Status of the Advanced LIGO Project

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LIGO-G1501274

Gravitational Waves

Predicted by Einstein in 1916 as a consequence of the General Theory of Relativity

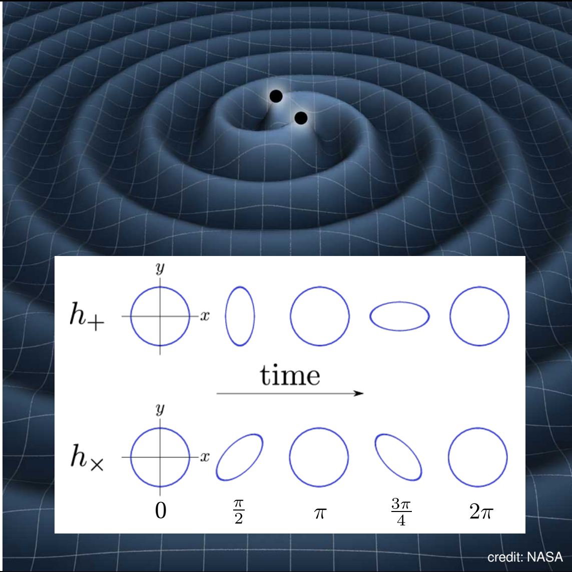
Generated from changing quadrupolar mass moments

Produce transverse strain: $h = \frac{\Delta L}{L}$

Two polarizations: h_+ and $h_\times$

Travel at the speed of light

Weakly interacting with matter

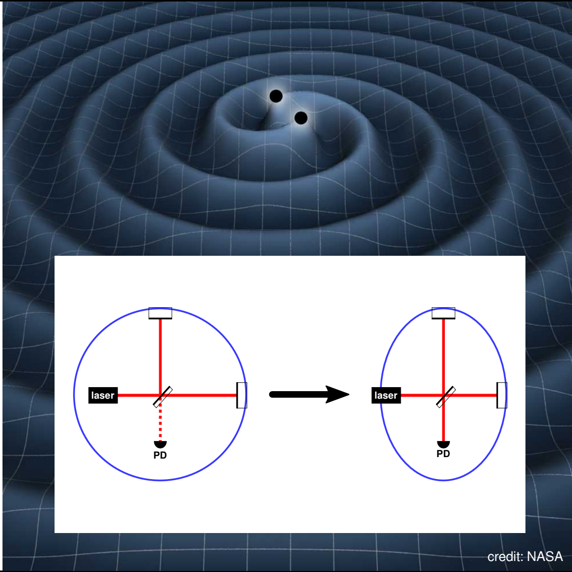


Gravitational Waves

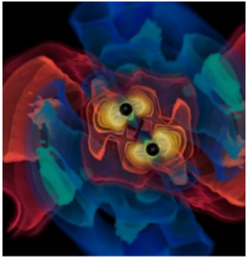
Prevailing concept for direct measurment of gravitational waves:

> look for deviations in light travel time due to passing gravitational waves

Interferometric detectors (e.g. LIGO) use light interference to measure differential length changes $\rightarrow$



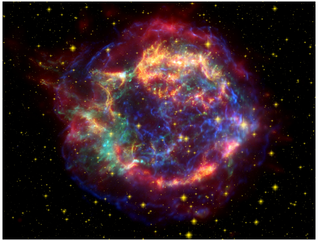
Potential Sources for Ground-based Detectors



credit: AEI/CCT/LSU

compact binary coalescense

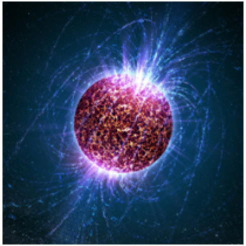
Neutron stars and stellar-mass black holes in binary systems are well-modeled and should be strong, plentiful, emitters of "chirp" signals.



credit: NASA/JPL-Caltech/Univ. of Minn.

core-collapse supernovae

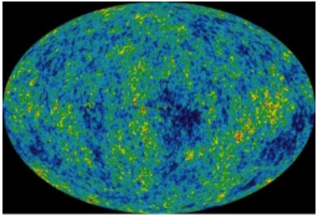
Weak and not well modeled, core-collapse supernovae could provide short bursts that could be detectable from nearby galaxies.



credit: Casey Reed, Penn State

spinning neutron stars

Neutron stars with "bumps" and/or strong magnetic fields could produce long-lasting, single-frequency waves.

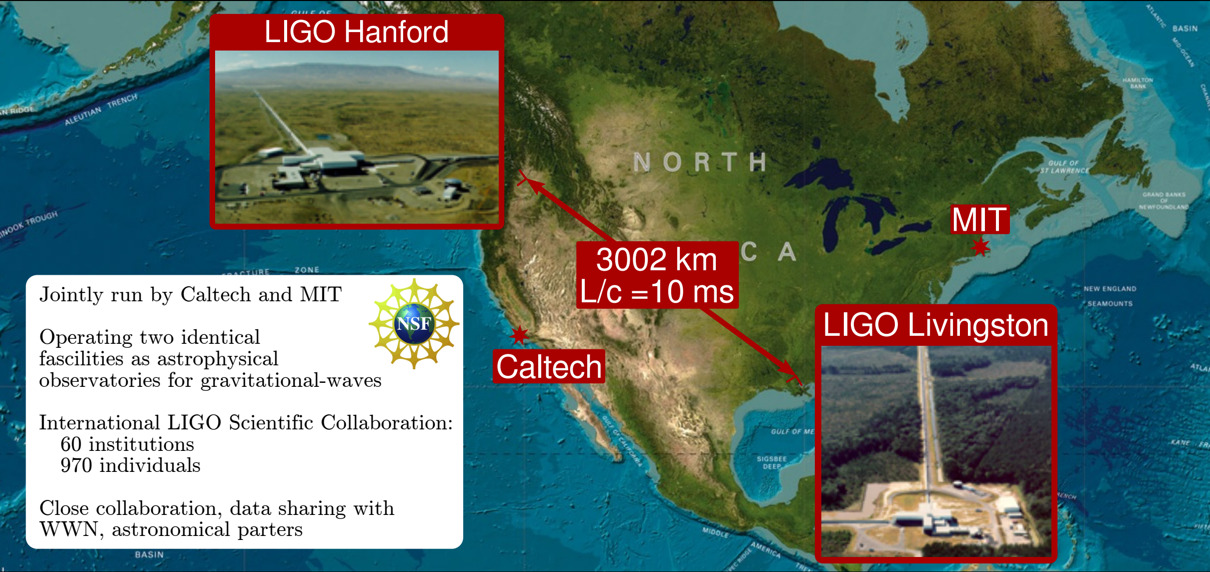


credit: NASA/WMAP

cosmic gravitational-wave background

Inflation after the Big Bang could have produced a stochastic gravitational-wave background.

The LIGO Laboratory



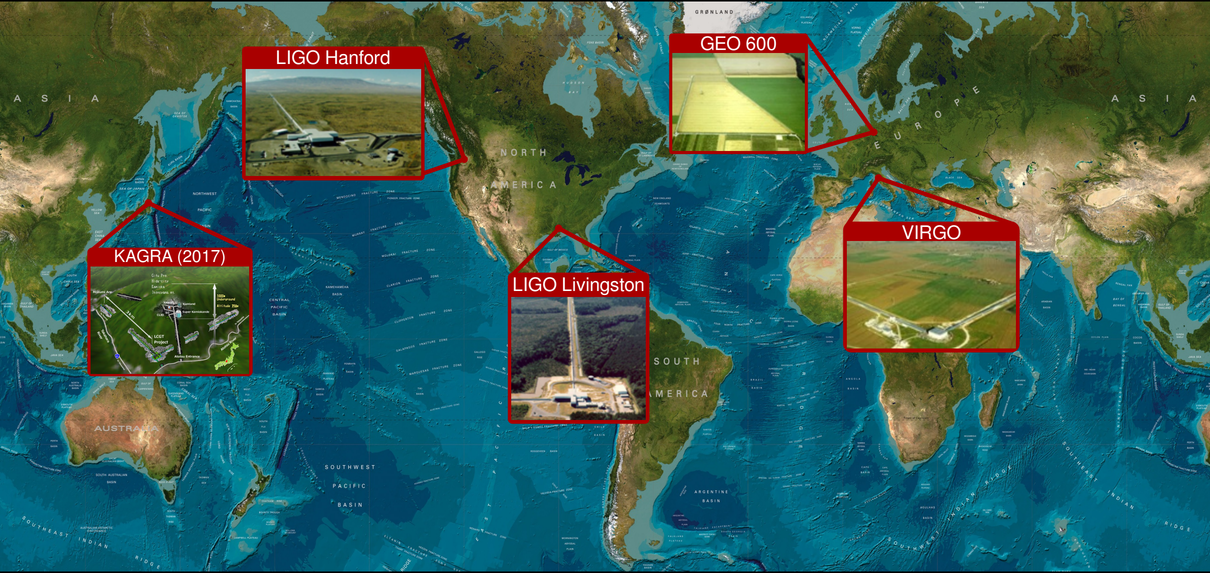
Jointly run by Caltech and MIT

Operating two identical fascilities as astrophysical observatories for gravitational-waves

International LIGO Scientific Collaboration:
- 60 institutions
- 970 individuals

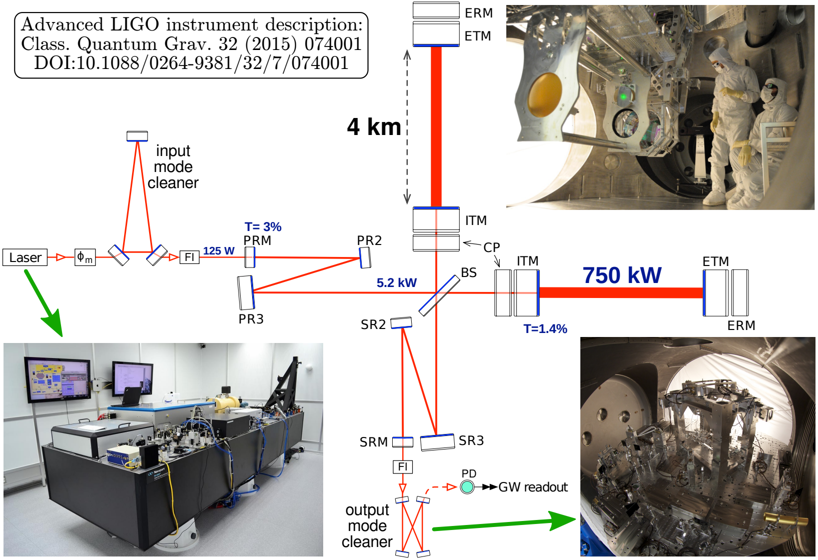
Close collaboration, data sharing with WWN, astronomical parters

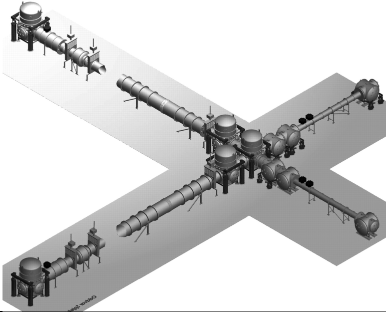
World Wide Network of LIGO-like Detectors



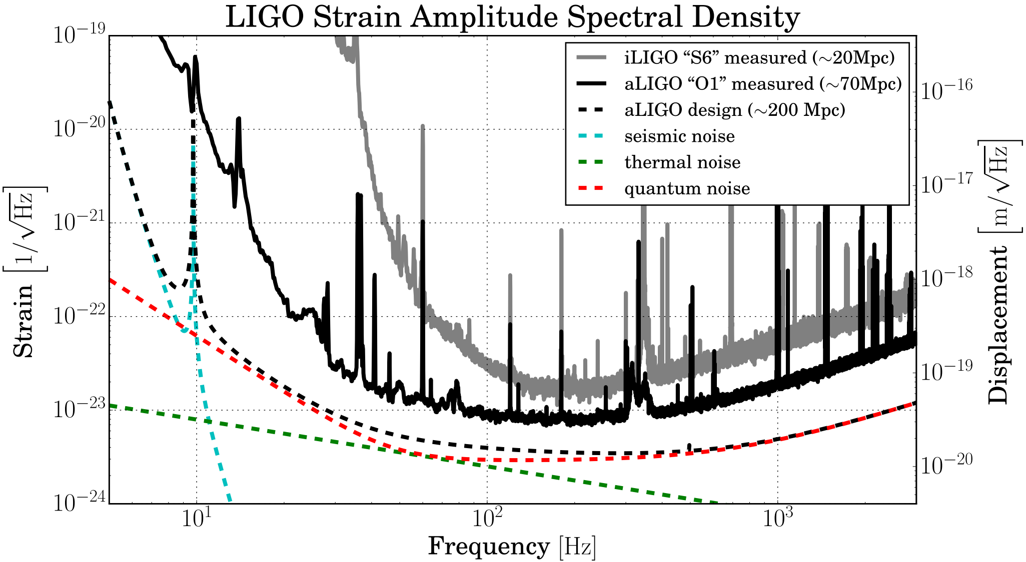
The Advanced LIGO Detectors

Advanced LIGO instrument description:
Class. Quantum Grav. 32 (2015) 074001
DOI:10.1088/0264-9381/32/7/074001

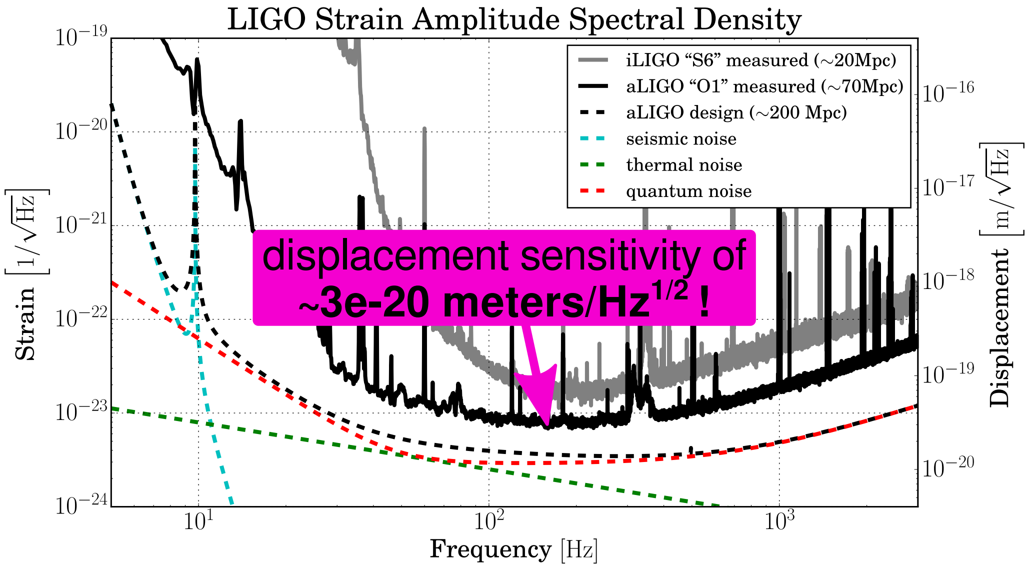




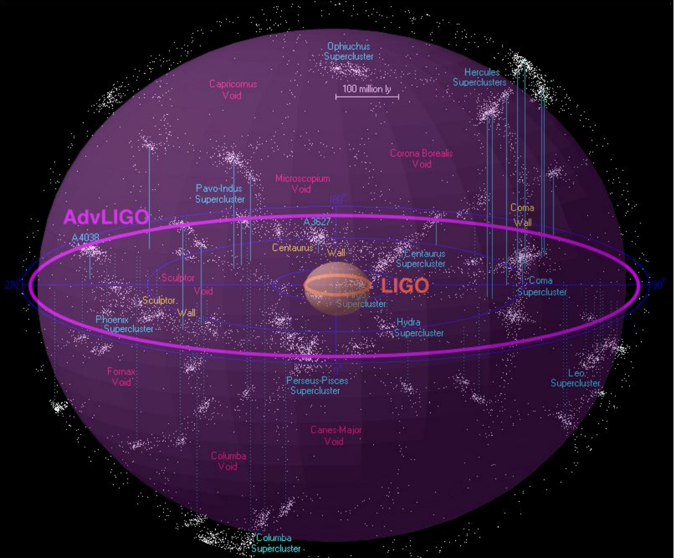
Detector Strain Sensitivity



Detector Strain Sensitivity



Potential Detection Rates



credit: Beverly Berger, Richard Powell

At full/design sensitivity, Advanced LIGO expects to see a neutron star binary merger rate of...

40 events per year!

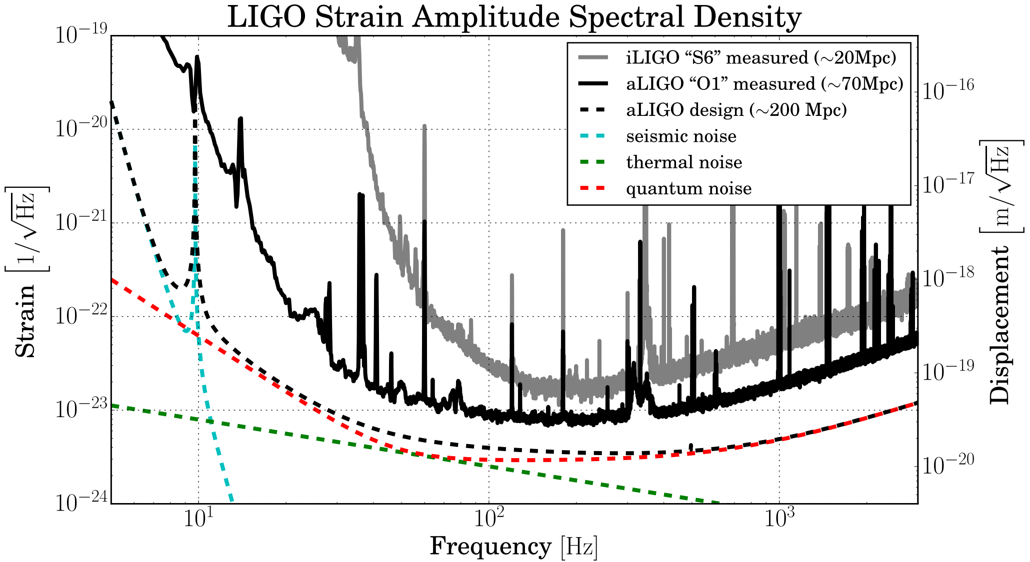
Not to mention other similar sources at similarly appreciable rates:

Table 5. Detection rates for compact binary coalescence sources.

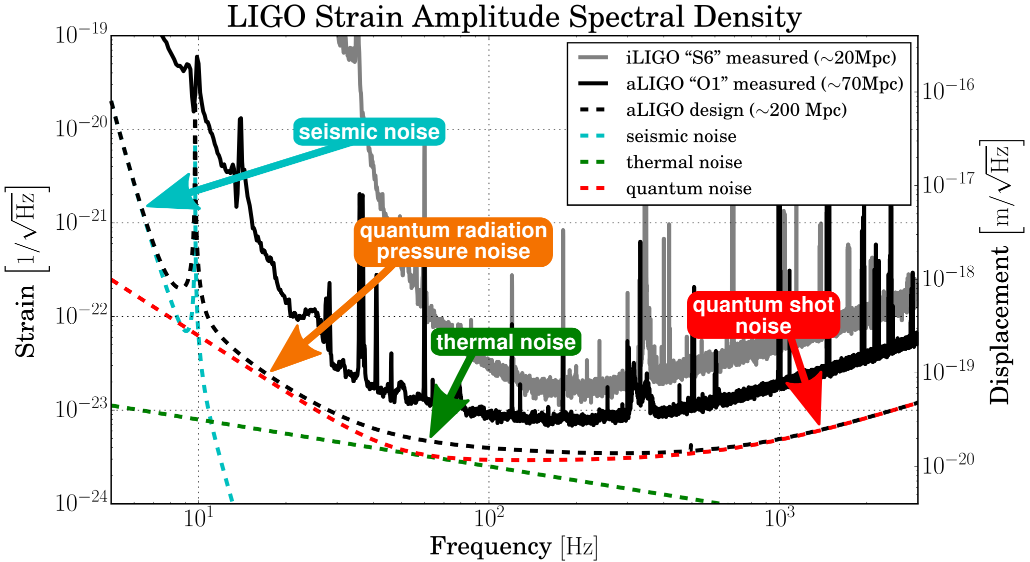
IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}
Initial	NS–NS	2×10^{-4}	0.02	0.2
	NS–BH	7×10^{-5}	0.004	0.1
	BH–BH	2×10^{-4}	0.007	0.5
	IMRI into IMBH			<0.001[b]
	IMBH-IMBH			10^{-4}[d]
Advanced	NS–NS	0.4	40	400
	NS–BH	0.2	10	300
	BH–BH	0.4	20	1000
	IMRI into IMBH			10[b]
	IMBH-IMBH			0.1[d]

Class. Quant. Grav, 27 (2010) 173001

Fundamental Noise Limits



Fundamental Noise Limits



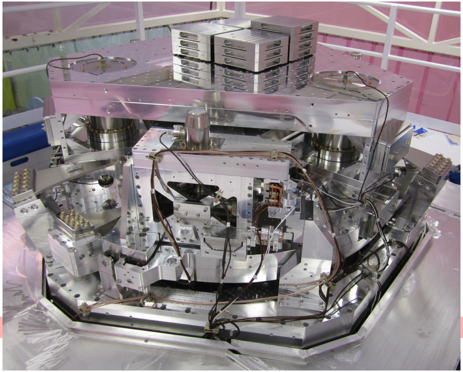
Seismic Isolation

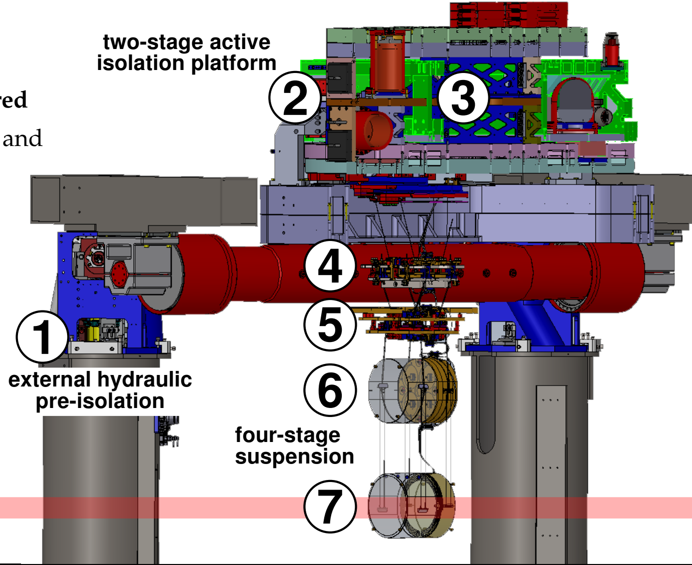
seismic noise

Ground motion at 10 Hz: 1x10^{-9} m/Hz$^{1/2}$

>10 orders of magnitude supression required

Test masses suspended from 7 stages of active and passive seismic isolation.





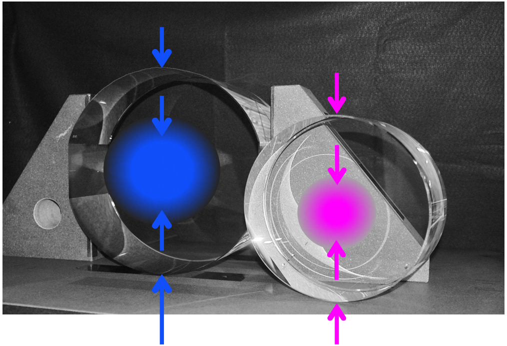
Optics and Suspension Systems

quantum radiation pressure noise

Increase optic mass to reduce effects of quantum radiation pressure.

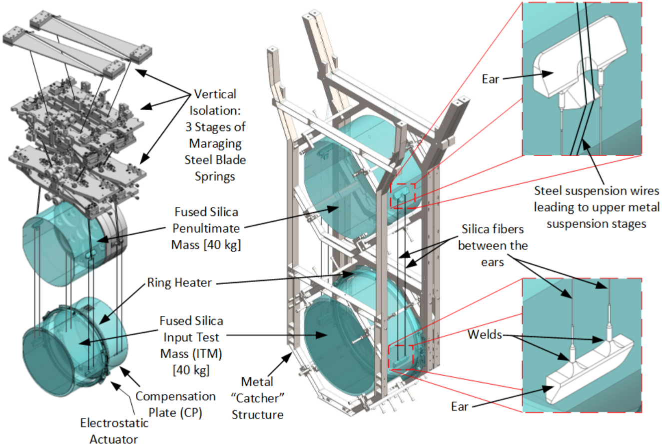
thermal noise

Increase optic/beam spot diameter to increase area over which thermal noise is integrated.

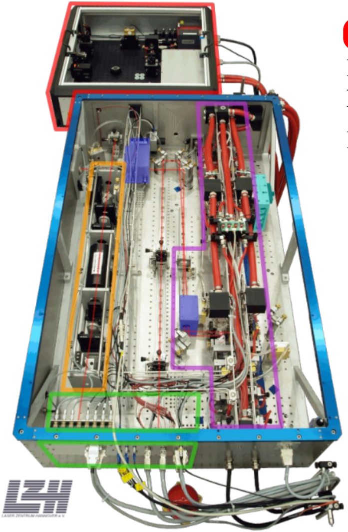


aLIGO mirrors:
34 cm diameter
40 kg mass
12 cm beam

iLIGO mirrors:
25 cm diameter
10 kg mass
8 cm beam



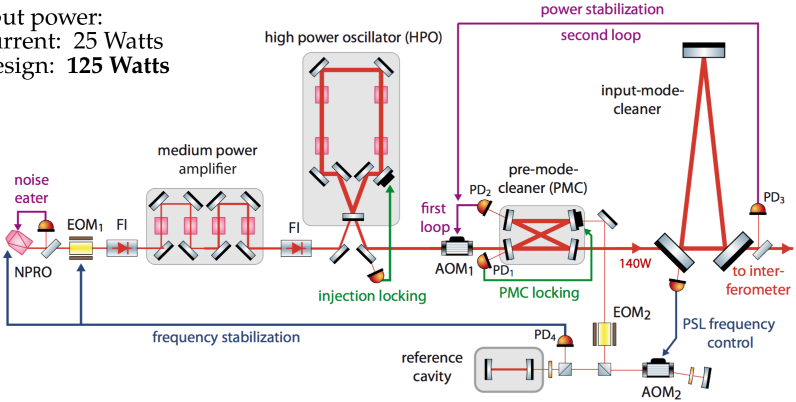
Pre-stabilized Laser

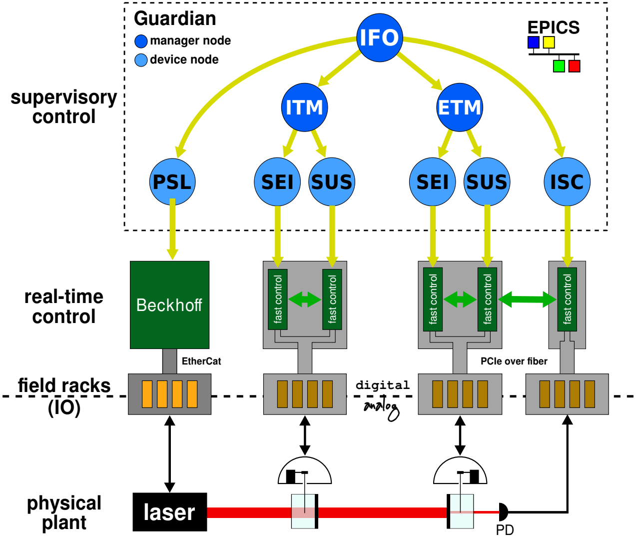


quantum shot noise

Increase laser power to reduce quantum shot noise from photon counting statistics.

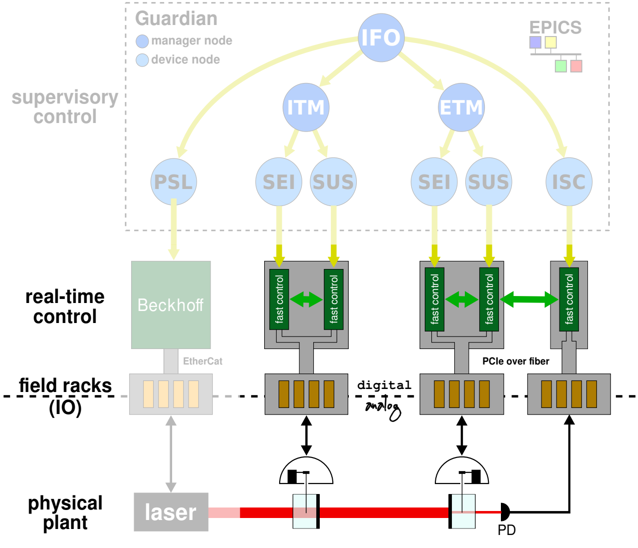
Input power:
current: 25 Watts
design: **125 Watts**





Advanced LIGO employs a hierarchical control structure for the full interferometer

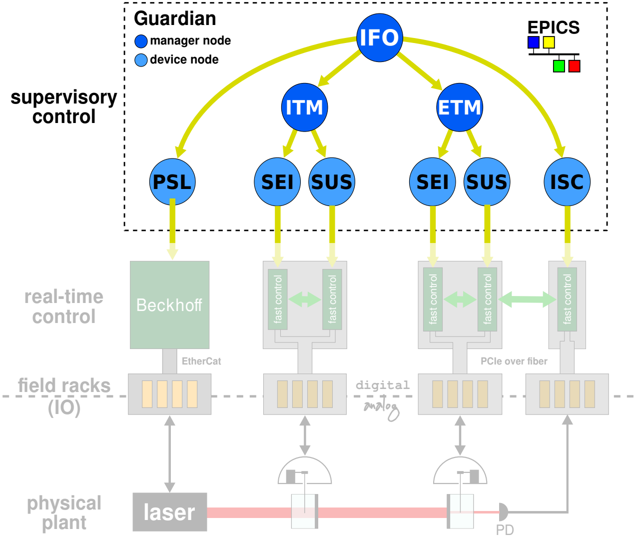
Interferometer Controls Overview



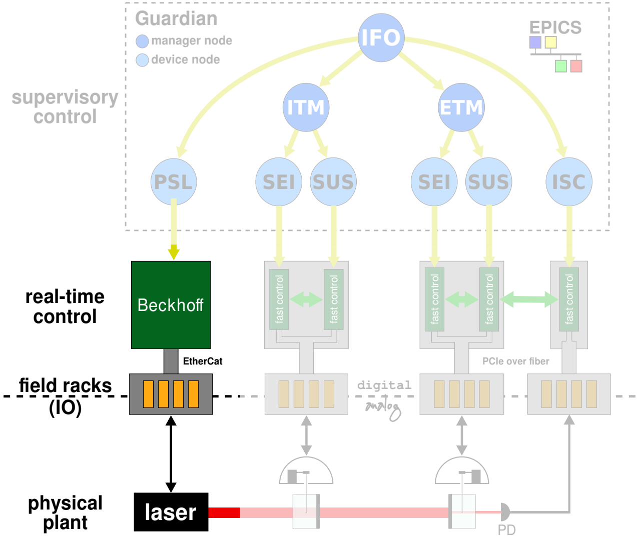
Fast feedback loops control all degrees of freedom (DOF) of the interferometer at the *microscopic* level via a custom built, modular, distributed, real-time digital control system (**RTS**).

Readbacks and settings of the RTS are exposed through EPICS for supervisory control and operator interfaces.

Interferometer Controls Overview



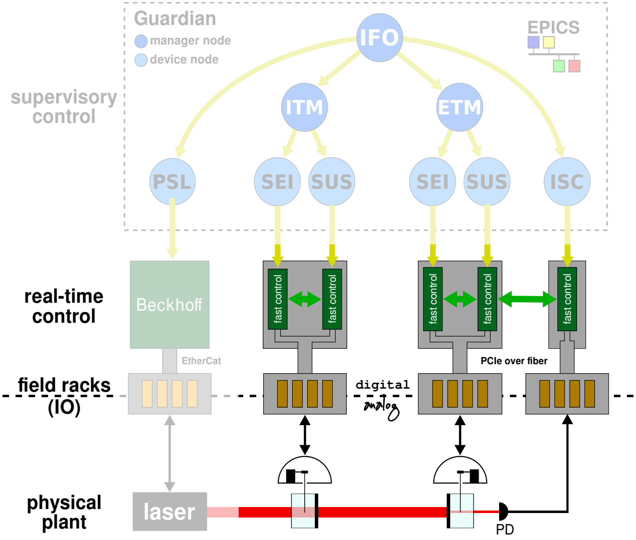
Supervisory control, i.e. automation, handled by a new hierarchical, modular, distributed, state machine platform called **Guardian**.



Additionally, a couple of auxiliary slow control systems are used:

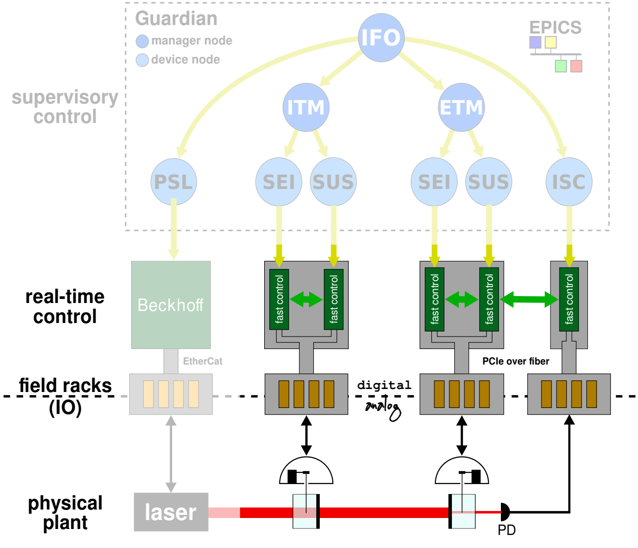
- Beckhoff TwinCAT (EtherCAT) with custom TwinCAT EPICS IOC bridge
- Acromag (Modbus)

Fast Feedback Control



Fast feedback control is the heart of aLIGO controls

Fast Feedback Control



Hundreds of feedback loops in the interferometer:

suspensions

active damping of 3 – 24 DOF per suspension ($\times$18)

seismic isolation

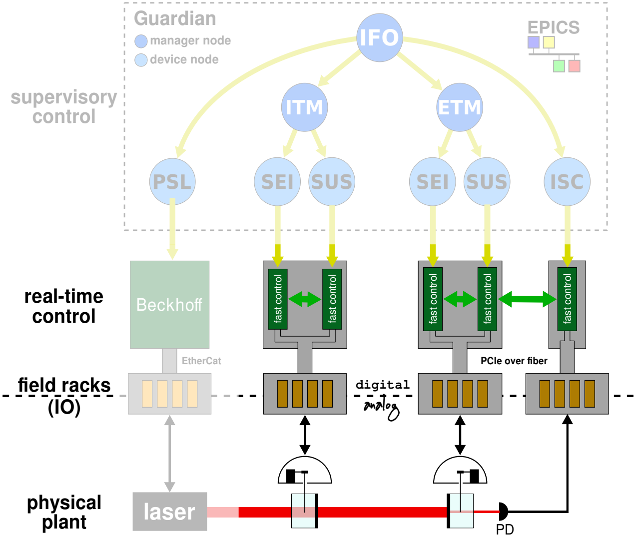
active damping and isolation of 18 DOF per seismic platform ($\times$9)

length control

5 global length DOF, 10 global angular DOF

many other auxiliary DOF...

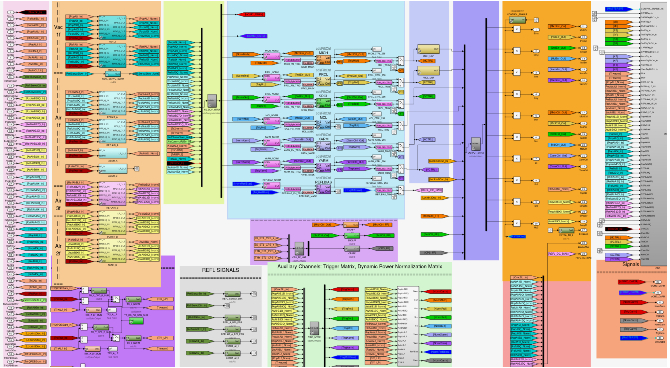
Fast Feedback Control



Overall sampling rate of 64 kHz.

Control loops run from 2k $\rightarrow$ 32k Hz

Real-time Computer Architecture



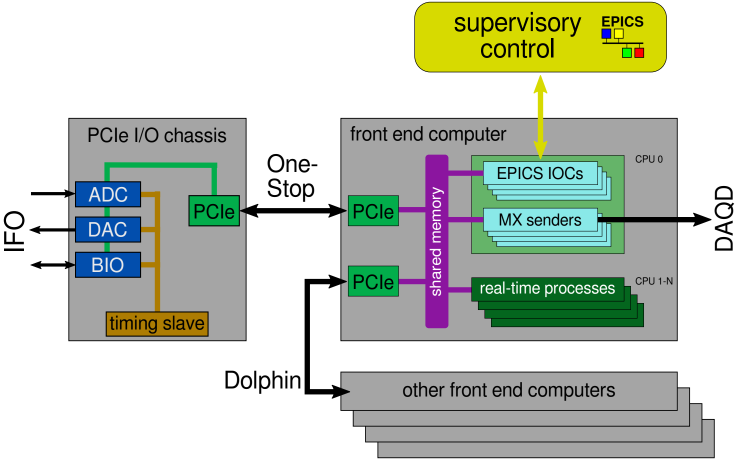
Simulink code for interferometer length DOF control

Controler signal flow and logic is drawn in MATLAB Simulink.

Real-time code generator (RCG) parses Simulink files to produce real-time code.

NOTE: This is a *custom* Simulink parser/code generator, not MATLAB.

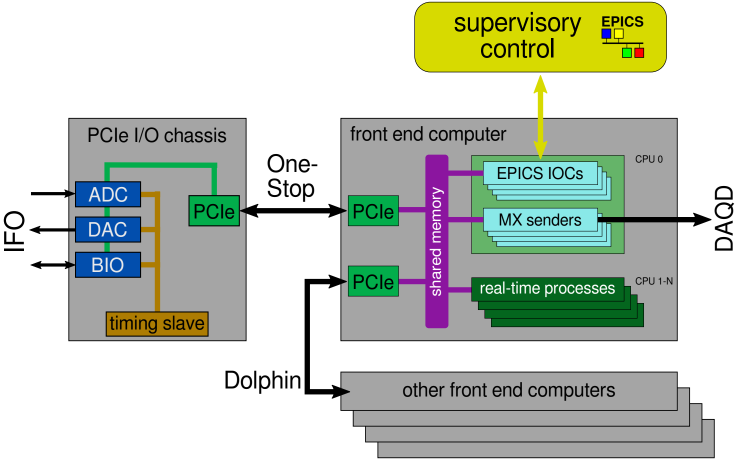
Real-time Computer Architecture



Real-time code is compiled into Linux kernel modules.

Linux kernel with custom patch loads modules and gives them each full control of a single CPU core.

CPU-0 is reserved for Linux user-space processes.



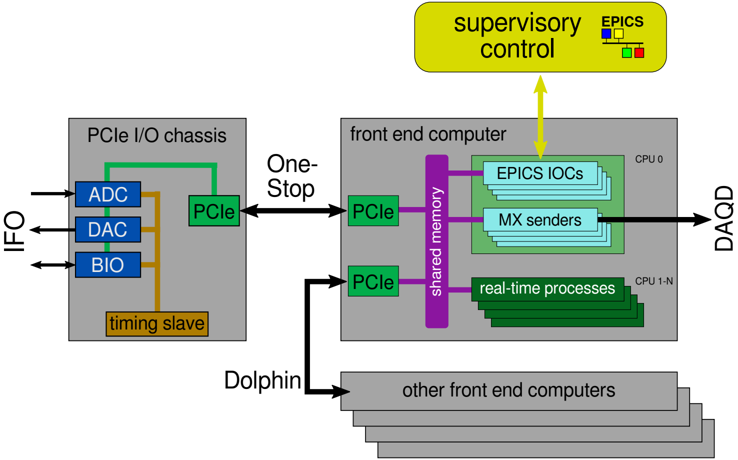
System is highly modular

Multiple real-time modules can be run on a single host.

Real-time modules on a single host can communicate via shared memory.

Modules on different hosts communicate via Dolphin PCIe shared memory network.

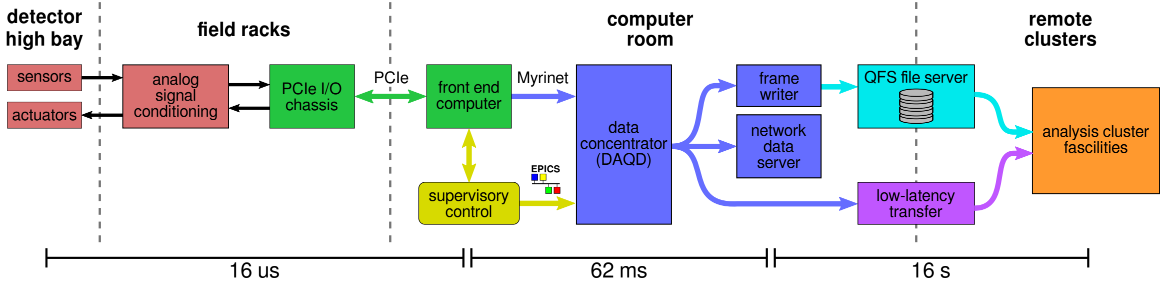
Real-time Computer Architecture



Linux user-space process interfaces to the real-time modules:

- EPICS IOC processes provide supervisory control interfaces
- `mx-stream` processes send fast and slow data over a dedicated network to the data acquisition host

Data Acquisition Pipeline



Front end ADCs and DACs operate at 64 kHz.

16-bit ADCs
18-bit DACs

DAQD recieves data from all front end controllers and assembles into 1/16-second frames.

~200k slow channels (16 Hz)
~7k fast channels (>512 Hz)

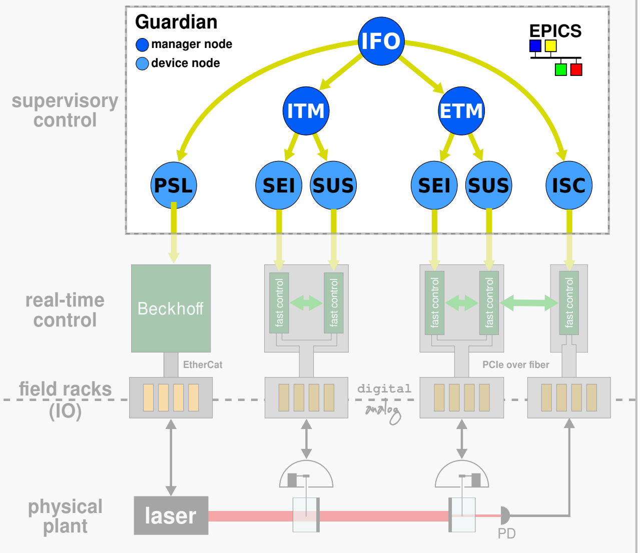
Overall 10 MB/s data rate (compressed)

Low latency (reduced channel count) frames arrive at analysis clusters in ~16 seconds.

Full frames replicated analysis cluster:

- on-site: ~5 minutes
- remote: ~30 minutes

Guardian Supervisory Control



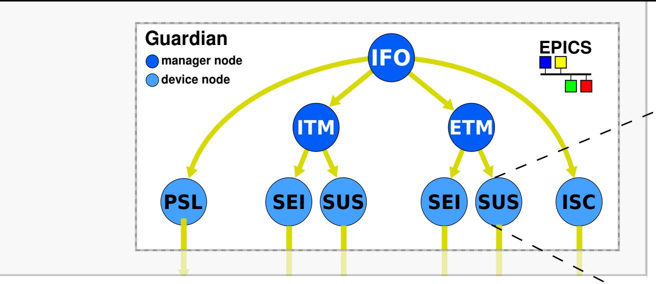
Guardian is aLIGO's new automation platform:

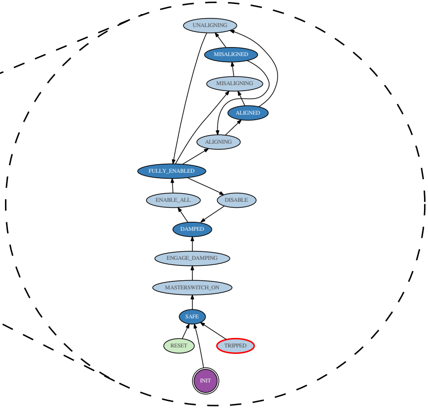
Guardian is a distributed hierarchy of automaton state machines

Individual nodes oversee specific sub-domains of the instrument.

A hierarchy of nodes control the full interferometer.

Guardian Supervisory Control





Highly modular

EPICS client-server

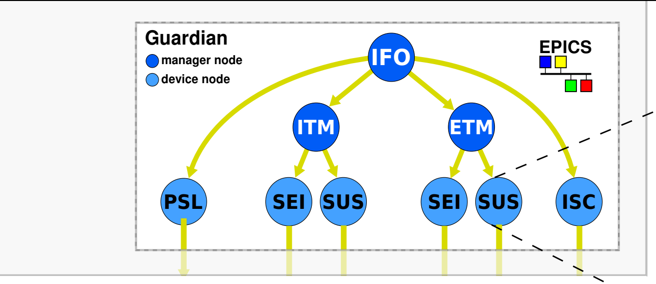
Soft real-time @ 16 Hz

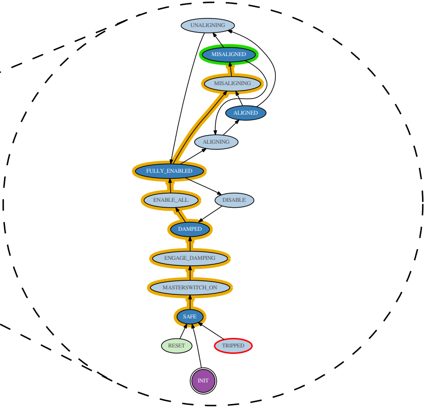
Python based

Designed for ease of commissioning:
usercode can be reloaded on the fly

Each system is represented by a **state graph**.

Guardian Supervisory Control

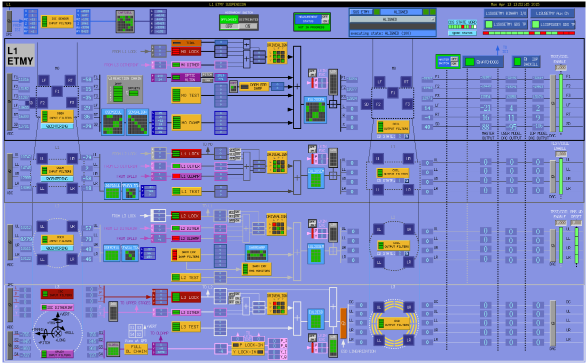




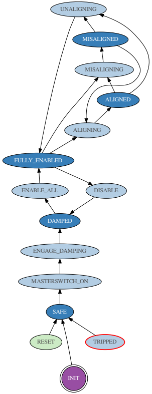
Actions take the form of state **requests**.

Guardian then follows **the shortest path** in graph from the current state to the request.

Guardian Supervisory Control

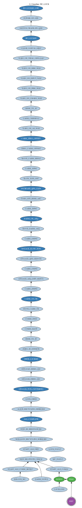


MEDM operator screen for 4-stage suspension



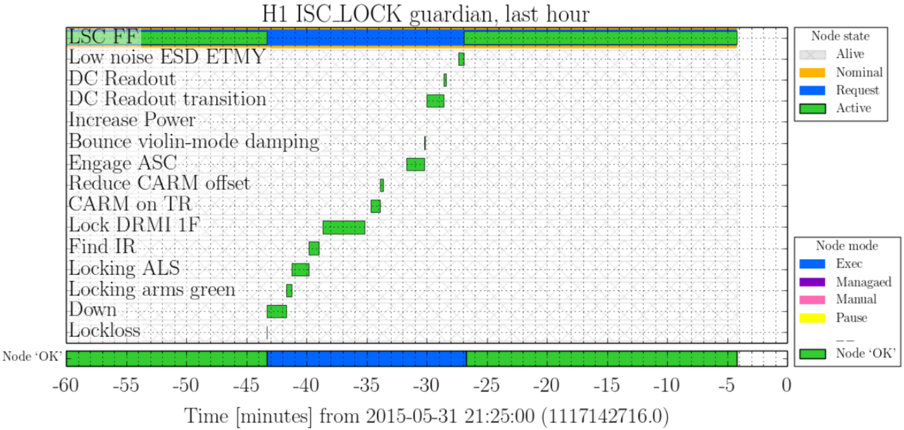
Guardian abstracts away the details and complexity of the control and reduces it to a finite set of desired system states.

Guardian Lock Acquisition



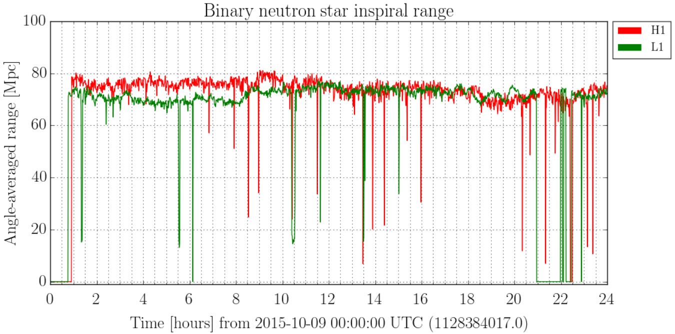
L1 ISC_LOCK

Guardian manages the complex **lock acquisition** procedure that closes and tunes all feedback loops and brings the instrument to its highest sensitivity level.



aLIGO started first Observing run on September 18, 2015.

The LIGO detectors are now the most sensitive gravitational-wave detectors ever made, by more than a factor of three.



A week of aLIGO is worth more than a *year* of iLIGO (in terms of time-volume product).

At full design sensitivity, aLIGO will probe 1000× more volume than iLIGO.

Many more detector improvements and observing runs to come...

Thank you