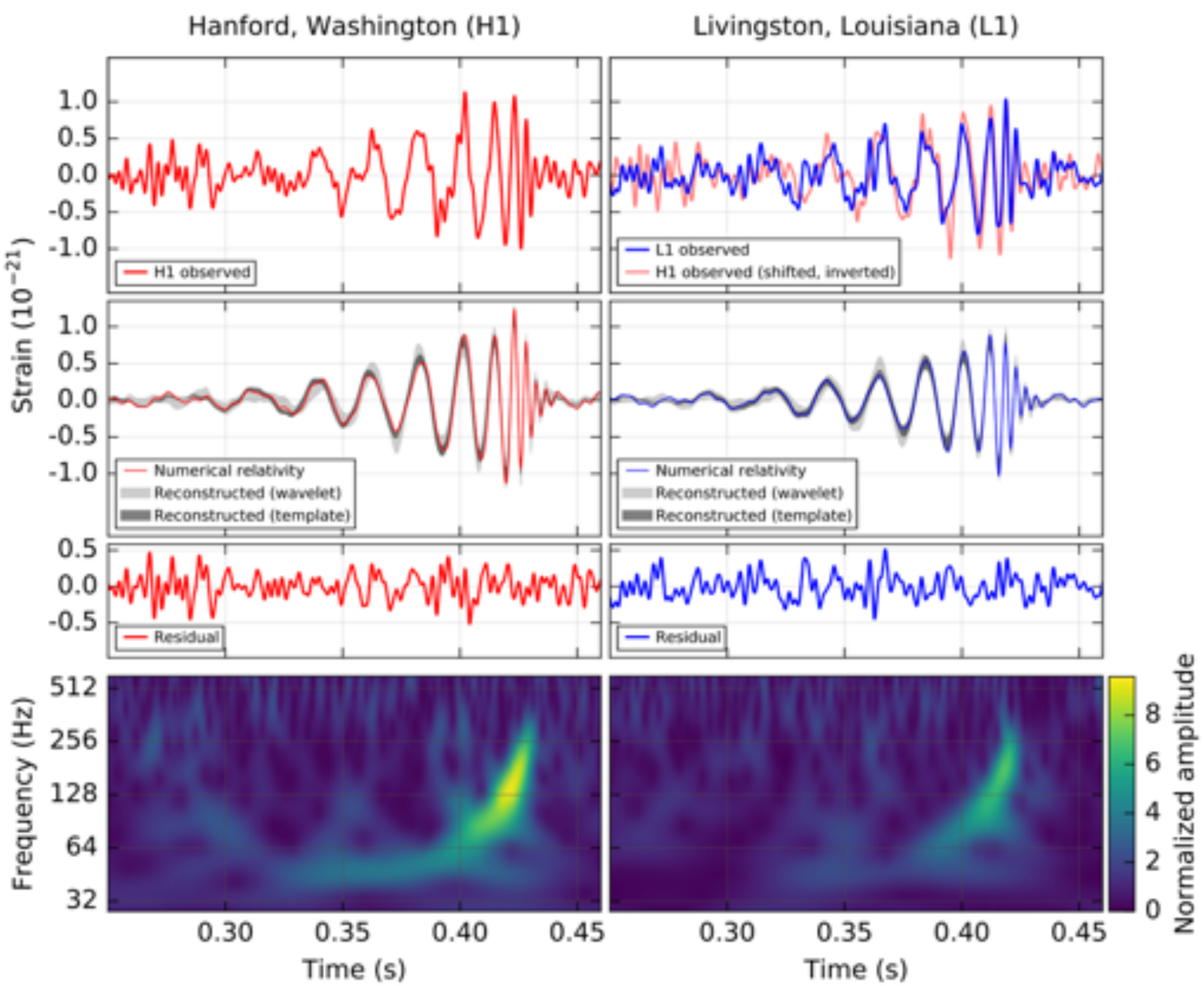
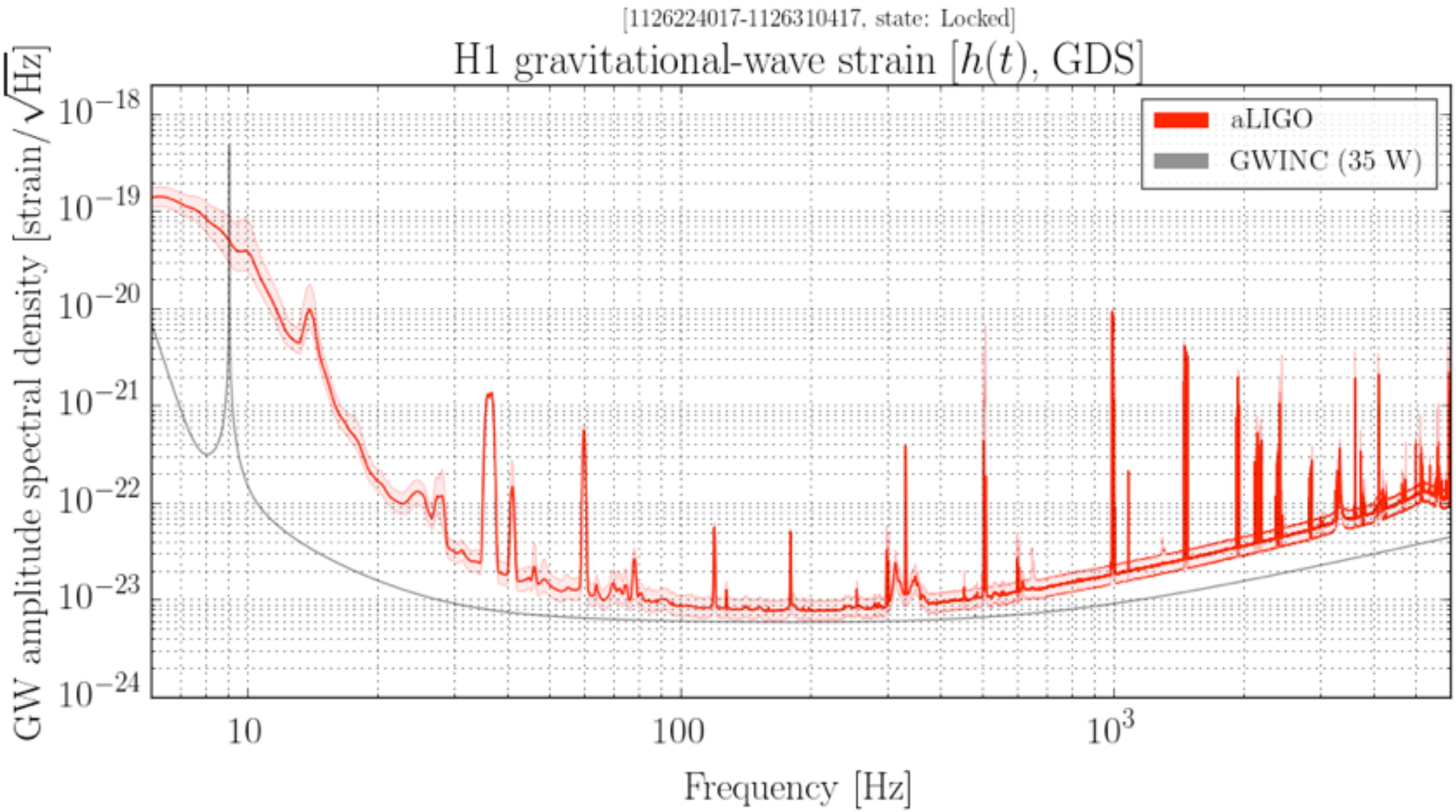
LIGO's auxiliary channels

Andrew Lundgren

The primary channel



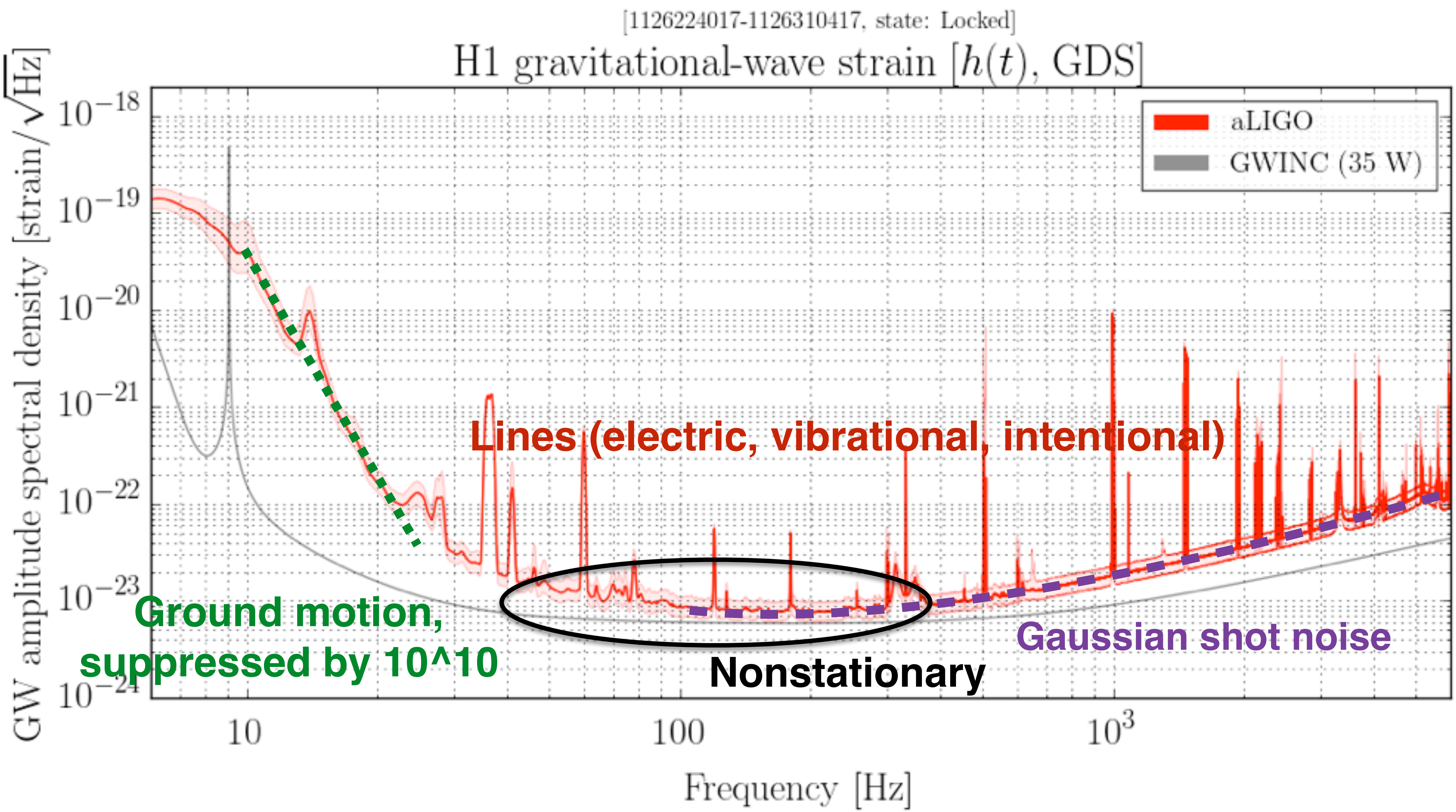
- The gravitational-wave channel
- Also called strain, h(t), DARM (differential arm)
- Sensitive to a 10^-22 relative length change of a 4 km Michelson interferometer



- Sampled at 16384 Hz (use powers of two everywhere for convenience)

- Sensitive range is 20 to 2000 kHz (basically audio)

Features of the noise



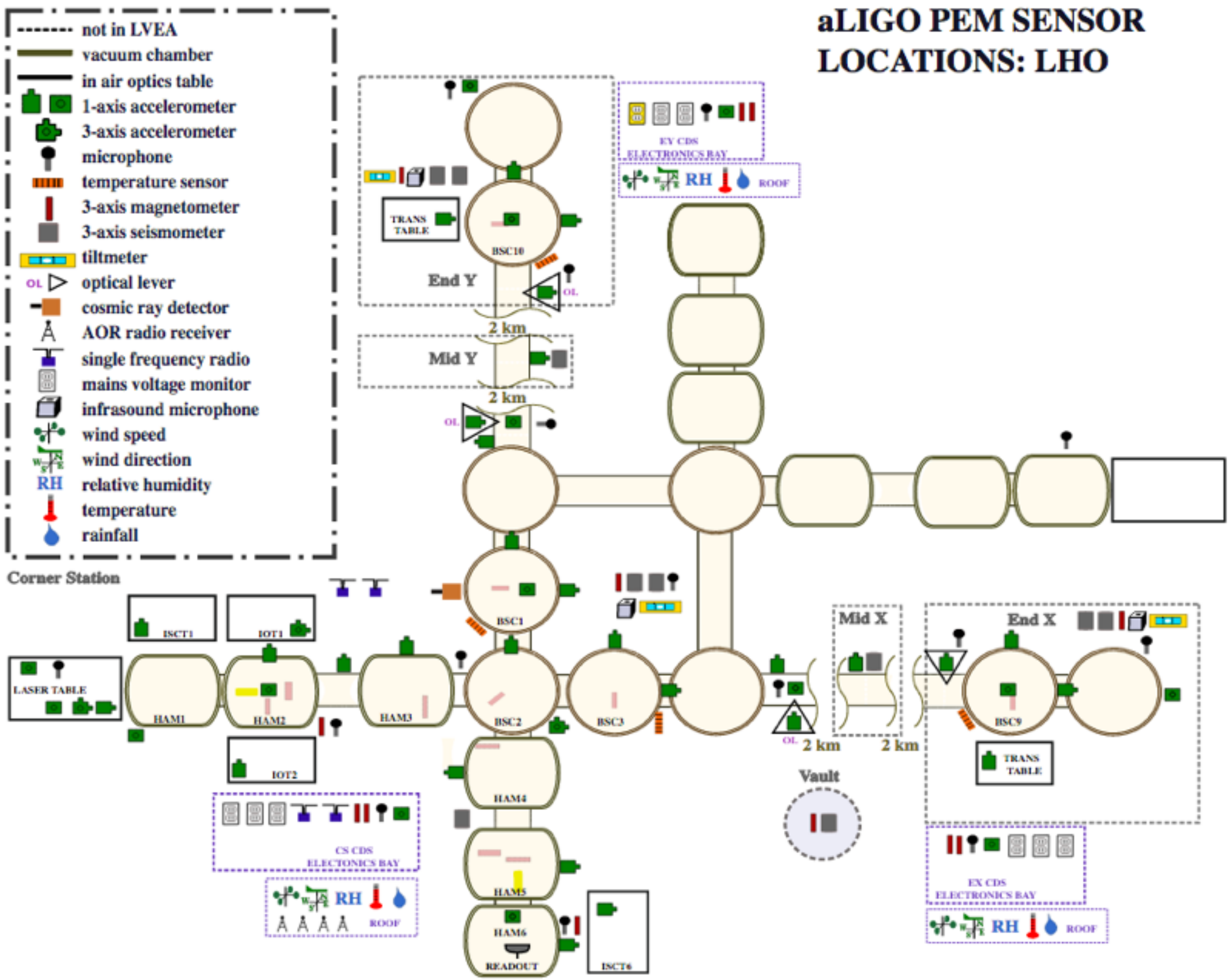
Auxiliary channels (per site)

- 3,000 fast channels (256 Hz to 16384 Hz)
- 200,000 slow channels (16 Hz)
- 1 terabyte per day
- Archived in 64-second chunks, all channels together, in our own frame format
- Also second and minute trends (min,max,mean,rms)

Kinds of auxiliary channels

- Physical and environmental monitoring
- Suspensions of the mirrors
- Instrumental
  - Sensing
  - Control

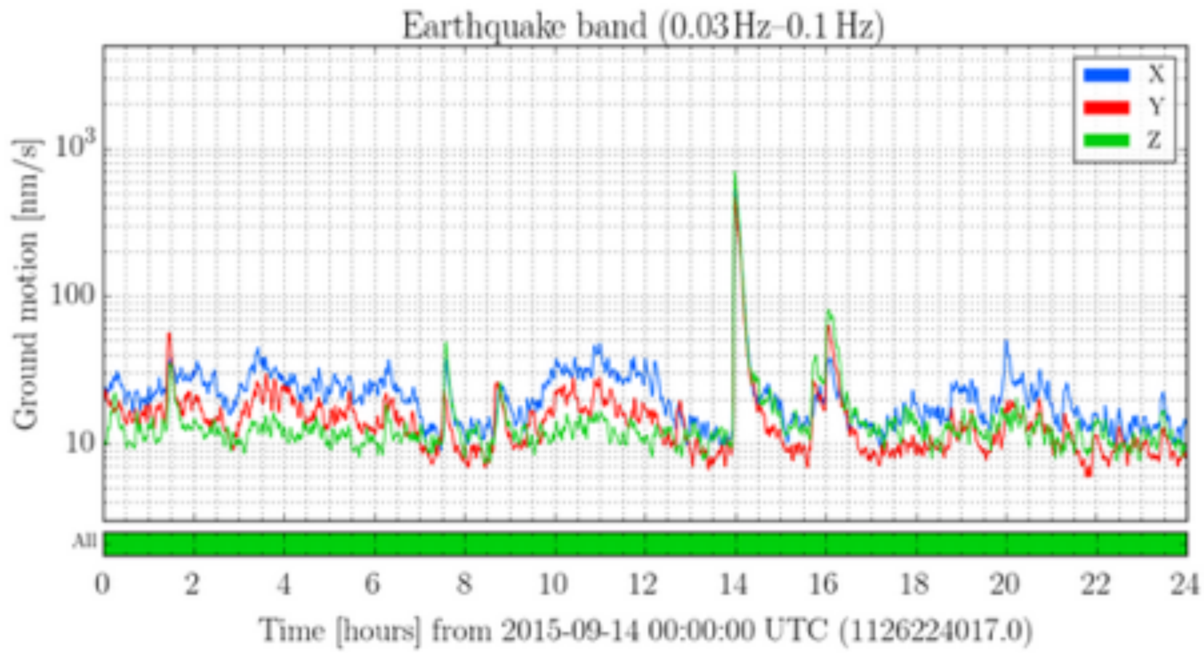
PEM (Environmental Monitoring)



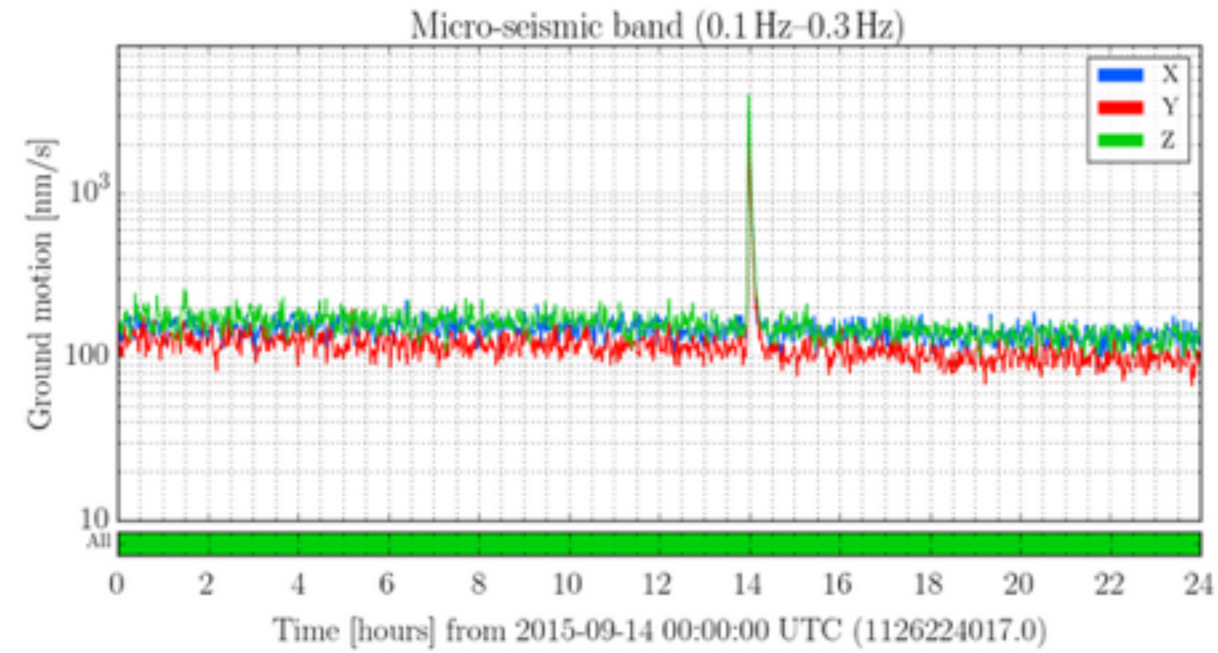
PEM

- PEM is (roughly) all sensors outside the instrument
- Ground motion: Many seismometers
- Acoustic: Microphones, accelerometers
- E&M: Many magnetometers, power mains monitor, radio receivers
- Weather: Humidity, wind, pressure

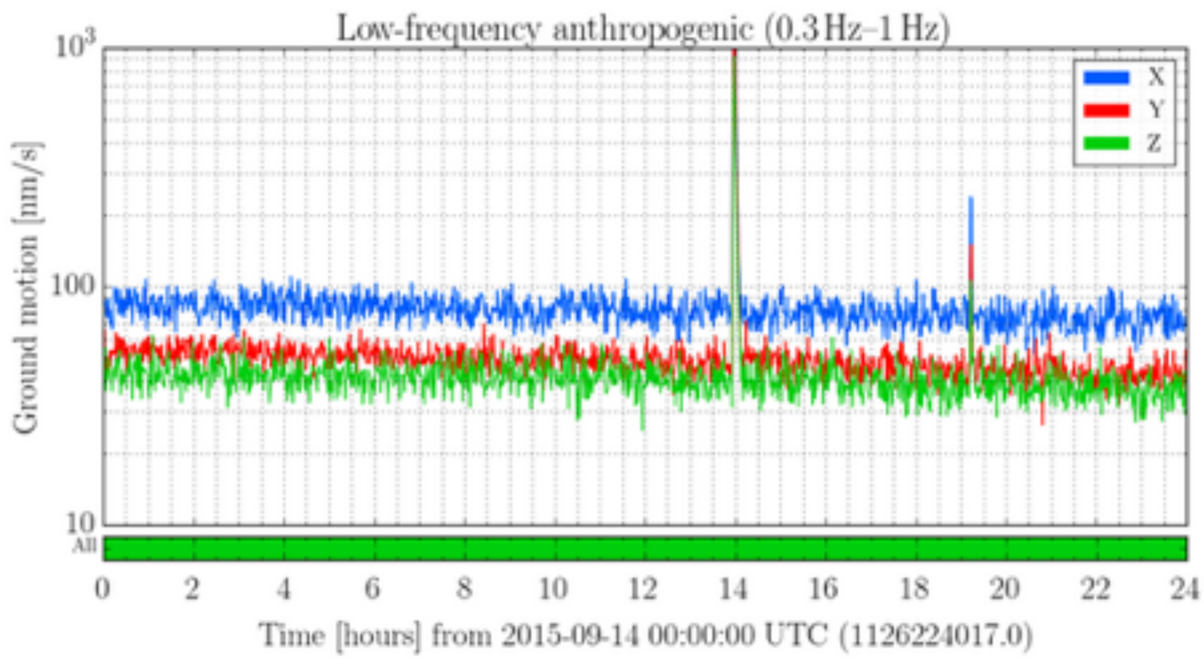
Seismic



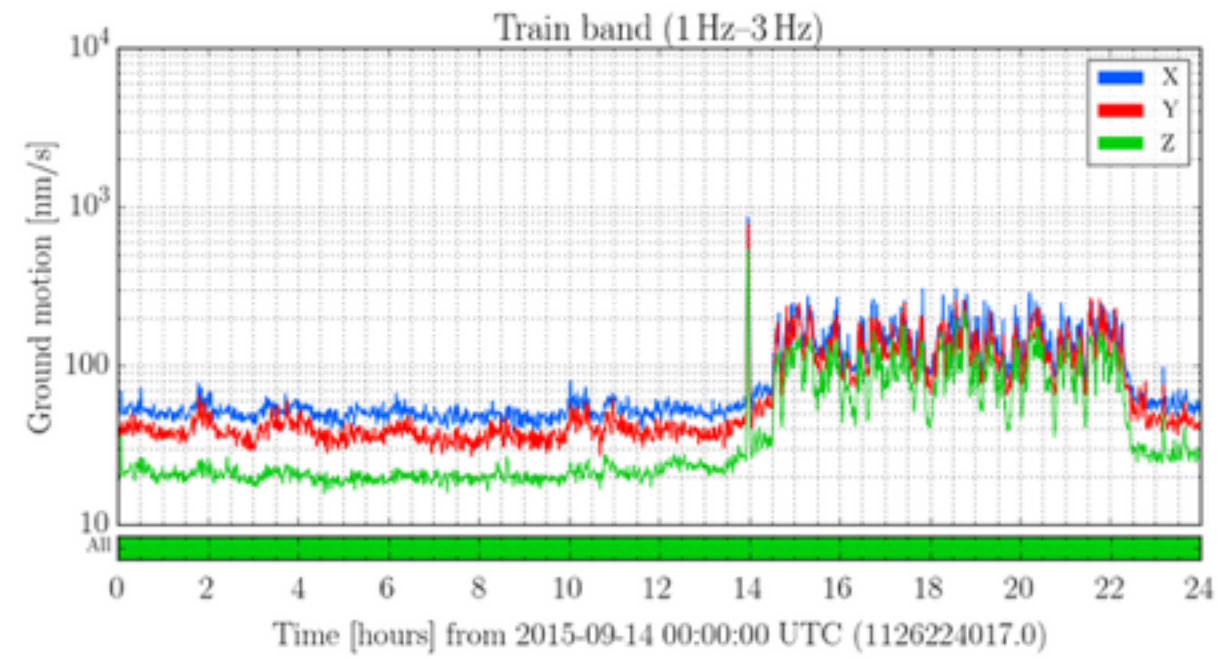
Earthquake band (0.03 Hz–0.1 Hz)
Ground motion [nm/s]
X
Y
Z
All
Time [hours] from 2015-09-14 00:00:00 UTC (1126224017.0)



Micro-seismic band (0.1 Hz–0.3 Hz)
Ground motion [nm/s]
X
Y
Z
All
Time [hours] from 2015-09-14 00:00:00 UTC (1126224017.0)



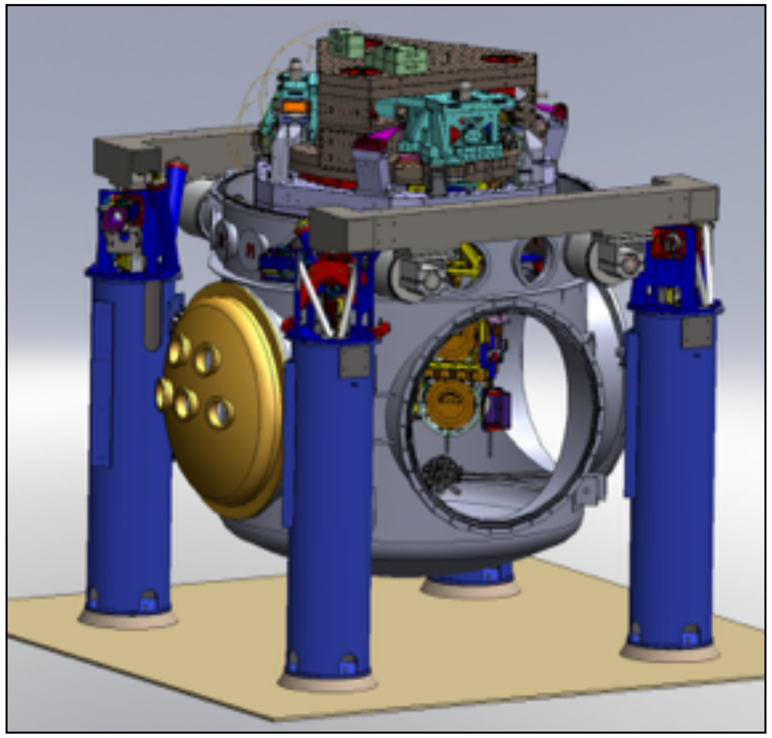
Low-frequency anthropogenic (0.3 Hz–1 Hz)
Ground motion [nm/s]
X
Y
Z
All
Time [hours] from 2015-09-14 00:00:00 UTC (1126224017.0)



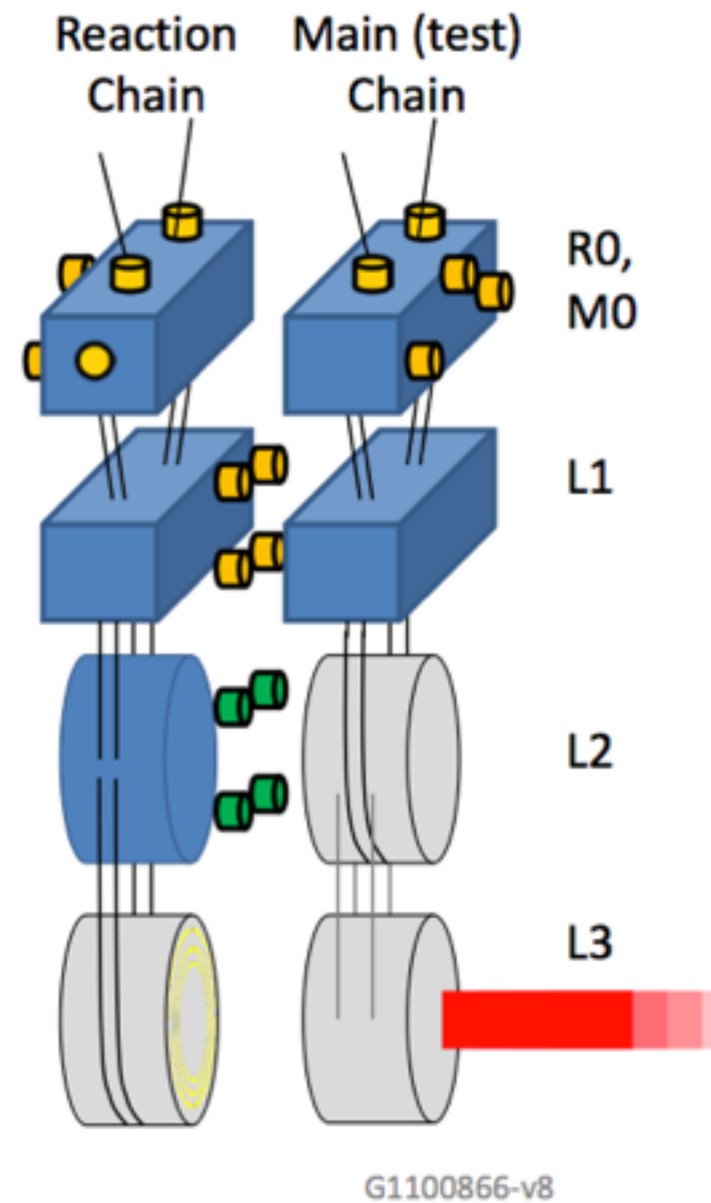
Train band (1 Hz–3 Hz)
Ground motion [nm/s]
X
Y
Z
All
Time [hours] from 2015-09-14 00:00:00 UTC (1126224017.0)

Acoustic/Vibration

- Mostly really well isolated
- Gets in at only a few different sites
    - Often by exciting a known mechanical resonance
- Test these with PEM injections (speakers/shakers)
- Have known coupling functions
    - But nonlinearity/upconversion are a problem

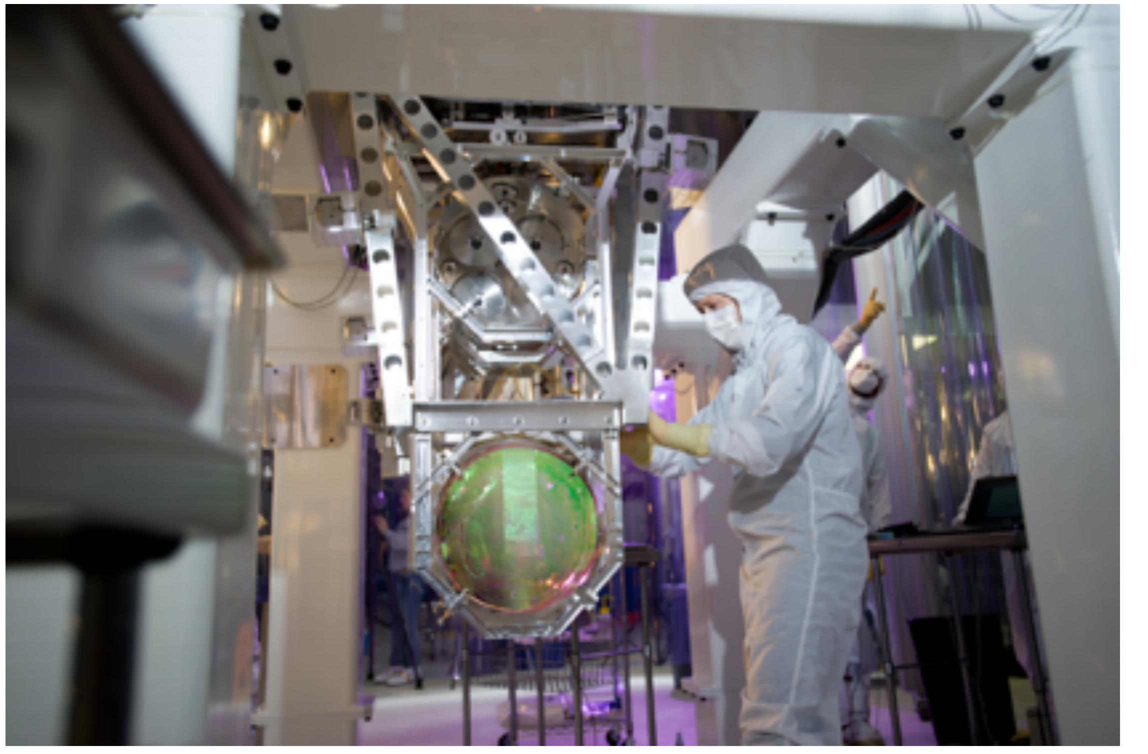


Suspensions



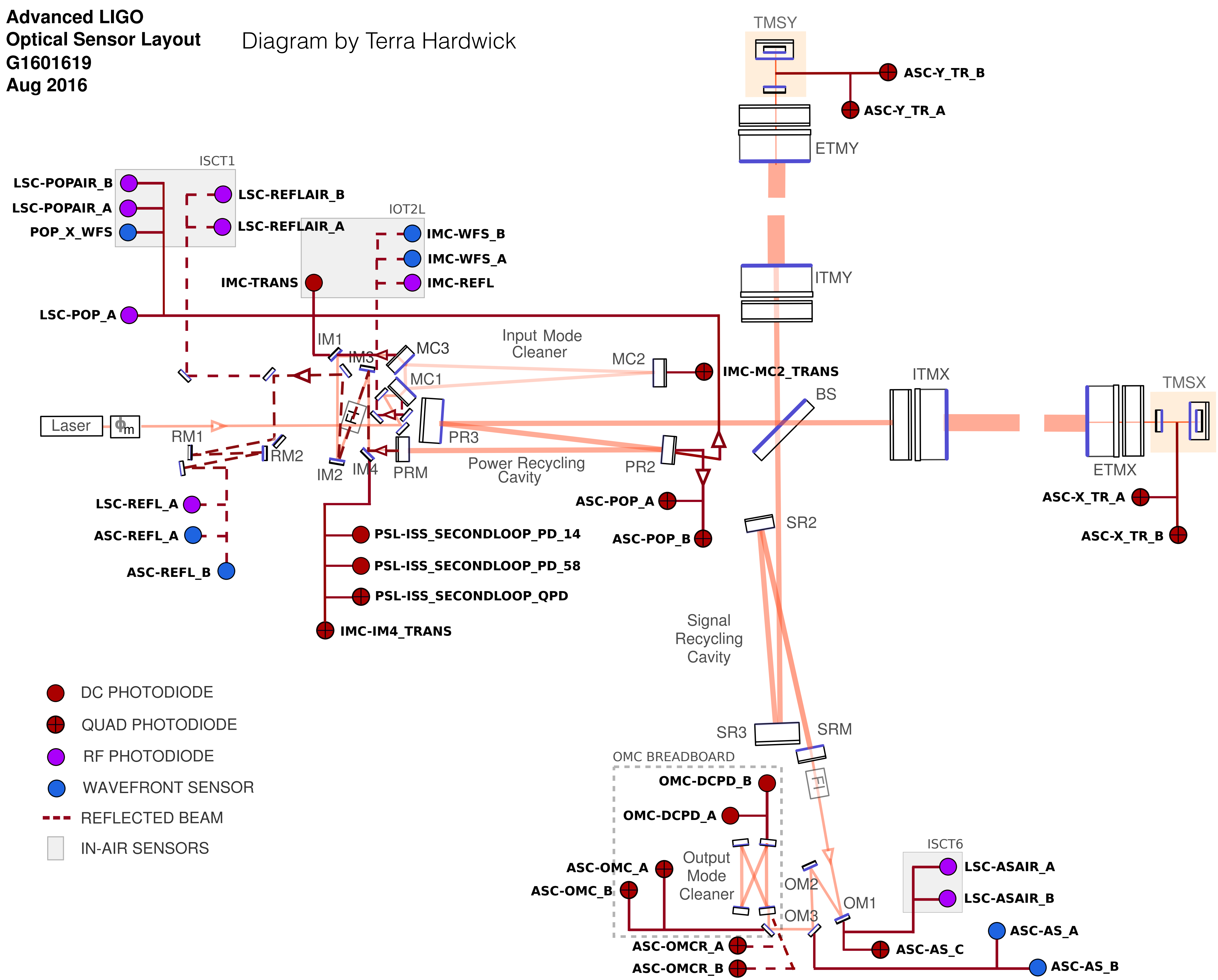
- All mirrors hung in vacuum (about 20)
- Multiple levels of pendula, control on each
- Also active seismic at the top
- Very complicated but works very well; not too much to investigate

Instrumental



- Multiple optical cavities
- Two big: common and differential arm
- Three small: Power and signal recycling cavities, and the small Michelson
- Also lots of steering mirrors, laser stabilization, output mode cleaner

All must be controlled in length and angles


Advanced LIGO
Optical Sensor Layout
G1601619
Aug 2016
Diagram by Terra Hardwick
TMSY
ASC-Y_TR_B
ASC-Y_TR_A
ETMY
ITMY
ISCT1
LSC-POPAIR_B
LSC-POPAIR_A
POP_X_WFS
LSC-REFLAIR_B
LSC-REFLAIR_A
IOT2L
IMC-WFS_B
IMC-WFS_A
IMC-REFL
IMC-TRANS
LSC-POP_A
IM1
IM3
MC3
Input Mode Cleaner
MC2
IMC-MC2_TRANS
MC1
ITMX
TMSX
BS
Laser
RM1
RM2
PR3
IM2
IM4
PRM
Power Recycling Cavity
PR2
ETMX
ASC-X_TR_A
ASC-X_TR_B
ASC-POP_A
ASC-POP_B
SR2
LSC-REFL_A
ASC-REFL_A
ASC-REFL_B
PSL-ISS_SECONDLOOP_PD_14
PSL-ISS_SECONDLOOP_PD_58
PSL-ISS_SECONDLOOP_QPD
IMC-IM4_TRANS
Signal Recycling Cavity
DC PHOTODIODE
QUAD PHOTODIODE
RF PHOTODIODE
WAVEFRONT SENSOR
REFLECTED BEAM
IN-AIR SENSORS
SR3
SRM
OMC BREADBOARD
OMC-DCPD_B
OMC-DCPD_A
FI
ISCT6
LSC-ASAIR_A
LSC-ASAIR_B
ASC-OMC_A
ASC-OMC_B
Output Mode Cleaner
OM2
OM1
OM3
ASC-AS_A
ASC-AS_C
ASC-AS_B
ASC-OMCR_A
ASC-OMCR_B

Instrumental

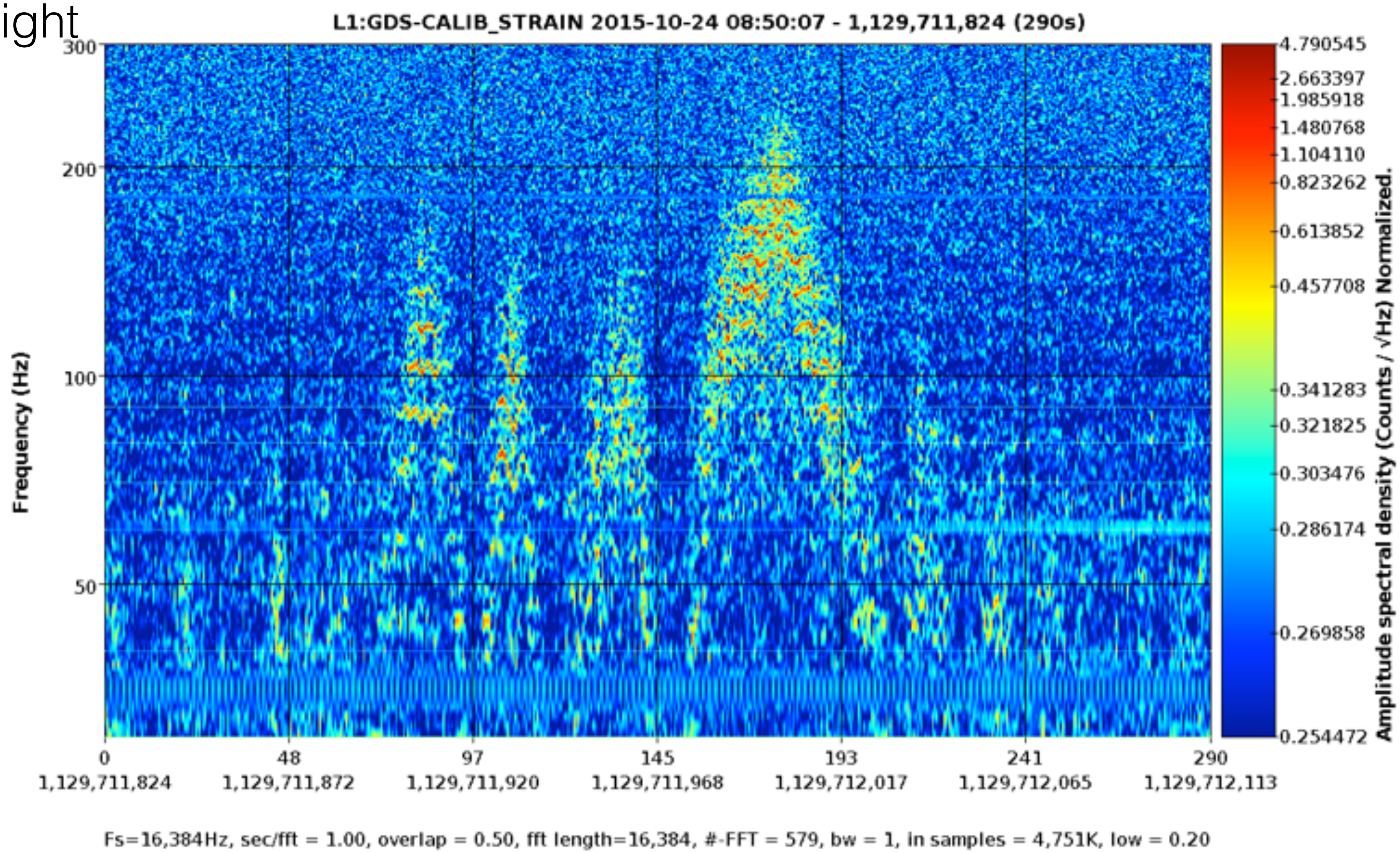
- Photodiodes, quadrant photodiodes, and wavefront sensors
- Look at DC light power and 9,45 MHz RF modulations
- Control loops take these noisy sensors and feed back

Artifacts and Misbehaviors

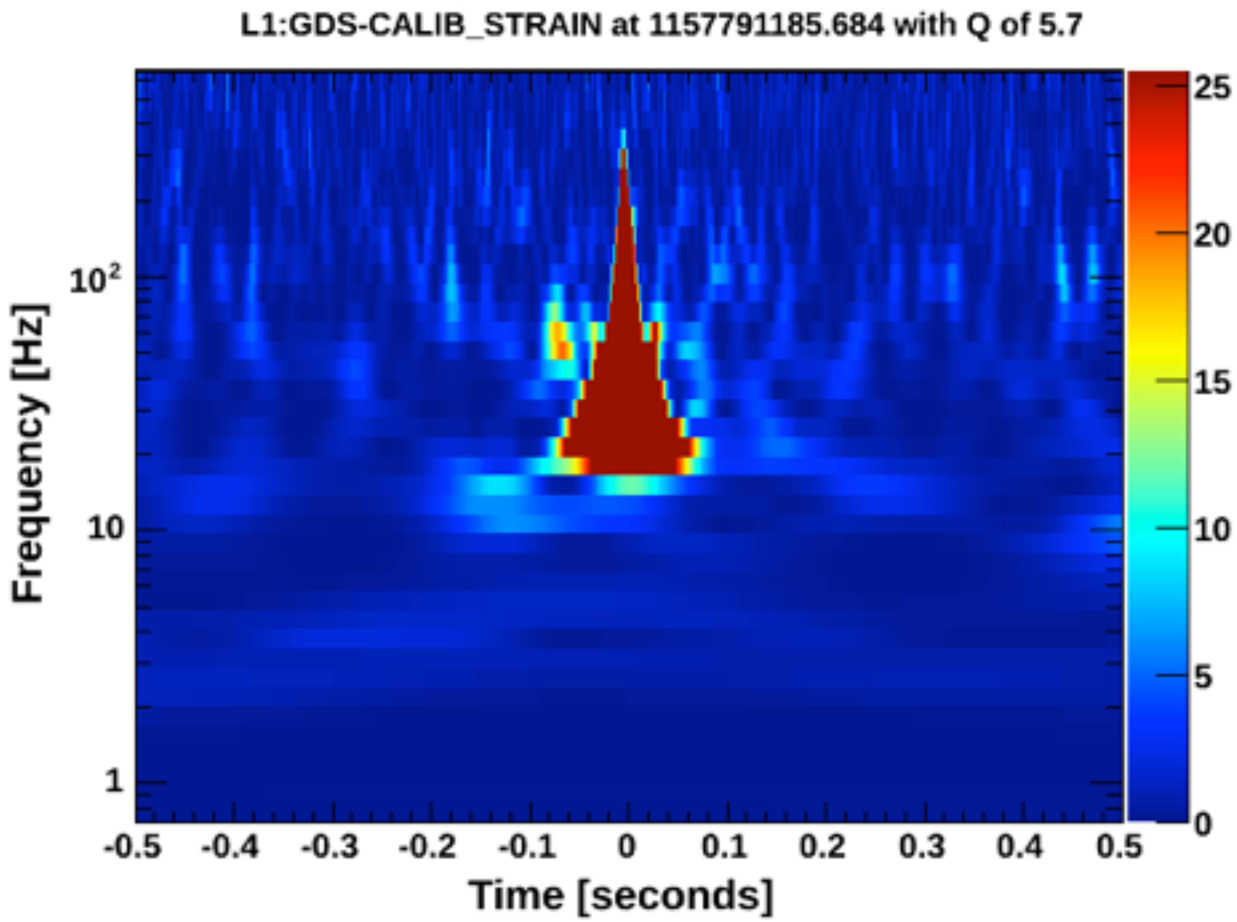
- Strain channel has the following things:
  - Mostly-stationary Gaussian noise (changes over minutes with slow changes in instrument)
  - Lines (some thermal, some 60 Hz power line harmonics, some modes of the various mirrors)
  - Bursts of noise on second and minute timescale
  - Glitches (short transients)

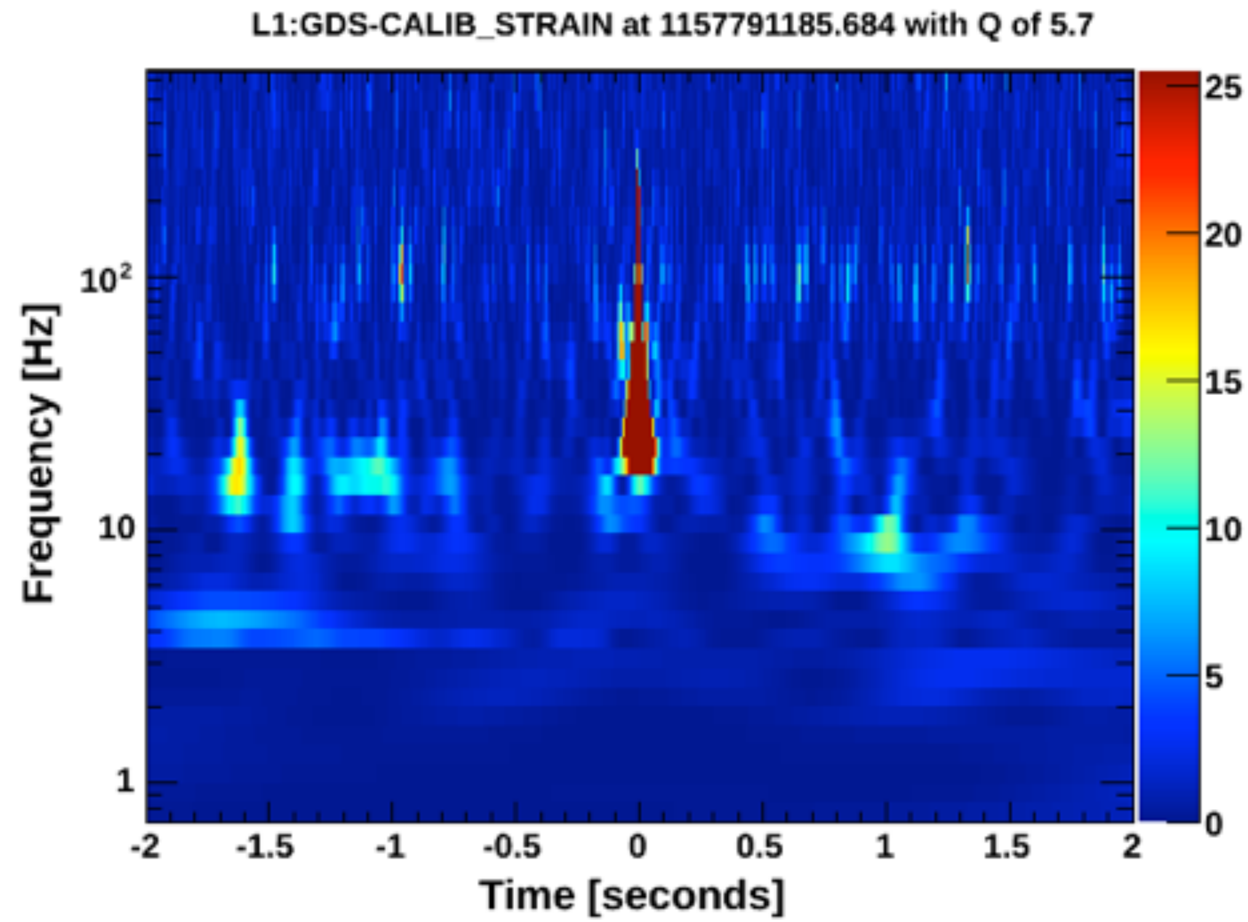
Non-stationary noise

- Many other channels are coupled to DARM when not on their operating point
- Or can be something getting through isolation
- Or scattered light



Glitches





- Short transients (usually few 100 ms)
- Variety of morphologies; can identify many by eye
- Some completely mysterious

Current Strategies

- sine-Gaussian basis to detect glitches
  - Look for aux. channel that reliably glitches at same time
- Look for coherence of DARM with aux channels
  - Or look for noise feature RMS correlated with some slow channel
- Or look directly for physical causes we know
  - E.g. DAC major-carry transitions, RF beatnotes, light scattered by moving mirror, big power draws

Interesting Problems 1

- Treat aux channels as a very high dimension feature space
  - Does some noise feature happen only in some region of the space?
  - Try to tune something that vetoes problems very reliably
- Difficulties:
  - imbalanced classes (more clean times than bad)
  - Mixture of several different causes
  - Time delays, slow drifts in alignment
  - Channels not valid over all range, have noise and lines

Interesting Problems 2

- Avoid overtraining
  - We need to be confident that we understand background; classifier can't just be memorizing what it's seen, or trigger off something accidental
- Change-point detection
  - Detect when something goes wrong with a channel or system, or something gets worse; problem is huge number of channels

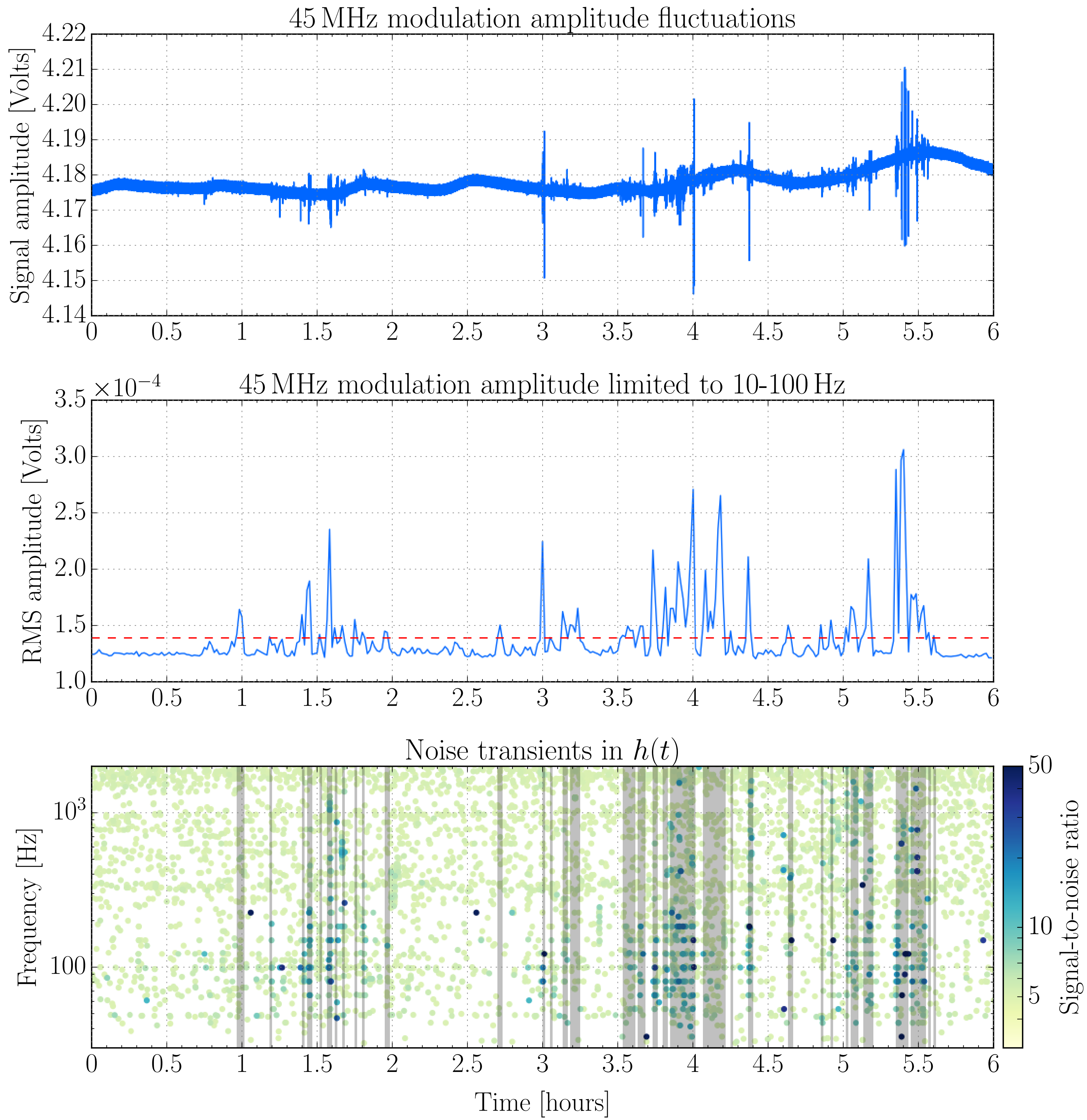
Interesting Problems 3

- Establishing causality
  - When lots of things are going wrong, which are causes and which are effects?
- Non-linearities
  - We do well with direct coherence, but bilinear and more complicated couplings can be very hard to understand

Caveats

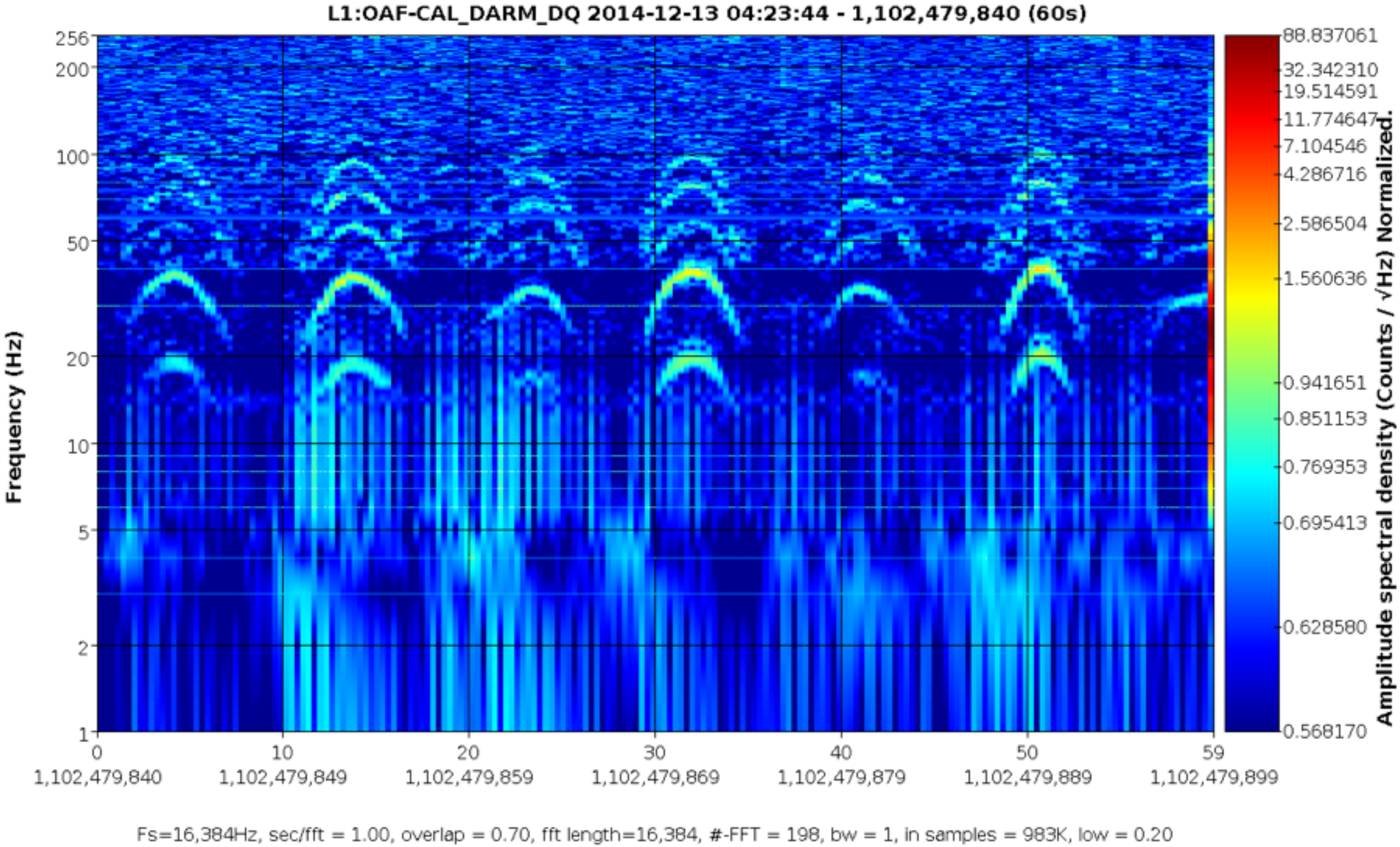
- With so many channels, multiple comparisons is a huge problem
- Some channels sense GW channel directly (called unsafe); must carefully avoid these
- Instrument changes over any time scale you can imagine
- In the end, always want to understand what is going on

Extra



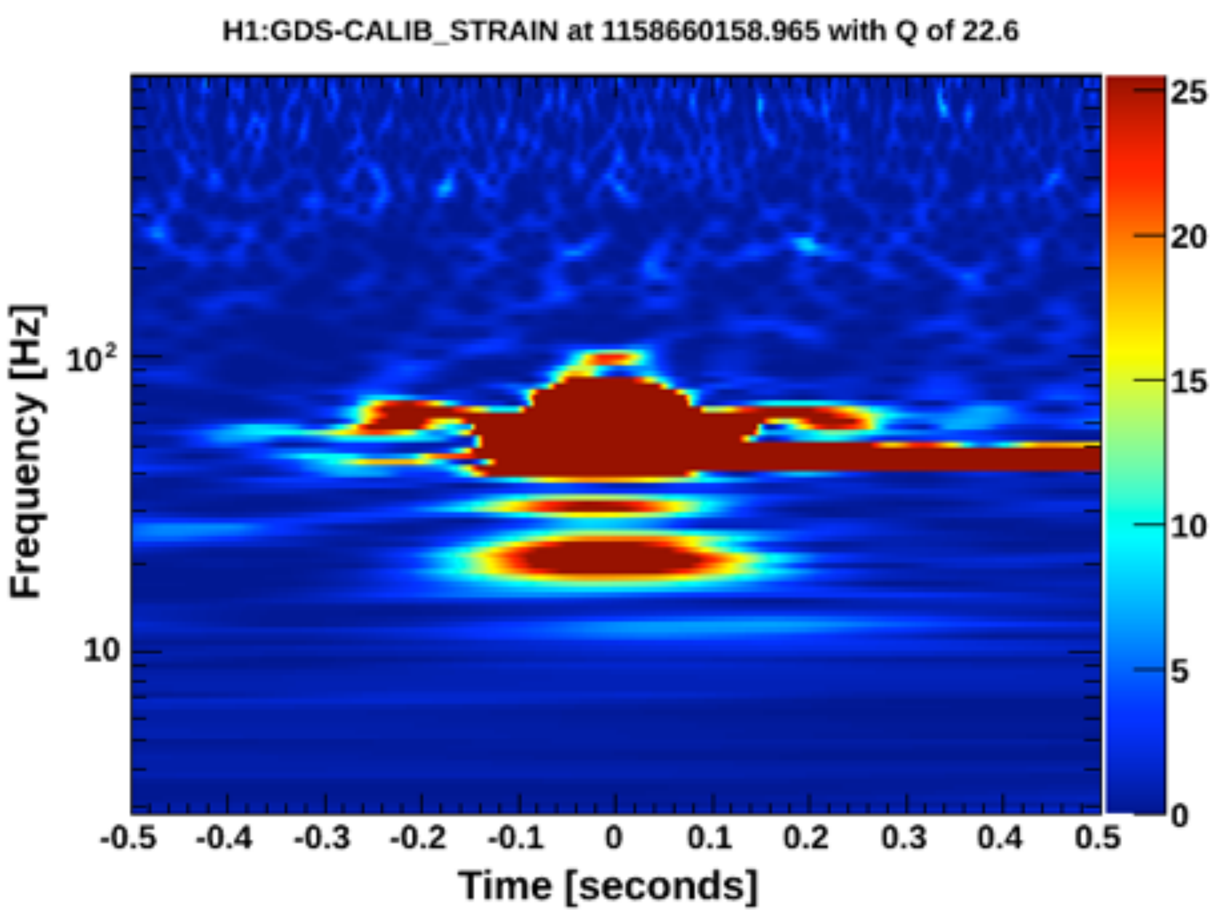
45 MHz modulation amplitude fluctuations
Signal amplitude [Volts]
4.22
4.21
4.20
4.19
4.18
4.17
4.16
4.15
4.14
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
45 MHz modulation amplitude limited to 10-100 Hz
RMS amplitude [Volts]
×10^{-4}
3.5
3.0
2.5
2.0
1.5
1.0
Noise transients in $h(t)$
Frequency [Hz]
10^3
100
Signal-to-noise ratio
50
10
5
Time [hours]

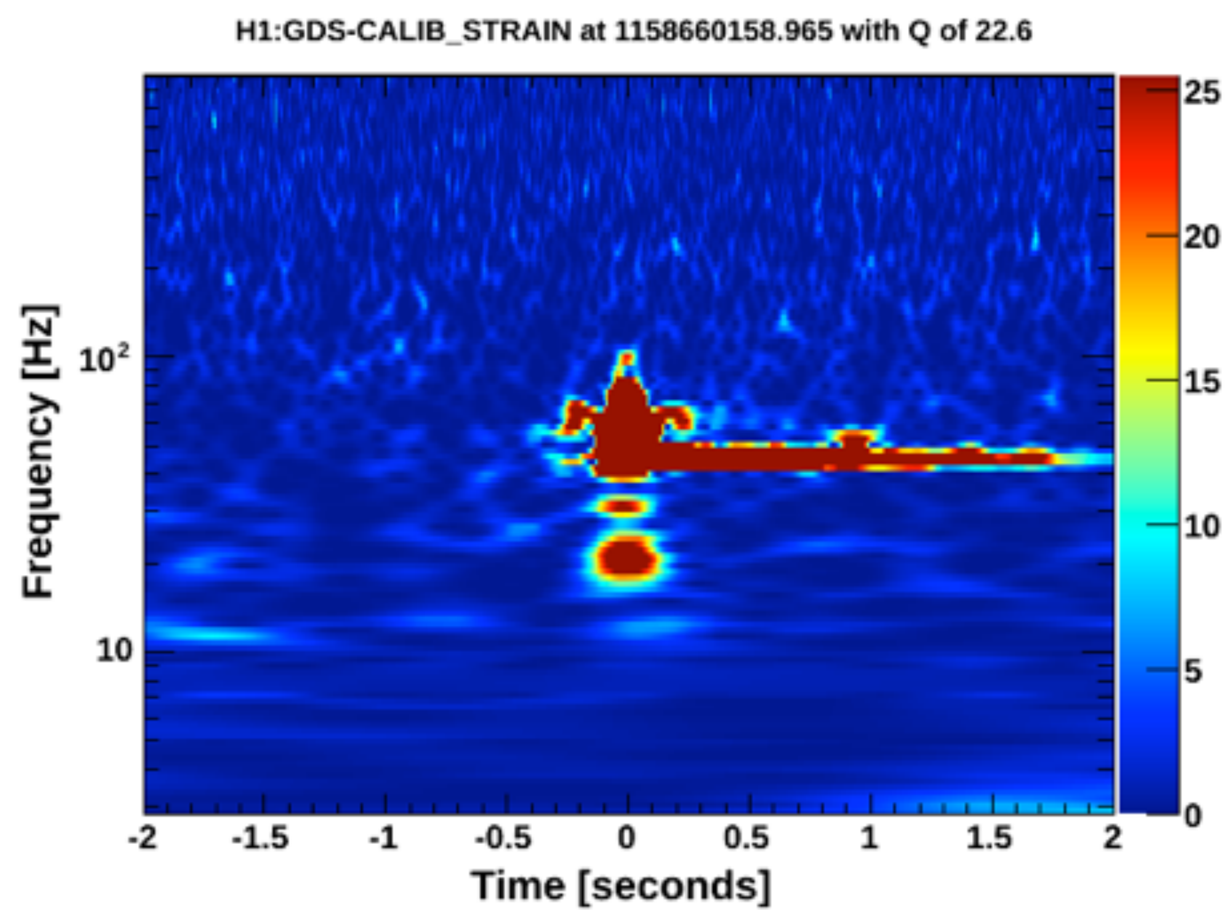
Extra



L1:OAF-CAL_DARM_DQ 2014-12-13 04:23:44 - 1,102,479,840 (60s)
Frequency (Hz)
256
200
100
50
20
10
5
2
1
0
10
20
30
40
50
59
1,102,479,840
1,102,479,849
1,102,479,859
1,102,479,869
1,102,479,879
1,102,479,889
1,102,479,899
88.837061
32.342310
19.514591
11.774647
7.104546
4.286716
2.586504
1.560636
0.941651
0.851153
0.769353
0.695413
0.628580
0.568170
Amplitude spectral density (Counts / √Hz) Normalized.
Fs=16,384Hz, sec/fft = 1.00, overlap = 0.70, fft length=16,384, #-FFT = 198, bw = 1, in samples = 983K, low = 0.20

Extra


H1:GDS-CALIB_STRAIN at 1158660158.965 with Q of 22.6
Frequency [Hz]
10^2
10
-0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5
Time [seconds]
25
20
15
10
5
0


H1:GDS-CALIB_STRAIN at 1158660158.965 with Q of 22.6
Frequency [Hz]
10^2
10
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
Time [seconds]
25
20
15
10
5
0