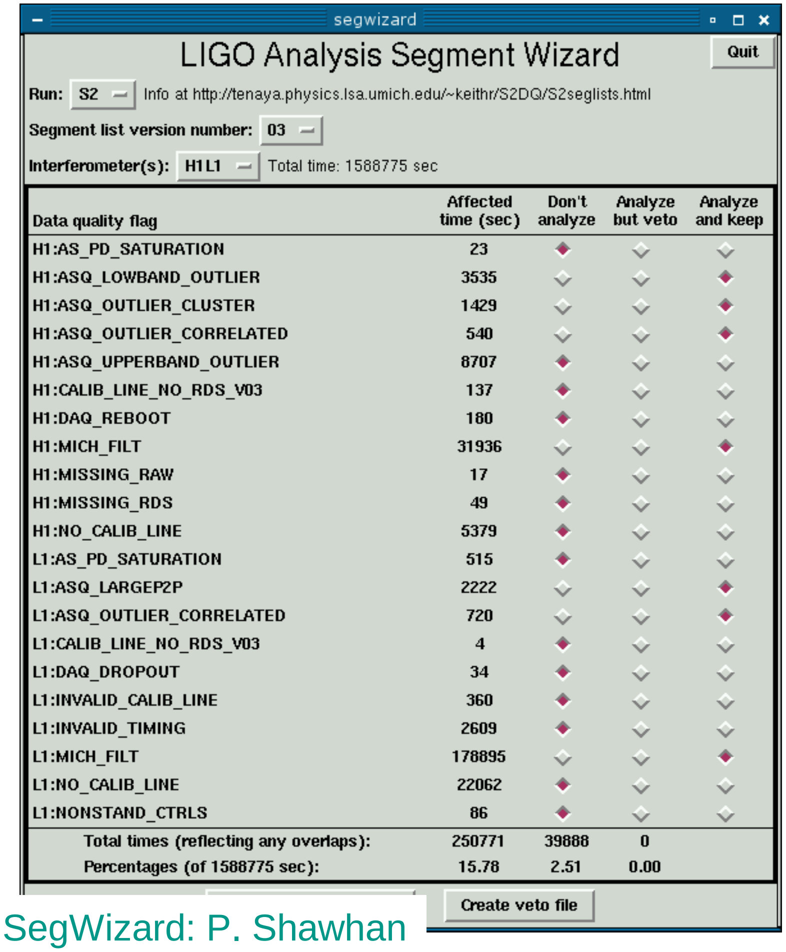
- Largest SNR trigger in S1 analysis – not a binary neutron star!
- S/N = 15.9, χ^2/dof = 2.2
- (m1,m2) = (1.3, 1.1) Msun





- What caused this?
- Appears to be saturation of a photodiode

What have we learned about instrumental vetoes so far?



LIGO Analysis Segment Wizard

Run: S2 Info at http://tenaya.physics.lsa.umich.edu/~keithr/S2DQ/S2seglists.html

Segment list version number: 03

Interferometer(s): H1L1 Total time: 1588775 sec

Data quality flag	Affected time (sec)	Don't analyze	Analyze but veto	Analyze and keep
H1:AS_PD_SATURATION	23	◆	◇	◇
H1:ASQ_LOWBAND_OUTLIER	3535	◇	◇	◆
H1:ASQ_OUTLIER_CLUSTER	1429	◇	◇	◆
H1:ASQ_OUTLIER_CORRELATED	540	◇	◇	◆
H1:ASQ_UPPERBAND_OUTLIER	8707	◆	◇	◇
H1:CALIB_LINE_NO_RDS_V03	137	◆	◇	◇
H1:DAQ_REBOOT	180	◆	◇	◇
H1:MICH_FILT	31936	◇	◇	◆
H1:MISSING_RAW	17	◆	◇	◇
H1:MISSING_RDS	49	◆	◇	◇
H1:NO_CALIB_LINE	5379	◆	◇	◇
L1:AS_PD_SATURATION	515	◆	◇	◇
L1:ASQ_LARGEP2P	2222	◇	◇	◆
L1:ASQ_OUTLIER_CORRELATED	720	◇	◇	◆
L1:CALIB_LINE_NO_RDS_V03	4	◆	◇	◇
L1:DAQ_DROPOUT	34	◆	◇	◇
L1:INVALID_CALIB_LINE	360	◆	◇	◇
L1:INVALID_TIMING	2609	◆	◇	◇
L1:MICH_FILT	178895	◇	◇	◆
L1:NO_CALIB_LINE	22062	◆	◇	◇
L1:NONSTAND_CTRLS	86	◆	◇	◇
Total times (reflecting any overlaps):		250771	39888	0
Percentages (of 1588775 sec):		15.78	2.51	0.00

SegWizard: P. Shawhan

- Apply data quality flags up front!
  - » Operators provide first line of defence
  - » Science mode data flagged as it is taken
- Extra information used in deciding what data to analyze:
  - » Exclude photodiode saturations
  - » Exclude data without calibration lines
  - » Exclude data with invalid timing
- Other lessons learned
  - » A cattle-guard at Livingston was identified as a problem following an enginering run
- But …….
  - » Still lack good instrumental vetoes
  - » A very difficult problem as expected

Target Population

- Simulate gravitational waves from a population of binary neutron stars
    - » Rate of binary inspirals expected to be proportional to star formation rate
    - » Population includes all galaxies out to maximum distance at SNR=5.5
- Inject signals from population into data from all three LIGO interferometers
    - » Inject in software
    - » Validated by hardware injections
- Determine efficiency, ε, for detection of simulated signals at threshold ρ^*
    - » Efficiency $\varepsilon = N_{det} / N_{inj}$

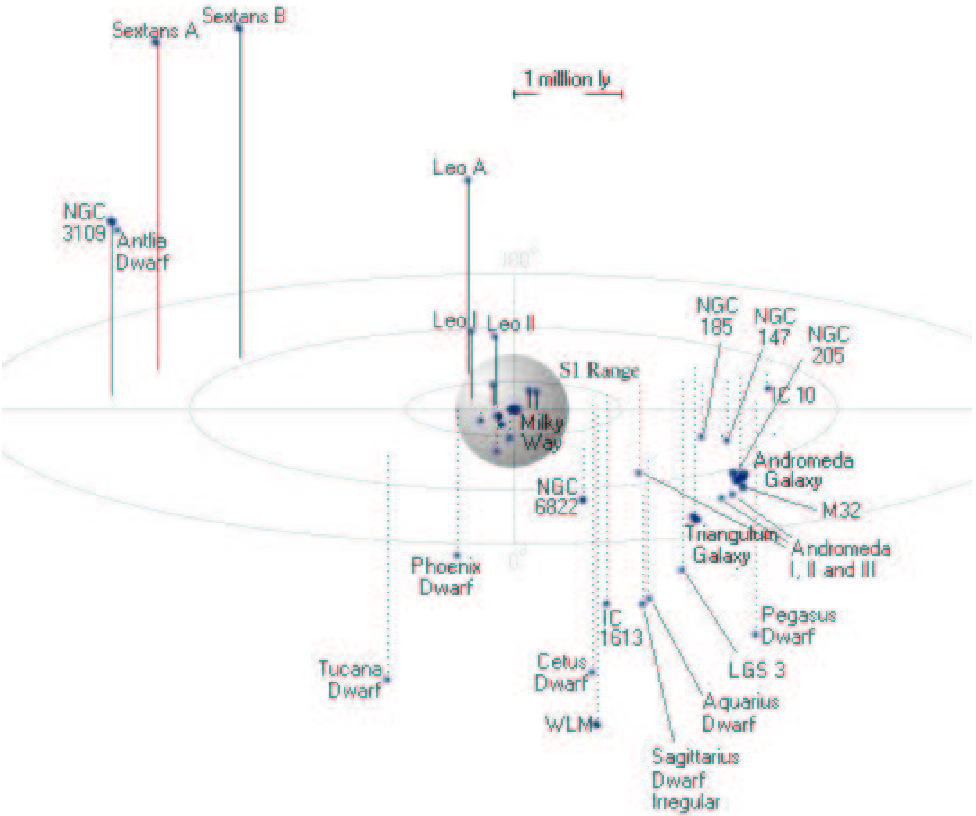
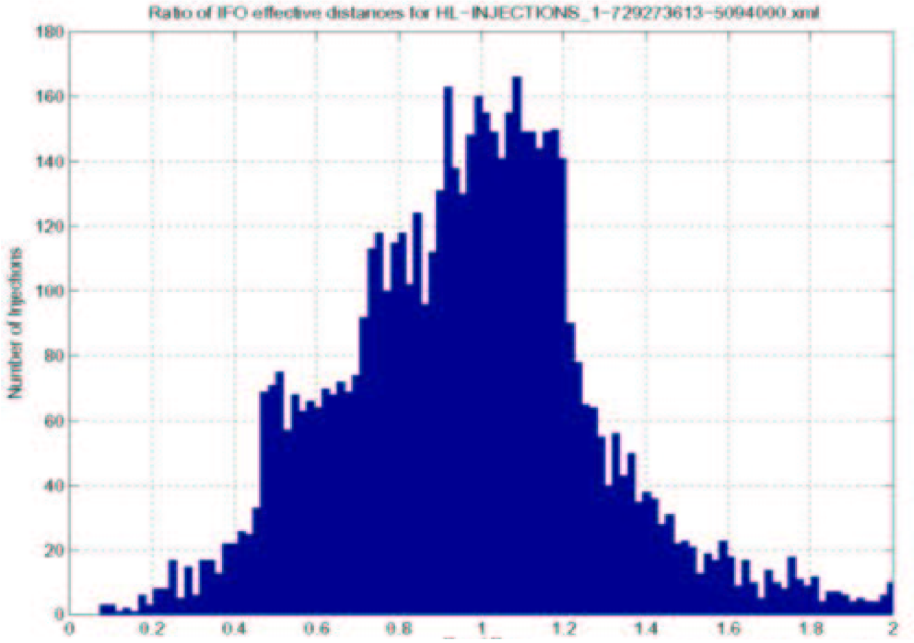


Image: R. Powell

Trigger coincidence test

- Look for coincident triggers
  - » Present in all interferometers
  - » Coincident to within 11 ms between sites, 1 ms at the same site
  - » Each mass parameter in the template must be the same to within 0.03 solar masses.
  - » Compare distances measured at Livingston (D_L) and Hanford (D_H)



D_H/D_L

- Livingston and Hanford detectors are not exactly co-aligned

- So ratio of effective distance varies with sky location and polarization of source

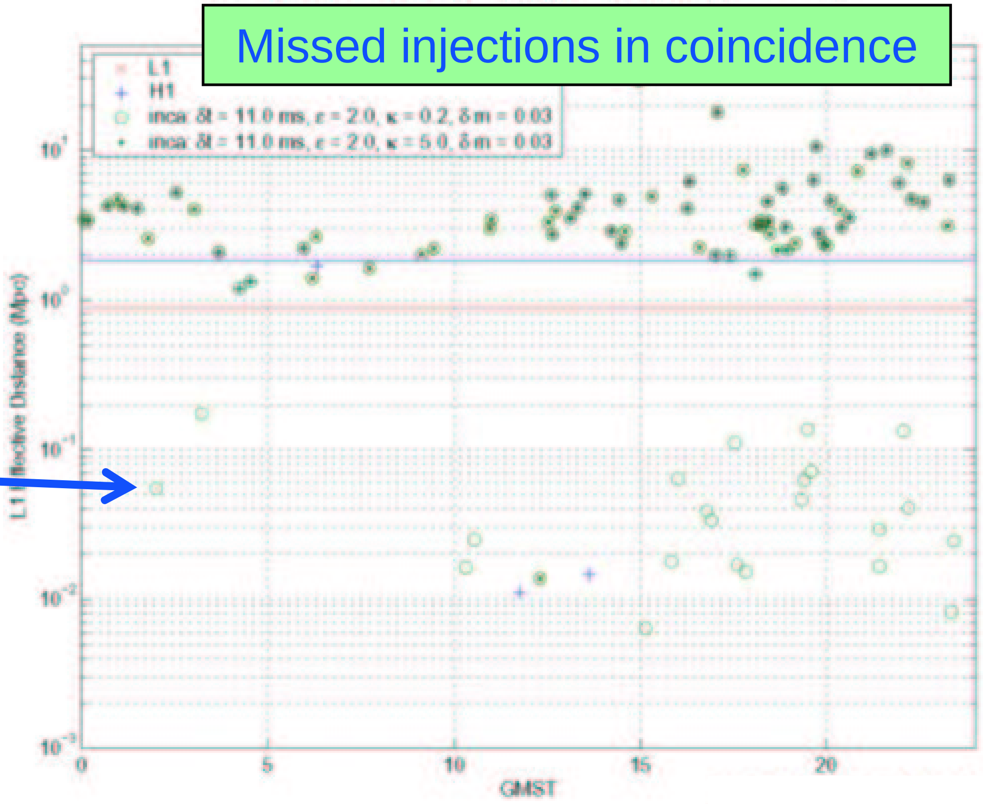
Tuning the amplitude cut

- Errors in distance estimates expected to decrease with increasing SNR

$$|D_L - D_H|/D_L < \varepsilon/\rho_H + \kappa$$

- ε and κ tunable constants

Remove amplitude cut to allow detection of these Milky Way events


Missed injections in coincidence

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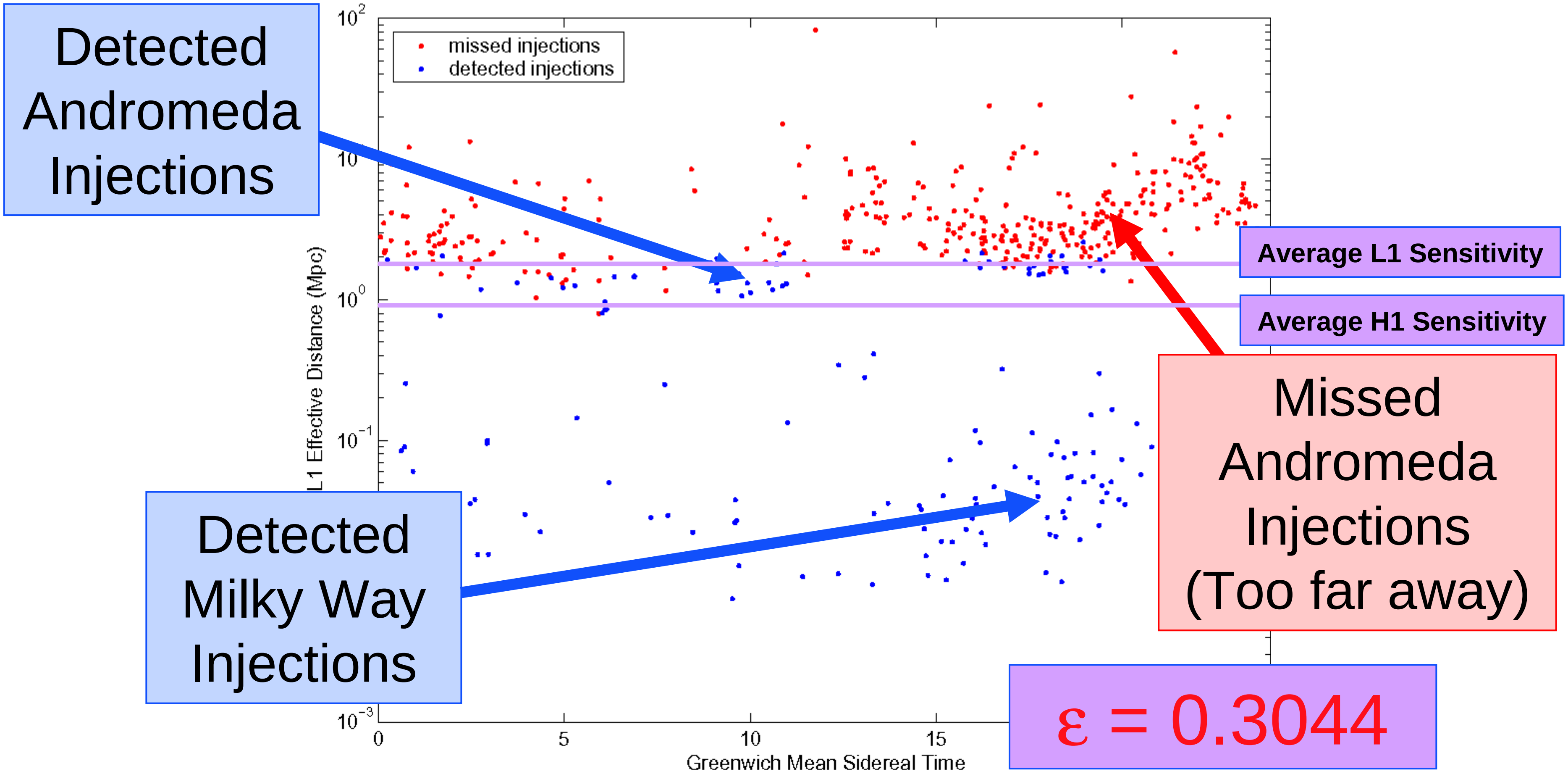
Playground Results: Pipeline Efficiency



Detected Andromeda Injections

Detected Milky Way Injections

Average L1 Sensitivity

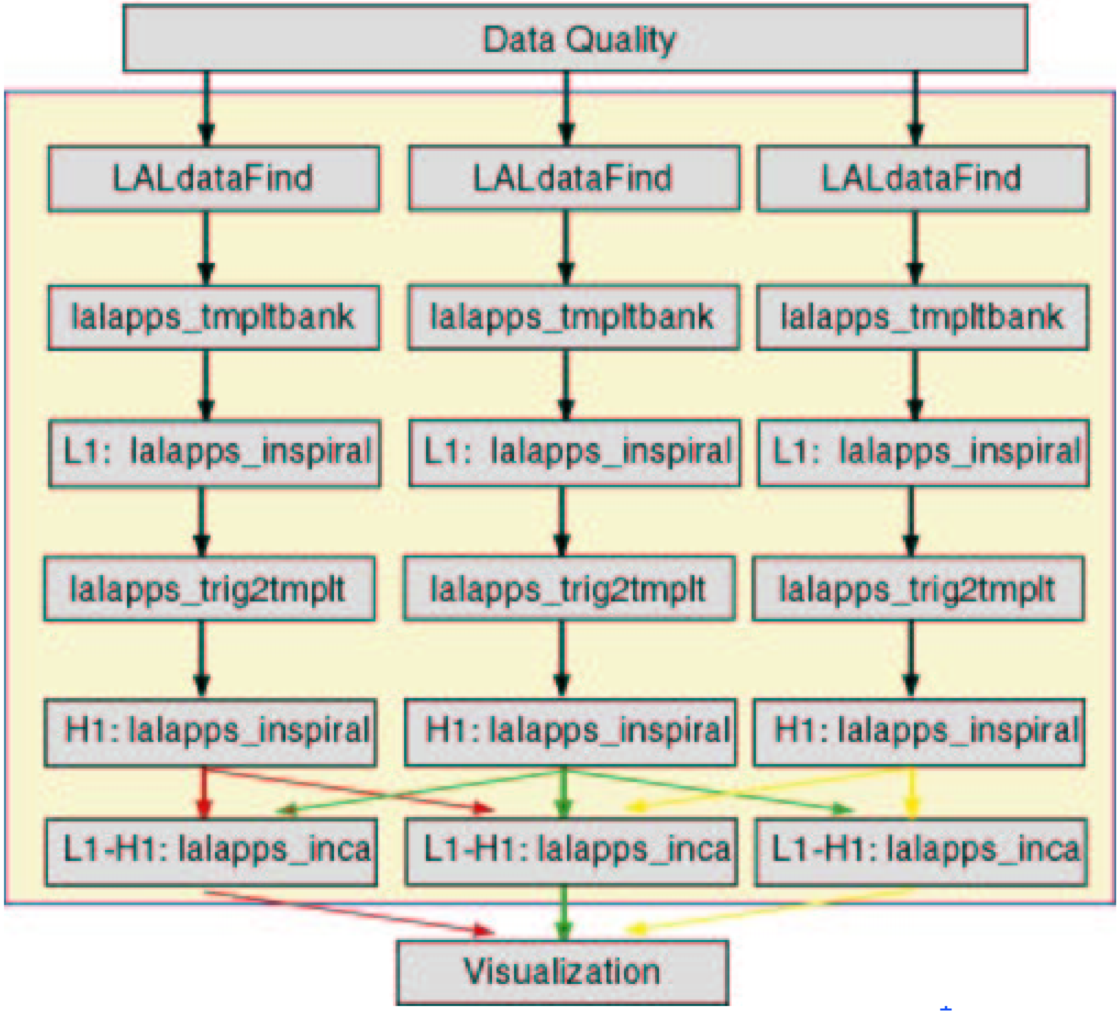
Average H1 Sensitivity

Missed Andromeda Injections (Too far away)

$\varepsilon = 0.3044$

Automating the analysis chain

- Search codes run standalone using Condor batch scheduler
  - » Directed Acyclic Graph describes workflow
- Use LALdataFind to locate data
  - » Interrogation of replica catalog maintained by LDR (S. Koranda)
- All search code in
  - » LAL and LALApps (many contributors)
- Inspiral code
  - » Generates triggers from each interferometer
- Coincidence stage of the search is part of the jobs we run
  - » Can add extra steps quite easily
- Code ready to run in LSC DataGrid
  - » Plan to do this in 2004



Concluding remarks

- Challenges and status:
  - » Non-Gaussian bursts: still need to get a handle on them
  - » Resonances require care in data processing and interpretation: could improve
  - » Calibration: understanding and implementation are well under way
  - » Algorithm design side of (near) optimal signal processing is in hand
  - » Still lots of implementation work to automate things
  - » Distributed computing is addressing some of computing requirements
- Implications for science:
  - » Experience from science runs is speeding up analysis
  - » New searches are getting under way
  - » Future is bright for gravitational-wave detection with LIGO
  - » Gravitational-wave astronomy is our ultimate challenge