15th Dec, 2025
IUCAA Pune

GW Detector Subsystems I & II

Anamaria Effler
Nikhil Mukund

Topics

Anamaria:

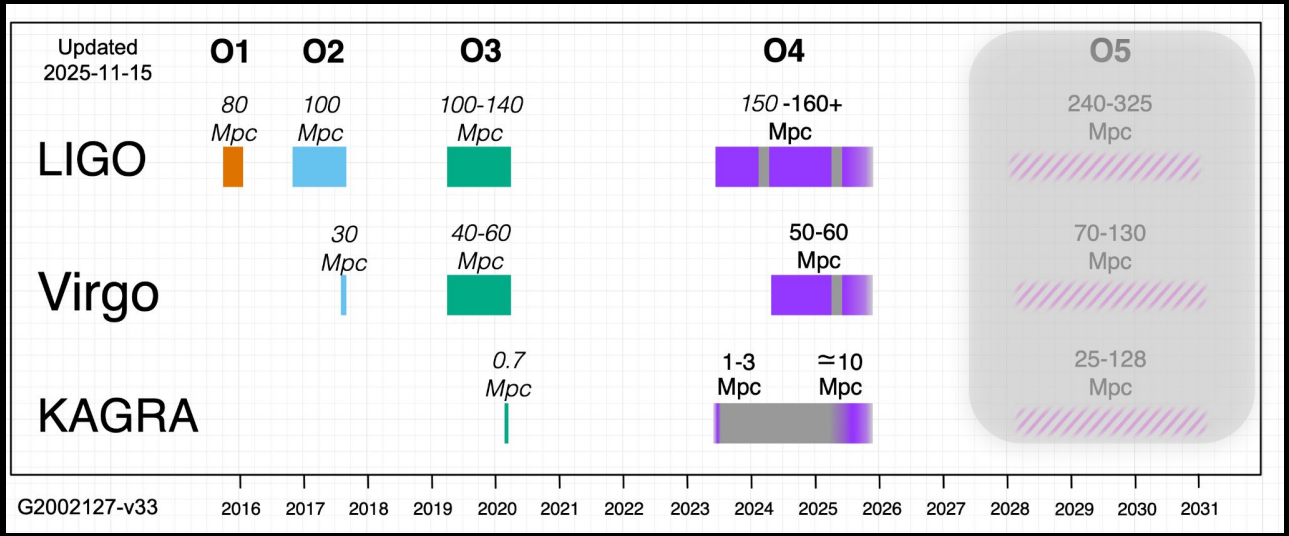
- Some LIGO history
- Michelson ifos
- LSC
- ISI and SUS
- PEM
- Noise budgeting

Nikhil:

- PSL
- IOO
- CDS
- ASC
- Control loops

Brief LIGO history

- First concept: R. Drever, K. Thorne, R. Weiss 1980's
- Funded by NSF 1992
- Construction finished circa 2000
- Initial LIGO era: 2002-2009
- Advanced LIGO: finished installation 2014
- First detection: Sep 14 2015



https://observing.docs.ligo.org/plan/

M. Fyffe

How does a Michelson interferometer detect gravitational waves

LIGO

Simple Michelson

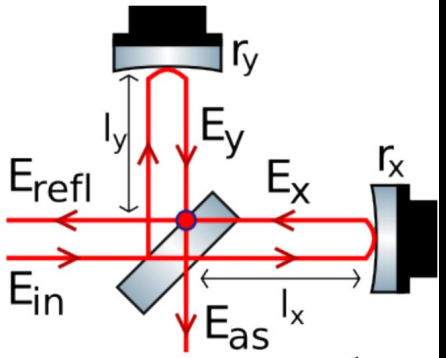
$$E_x = -\frac{1}{\sqrt{2}} r_x E_{in} e^{2ikl_x},\ E_y = \frac{1}{\sqrt{2}} r_y E_{in} e^{2ikl_y}$$

$$E_{as} = \frac{1}{\sqrt{2}}(E_x + E_y) = \frac{1}{2} E_{in}(r_y e^{2ikl_y} - r_x e^{2ikl_x})$$

$$P_{as} = \mid E_{as} \mid^2 = \frac{1}{4} P_{in}[(r_x - r_y)^2 + 4 r_x r_y \sin(k(l_x - l_y))]$$

dark fringe (min): $P_{as} = \frac{1}{4} P_{in}(r_x - r_y)^2$

bright fringe (max) : $P_{as} = \frac{1}{4} P_{in}(r_x + r_y)^2$



$r_{BS} = t_{BS} = \frac{1}{\sqrt{2}}$

–redefine with $\Delta l = l_x - l_y$ and $l = \frac{l_x + l_y}{2}$

$$E_{as} = -\frac{1}{2} E_{in} e^{i2kl}(r_x e^{ik\Delta L} - r_y e^{-ik\Delta L})$$

$$E_{as} = -\frac{1}{2} E_{in} e^{i2kl}((r_x - r_y)\cos(k\Delta L) + i(r_x + r_y)\sin(k\Delta L))$$

$$E_{as} \approx -E_{in} i e^{i2kl} \sin(k\Delta L)$$

–the effect of a GW is only on $\Delta L \to \Delta L + 2hl$

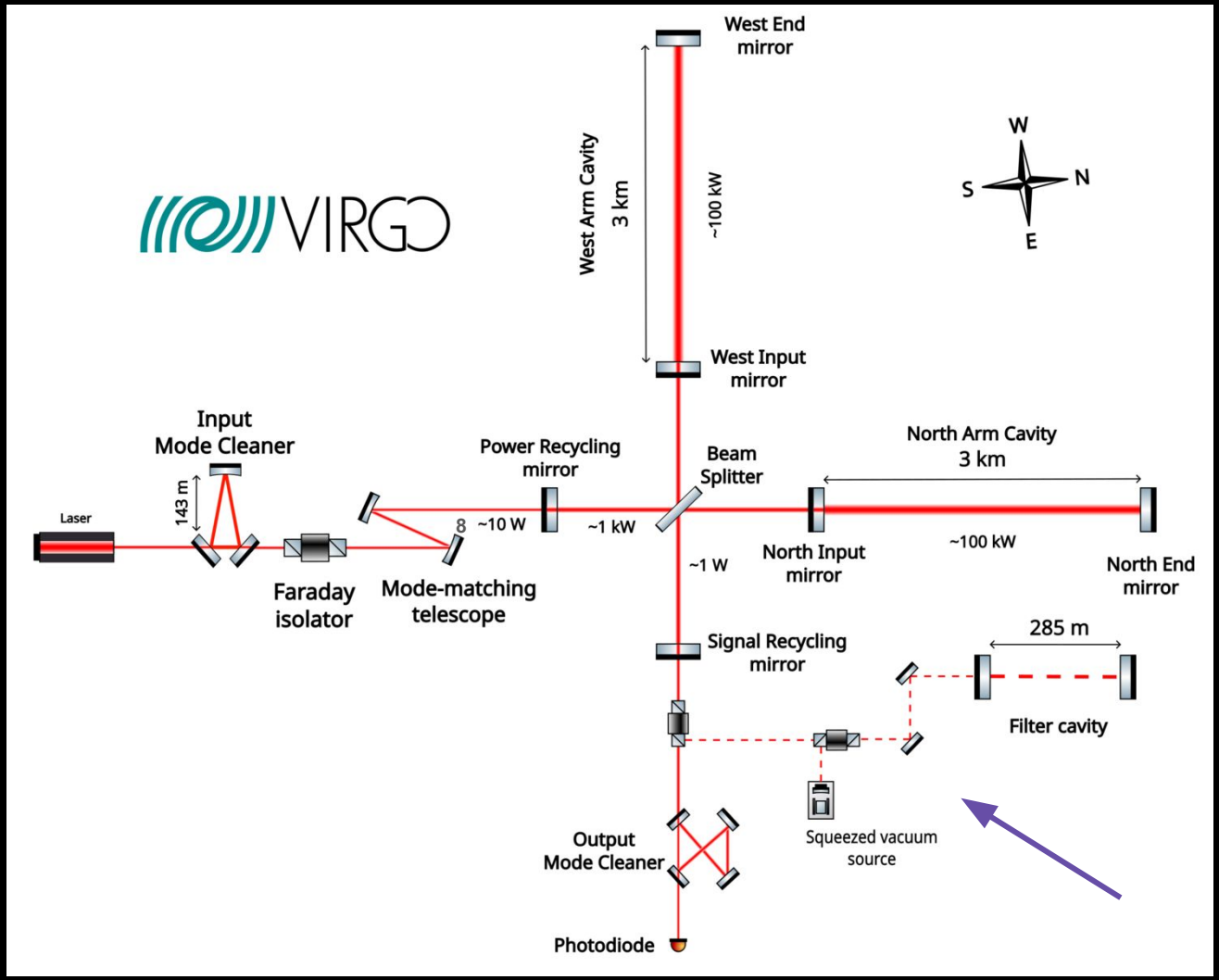
$$P_{as} = \mid E_{as} \mid^2 \sim \sin^2(k\Delta L + 2khl) \sim \sin^2(k\Delta L) + \sin(2k\Delta L) 2khl$$

if ΔL is 0, we see no signal to first order ?! $\Longrightarrow$ we need Schnupp assymetry, a macroscopic length difference between arms

G1400346

More realistic layout

Virgo has a similar layout, biggest difference is a few lengths and non-folded recycling cavities



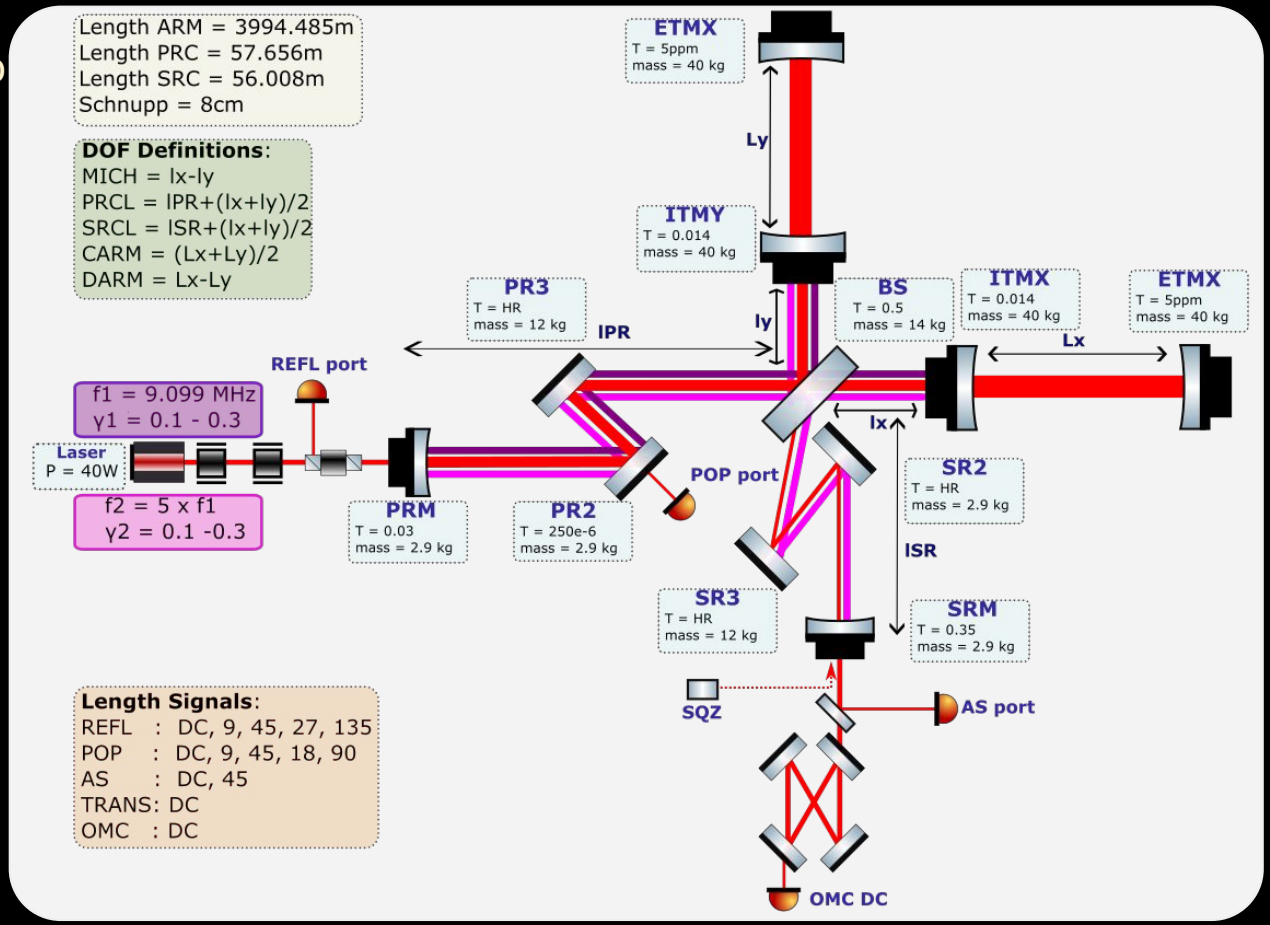
How do we control all these Degrees of Freedom (DoF's)

LIGO has 5 main lengths to control (angular DoF's covered later)

Use RF modulations to extract various signals at a few pick-off ports (~PDH)

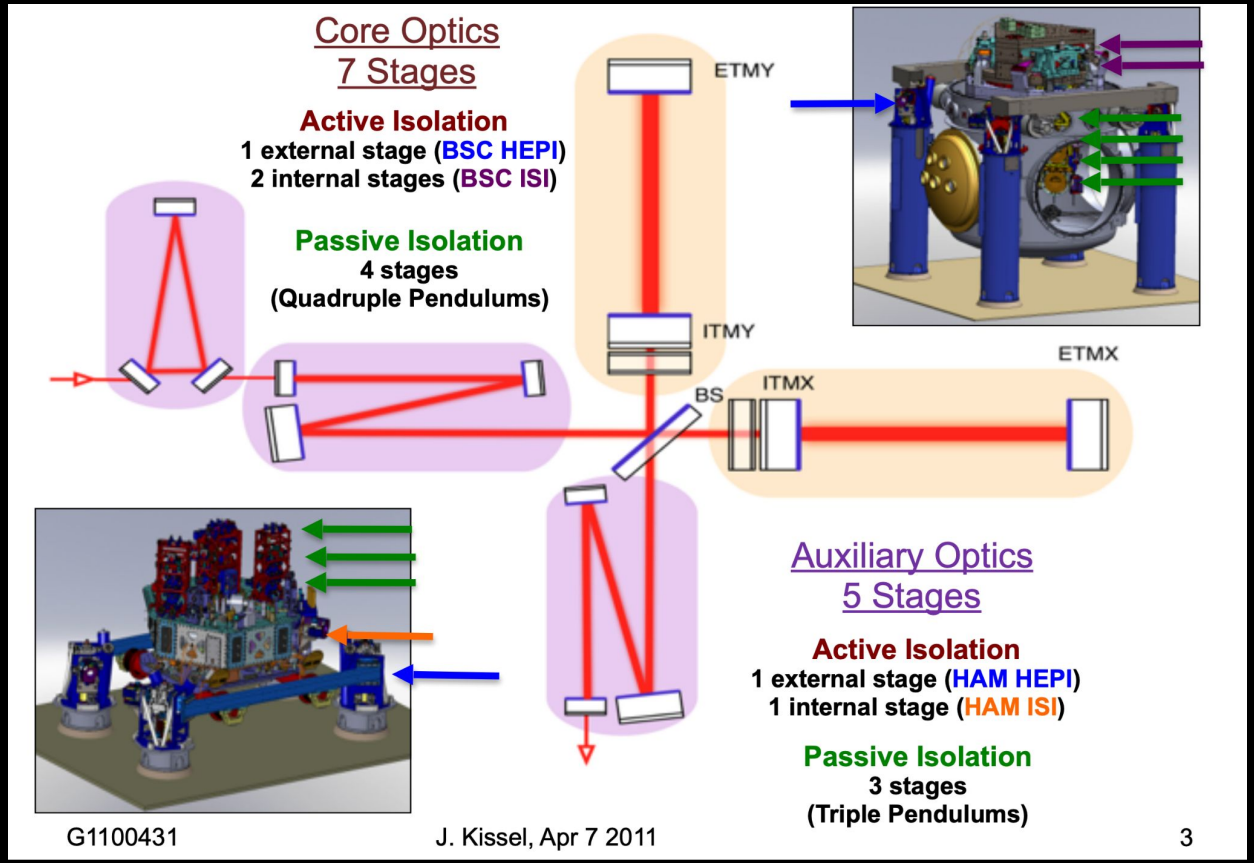
Measure the sensing strength at each port and choose strongest or some diagonalization

Some natural diagonalization common versus differential

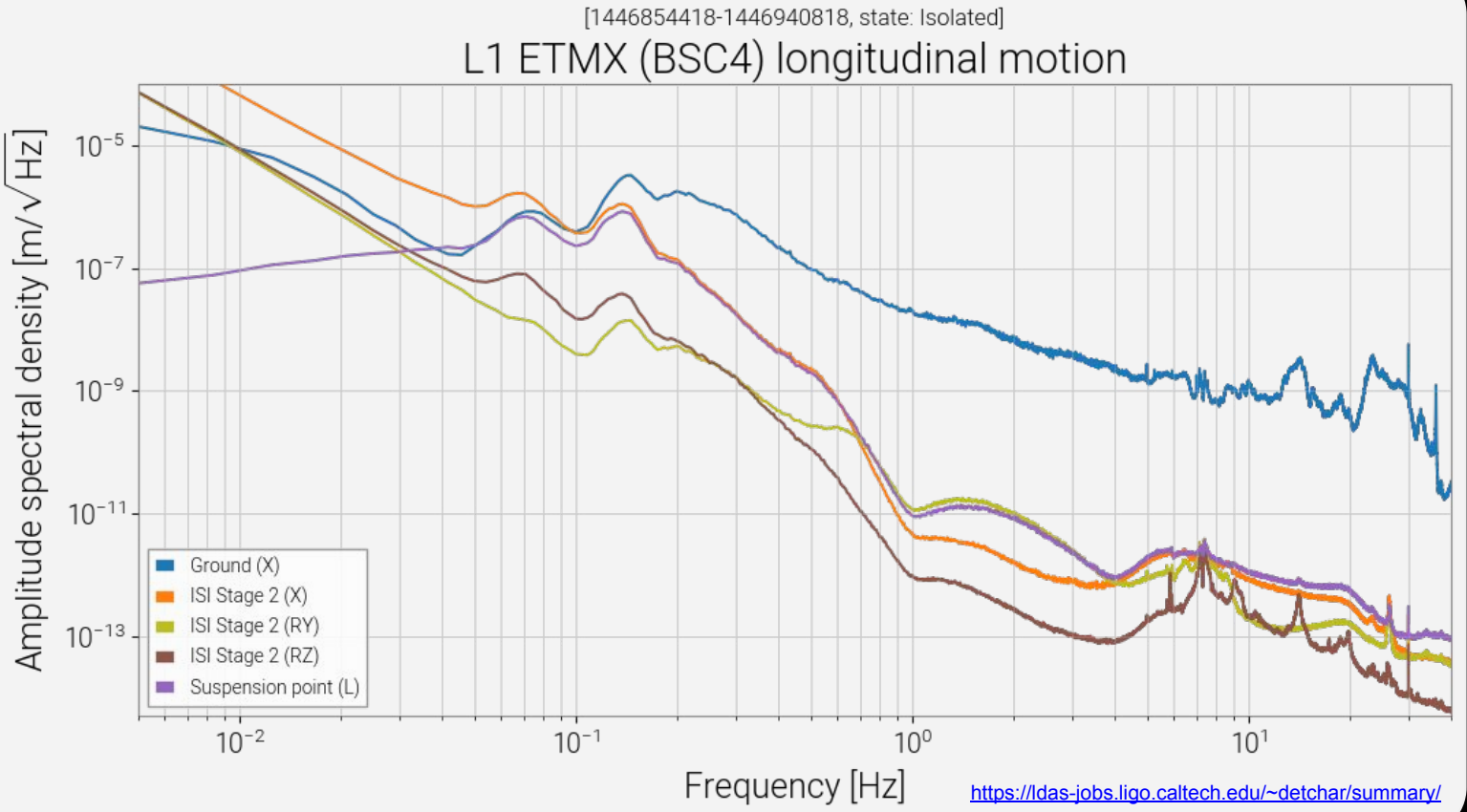


Seismic Isolation

- LIGO has two types:
  - HAM one stage table
  - BSC two-stage table
- Active isolation
  - Several types of sensors and actuators

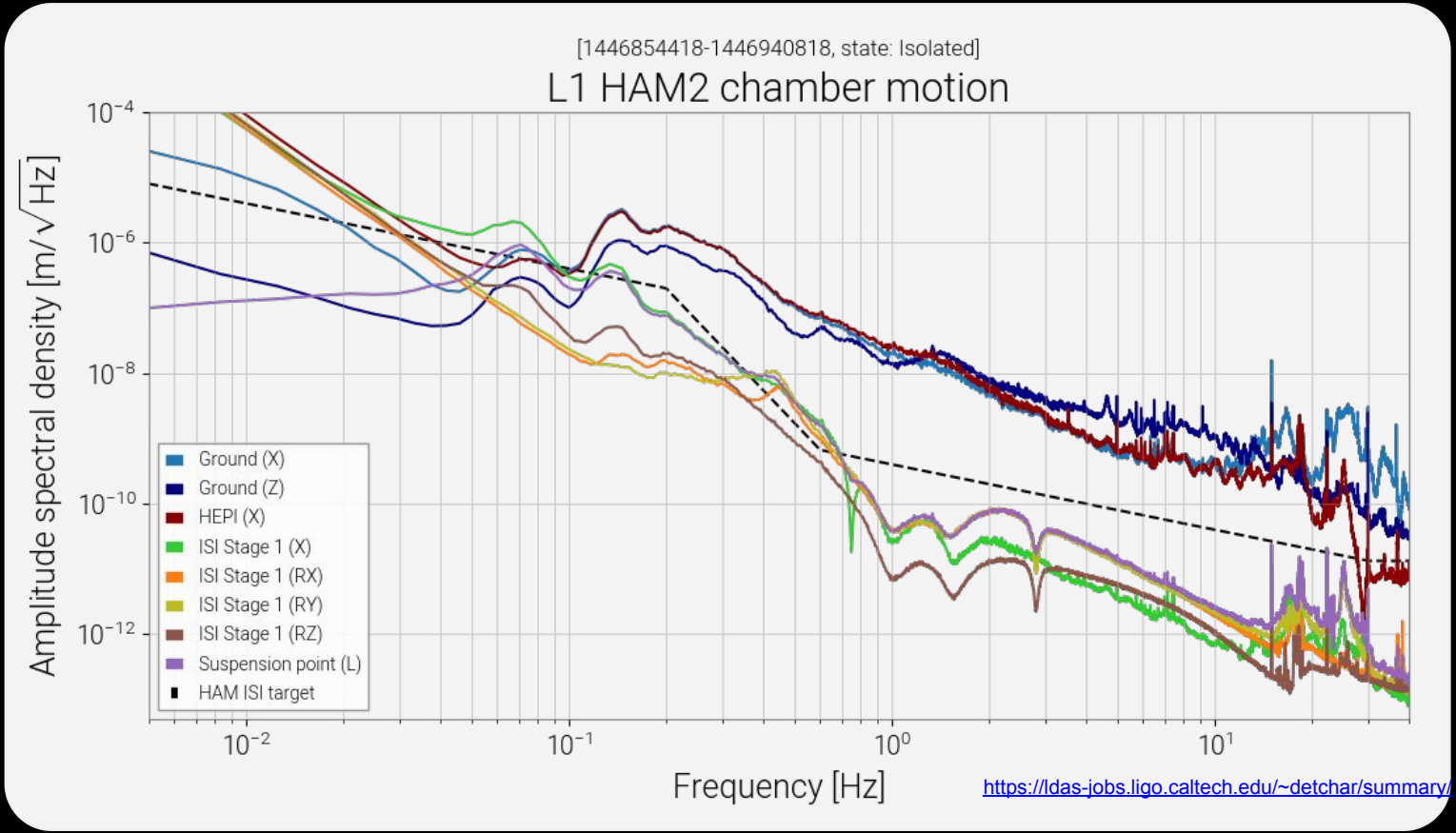


How well does BSC (2-stage) isolate?



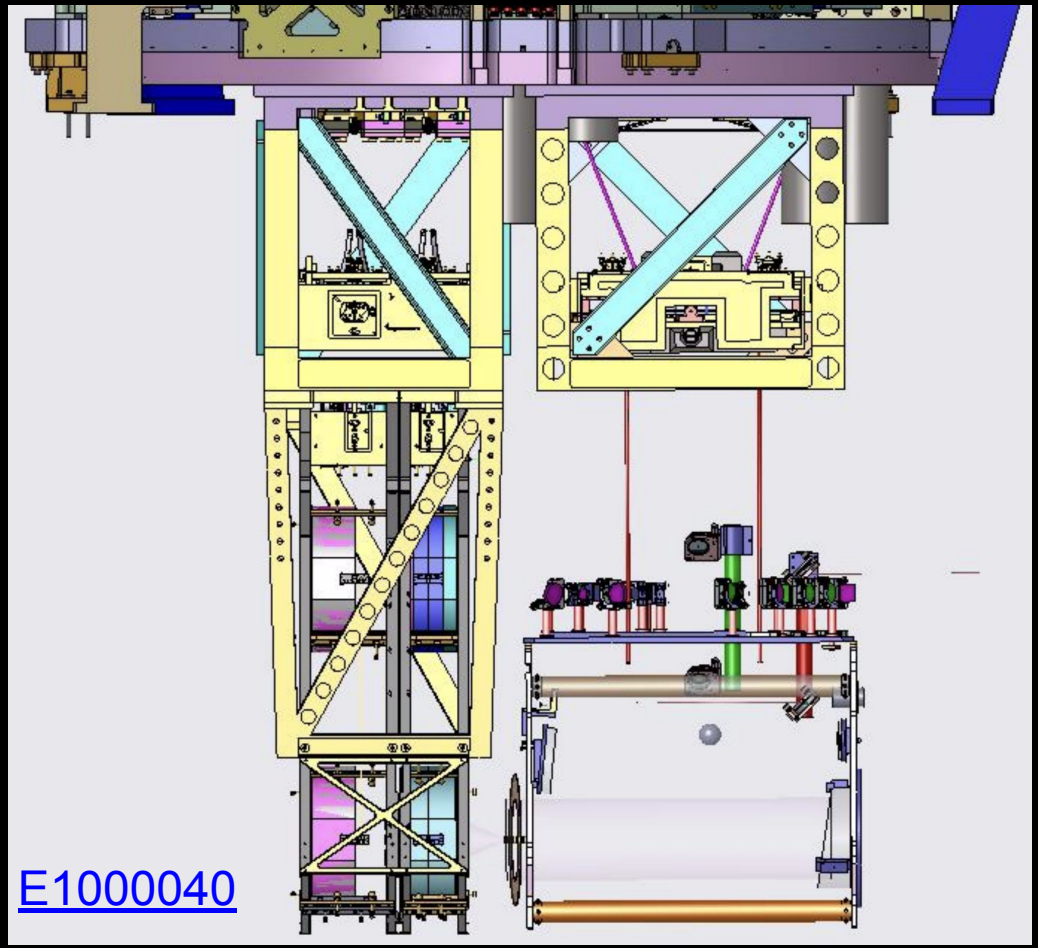
https://ldas-jobs.ligo.caltech.edu/~detchar/summary/

How well does HAM (1-stage) isolate?



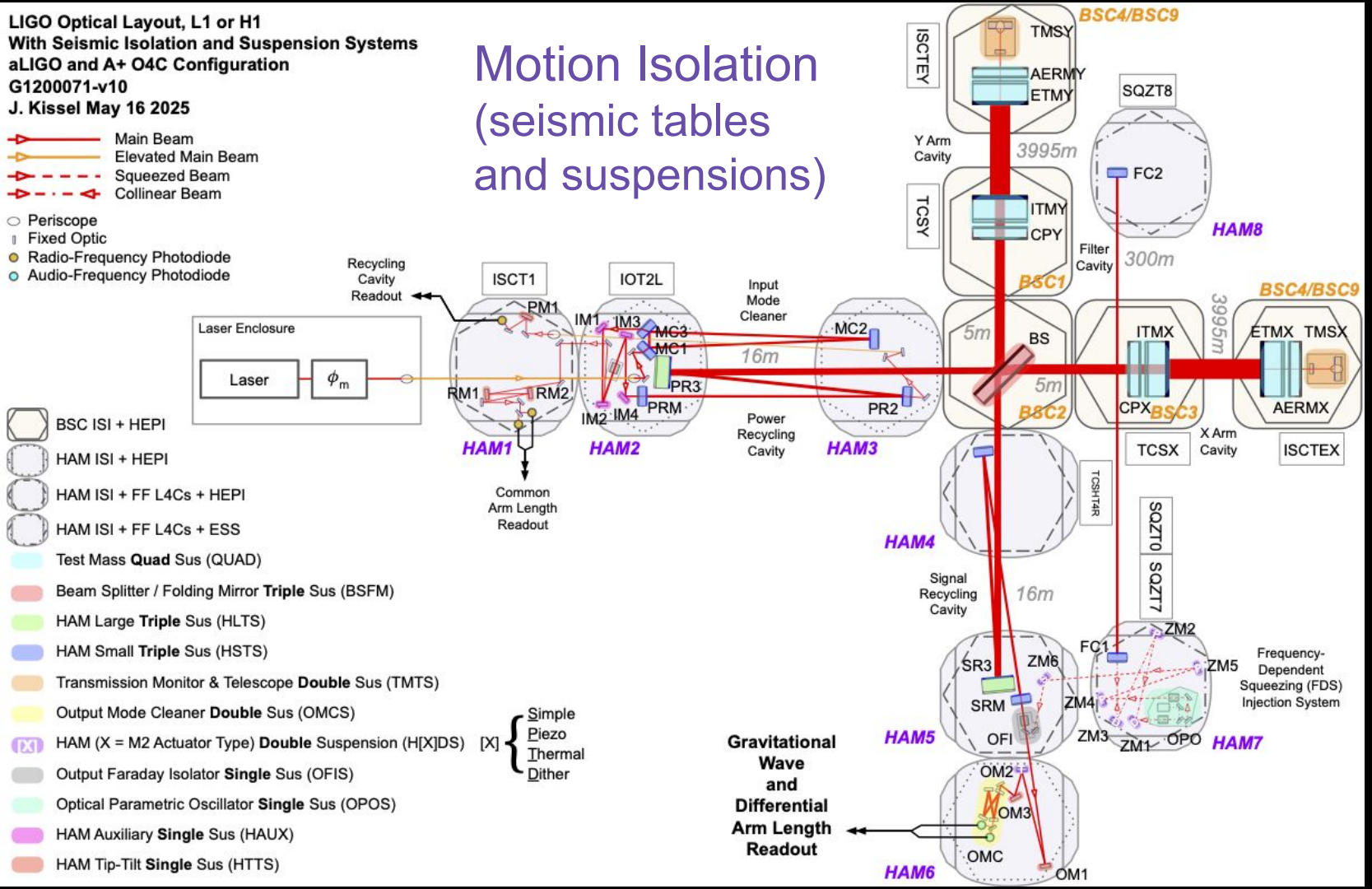
Suspensions - fewest pendula needed

- Each pendulum gives a 1/f^2
- Complexity depends on isolation needed
- Main/arm optics are quadruple suspensions with a quadruple reaction chain
- Other optics (PRC/SRC) are triples
- Even have double and single for sensing



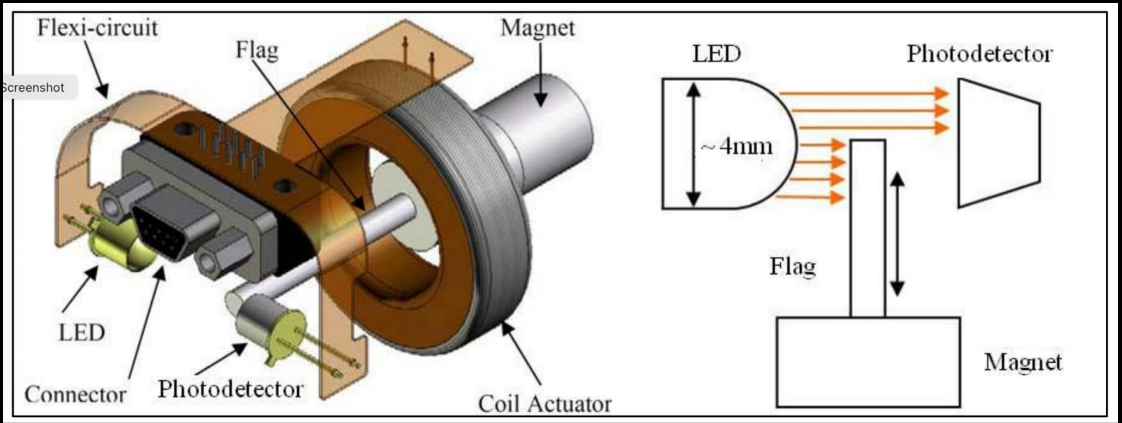
E1000040

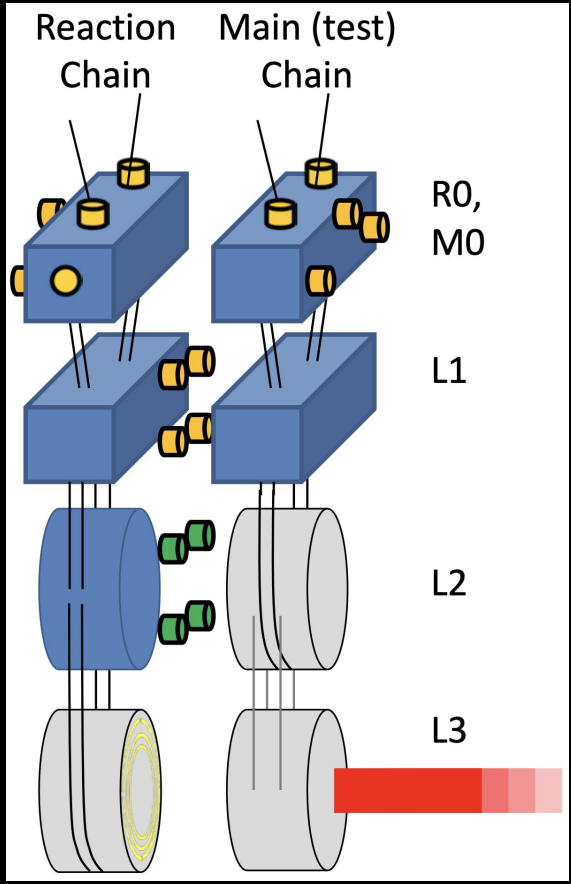
Motion Isolation (seismic tables and suspensions)



Suspension Control

- Most suspensions have OSEMs (optical sensing and electromagnetic actuation) = shadow sensor + coil-magnet
- Test mass has ESD (electrostatic drive) at the bottom
- Some controls are in-between chains
- Each stage has to have quiet actuation
  - Ie the lower we go, the less range
- Sensor noise matters!
  - Can only damp at the top
  - Coming soon: better sensors!

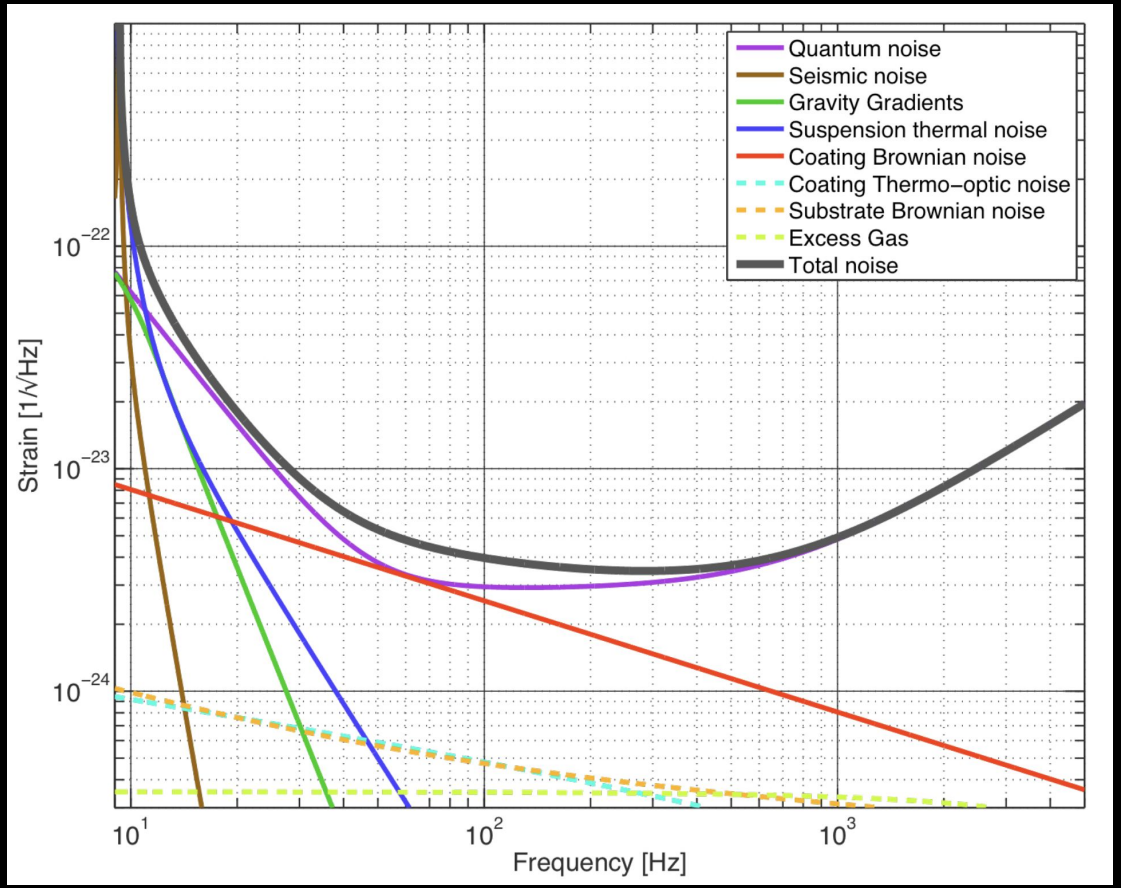




G1100866

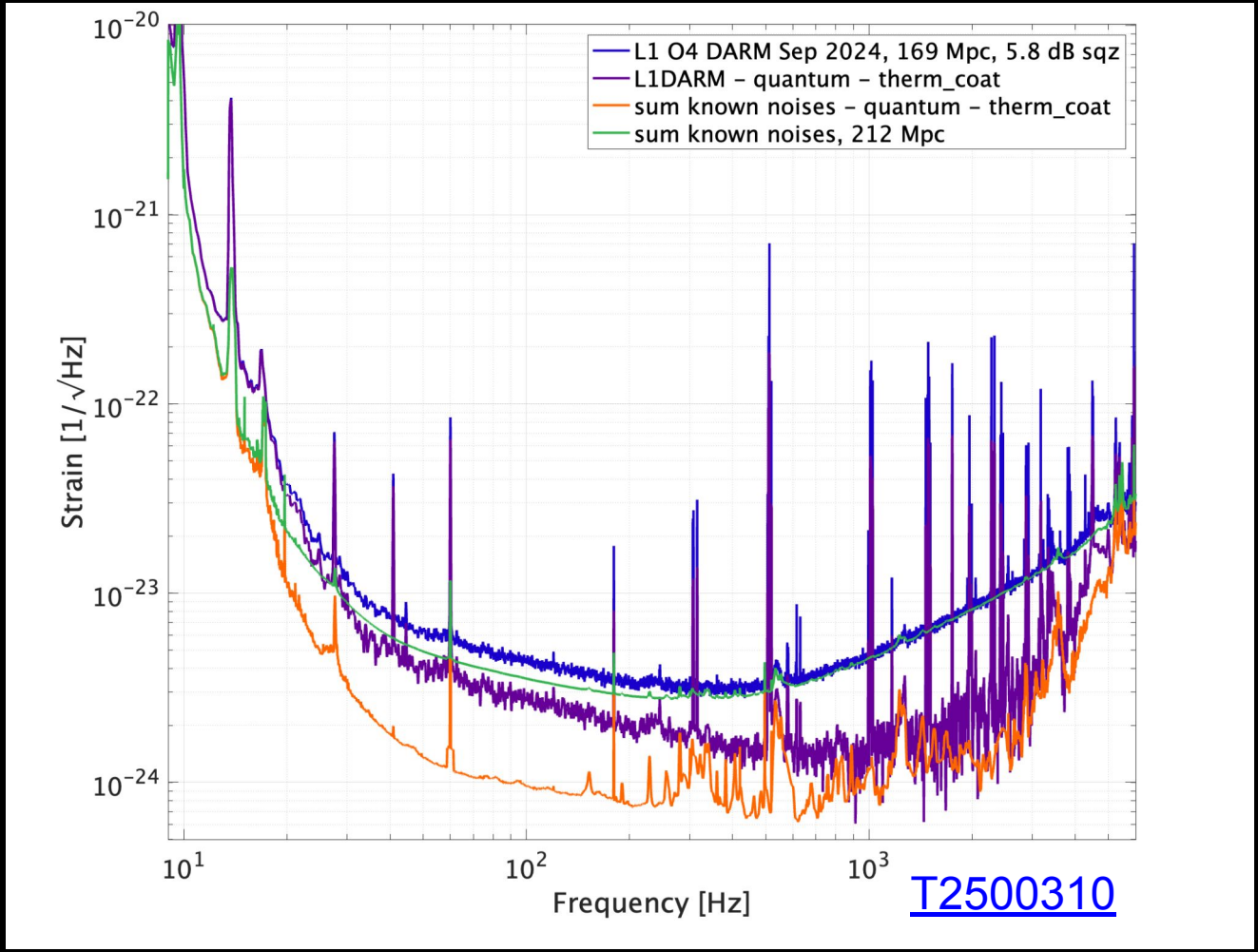
Fundamental noise sources

- Thermal noise
  - Trying to push this down for O5 with new test mass coatings
- Quantum noise
  - More power and more squeezing
  - Radiation pressure at low frequency
- Seismic noise
- Gravity Gradient (newtonian noise)
  - Not yet seen
- Residual gas noise
  - Keep vacuum good

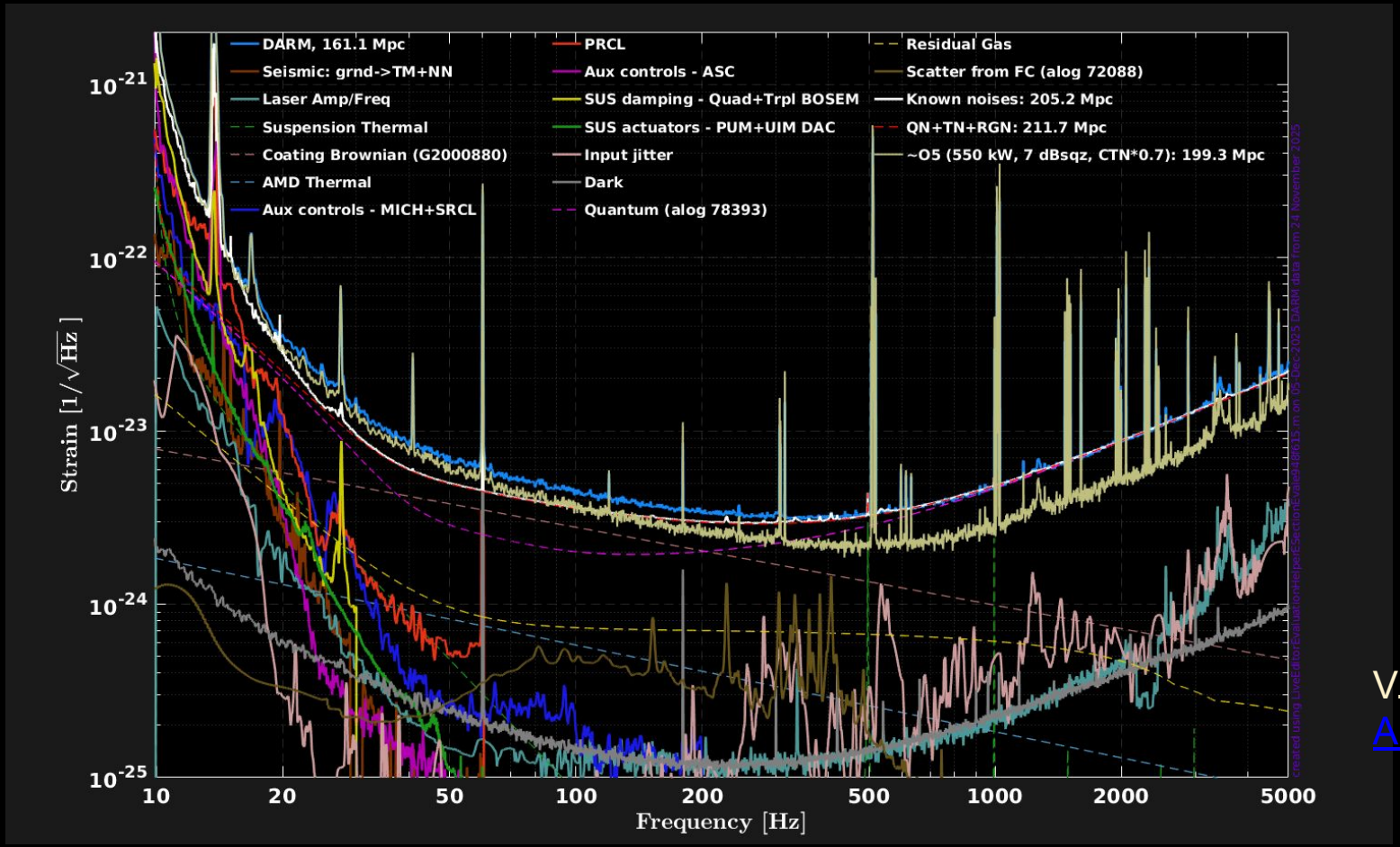


Paper: Advanced LIGO

Other noise?


L1 O4 DARM Sep 2024, 169 Mpc, 5.8 dB sqz
L1DARM – quantum – therm_coat
sum known noises – quantum – therm_coat
sum known noises, 212 Mpc
Strain [1/√Hz]
Frequency [Hz]
T2500310

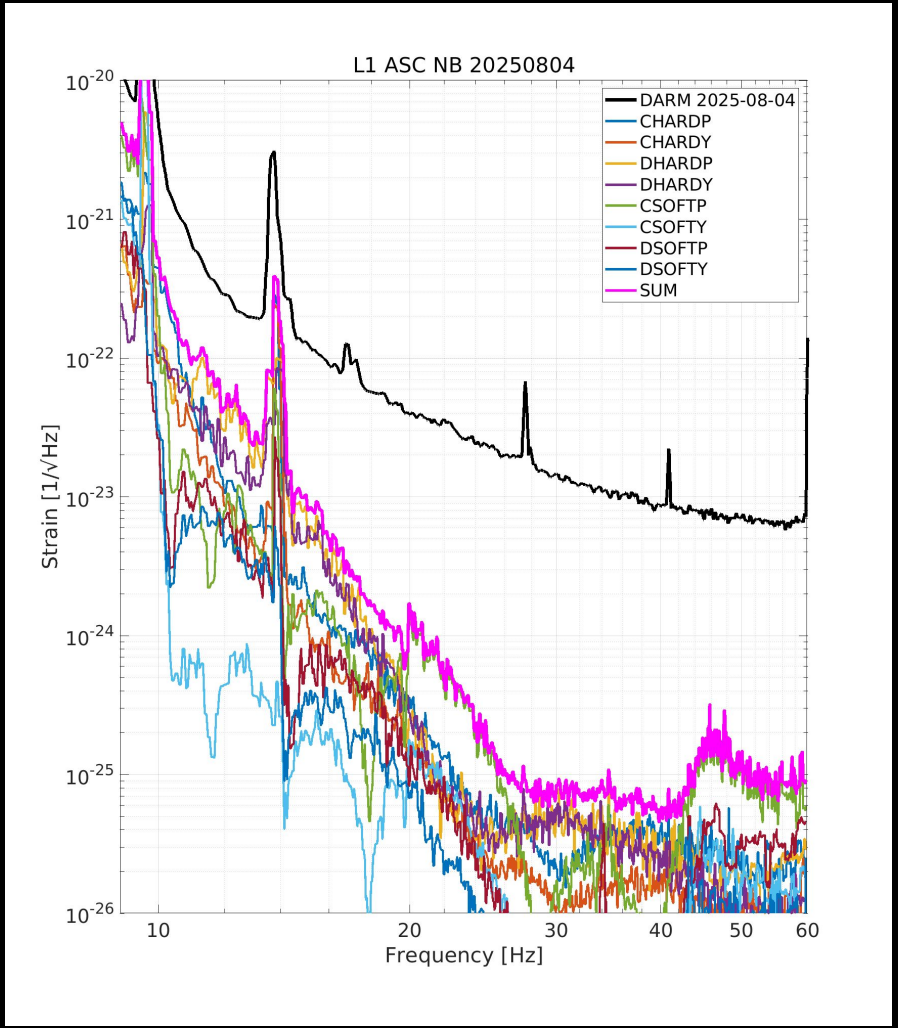
Technical noise sources



V.Frolov
Alog 79720

Example: ASC breakdown

- Measure each of a type of noise and add in quadrature
- Careful not to double count!



How to measure: injection methods

- Main idea: inject relevant noise, have relevant witness, measure the “transfer function” and then apply it to ambient witness noise
- Transfer functions require coherence, so maybe measure “power-to-power”
  - The difference can tell you the non-linearity of the coupling
  - The scaling can be linear even if the coupling is not
- Is the witness actually relevant?
  - Many channels see injections, but they’re not causally involved
- Is the witness noise the same noise that affects DARM?
  - Eg if limited by sensor noise, then it’s not
- Up/downconversion - eg scatter fringe wrapping

$$\mathrm{CF}(f) = \sqrt{\frac{[Y_{\mathrm{inj}}(f)]^2 - [Y_{\mathrm{bkg}}(f)]^2}{[X_{\mathrm{inj}}(f)]^2 - [X_{\mathrm{bkg}}(f)]^2}} \qquad (1)$$

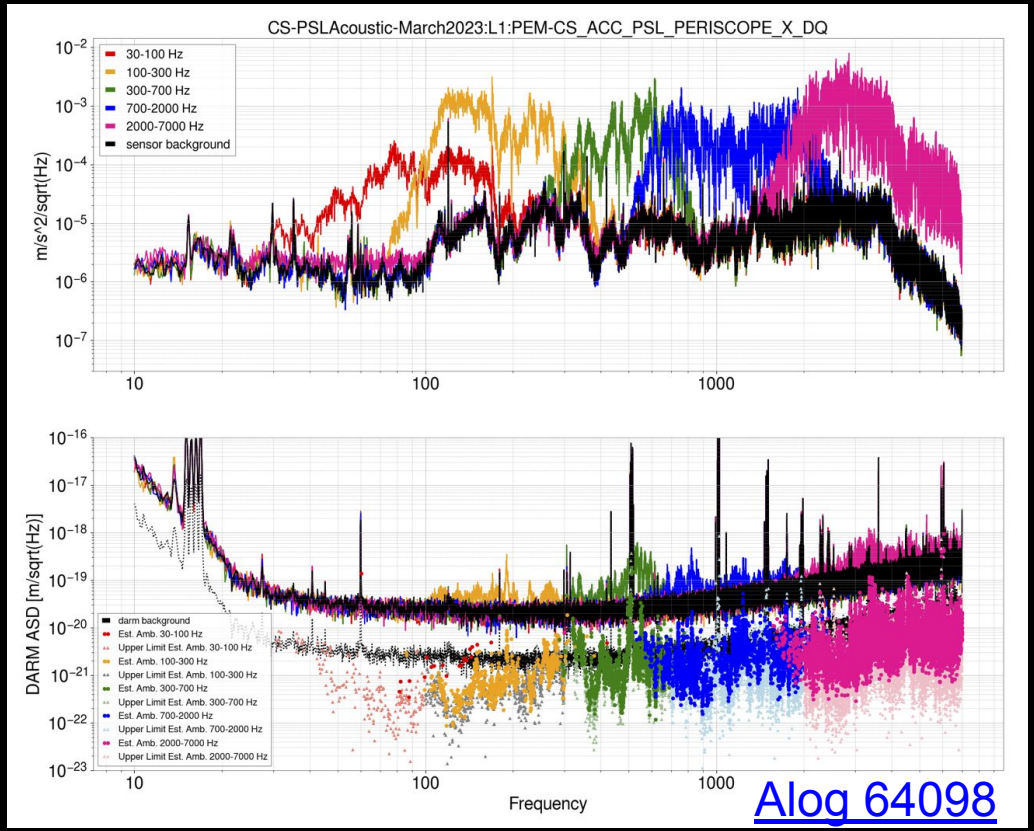
DARM_noise(f) = CF(f) * Xbkg(f)

where $X_{\mathrm{bkg}}(f)$ and $X_{\mathrm{inj}}(f)$ are the ASDs of the witness sensor at background and injection times, respectively, and $Y_{\mathrm{bkg}}(f)$ and $Y_{\mathrm{inj}}(f)$ are the ASDs of DARM at background and injection times. We use *coupling factor* to refer to the value of a coupling function at a single frequency bin.

O3 pem paper

Example: Measuring Input Jitter

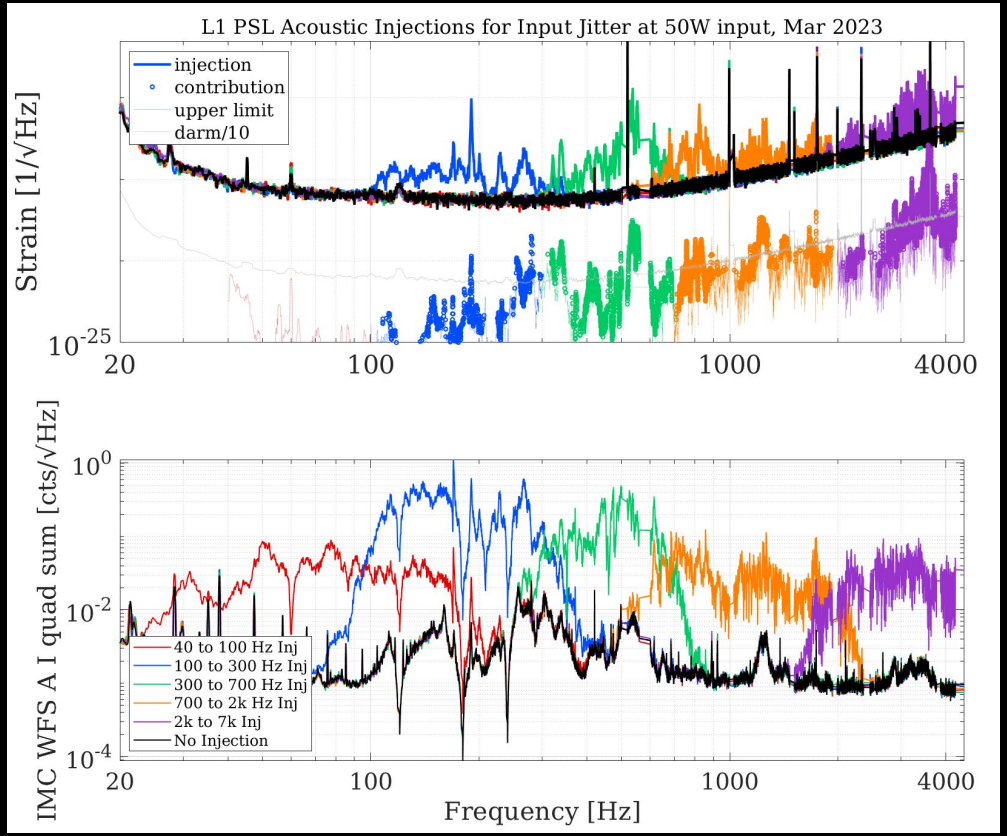
- Inject acoustics
  - Few bands to focus power
  - Low-freq use piezo
  - Could use shaker or other injectors
- What sensor to use?
  - PSL periscope is good, others are not
  - But can find better



[Alog 64098]

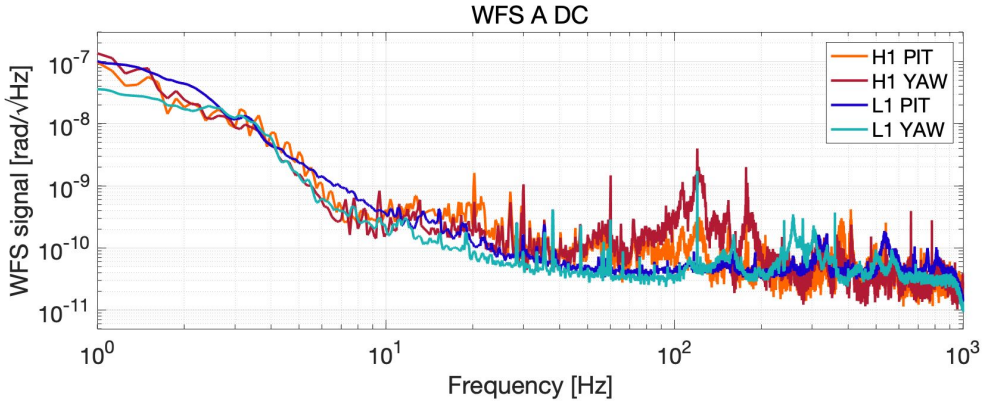
Example: Measuring Input Jitter

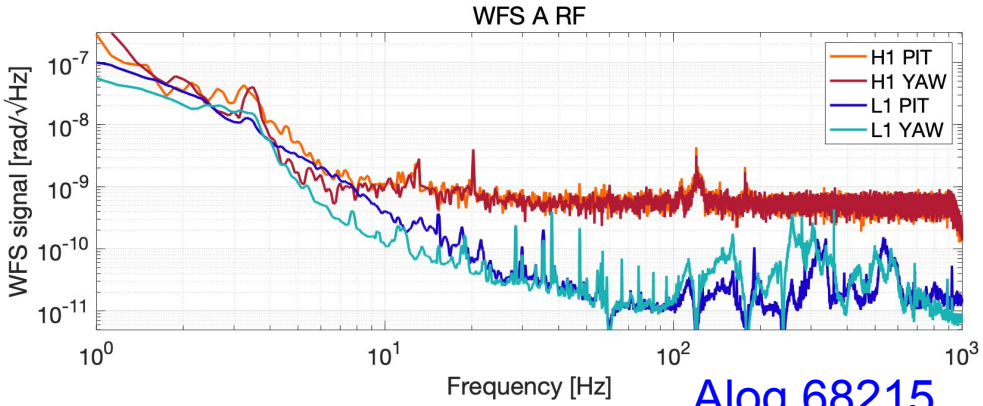
- IMC WFS are even better, and predict signal in DARM correctly!
- We add pit and yaw in quadrature since we can't distinguish



Example: Measuring Input Jitter H1 vs L1

- H1 and L1 have similar coupling but H1 has a bit more ambient noise
- H1 and L1 have different best sensors!
  - H1: IMC WFS A DC
  - L1: IMC WFS A RF
- This coupling is subtracted in CALIB_STRAIN_CLEAN
- For O5 installing JAC (jitter attenuation cavity) to reduce by ~factor of 10

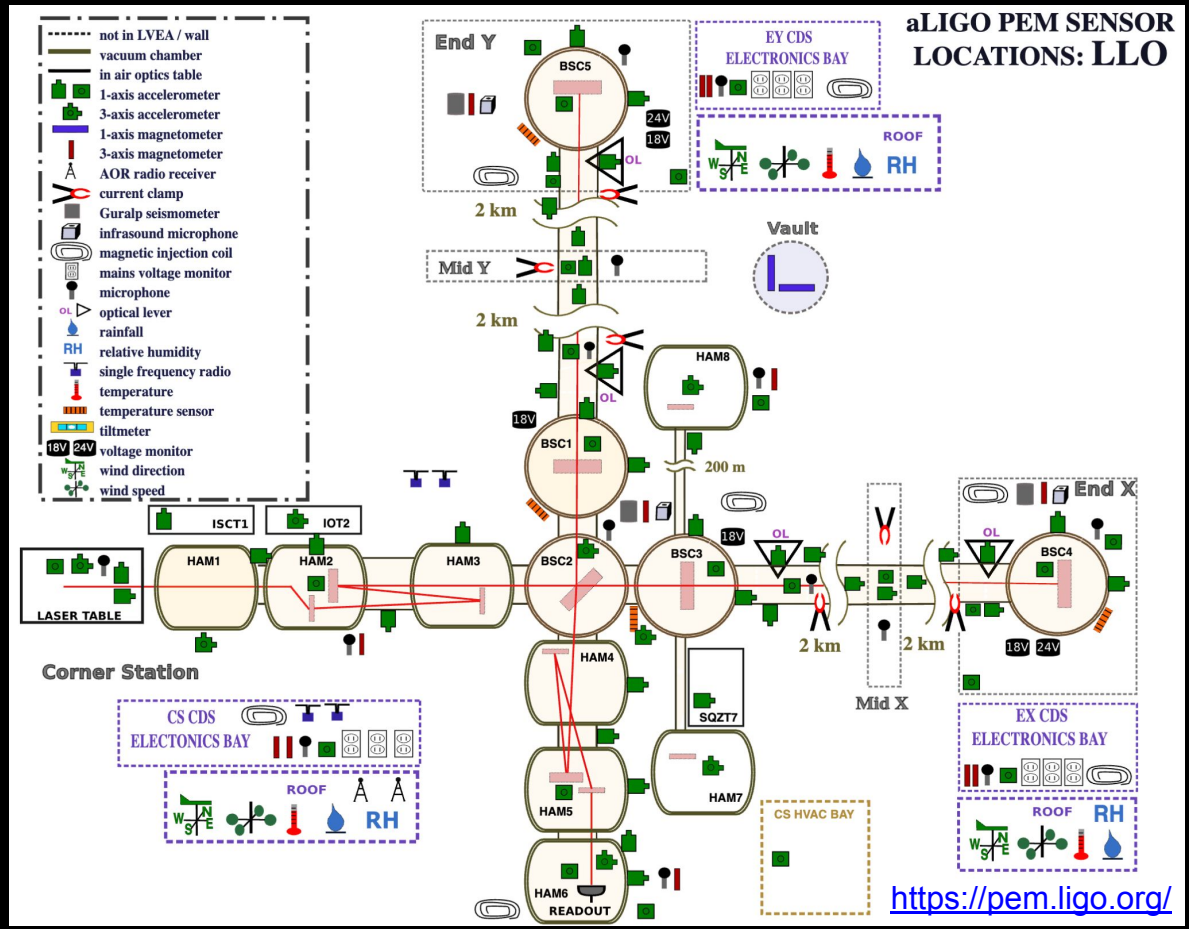




Alog 68215

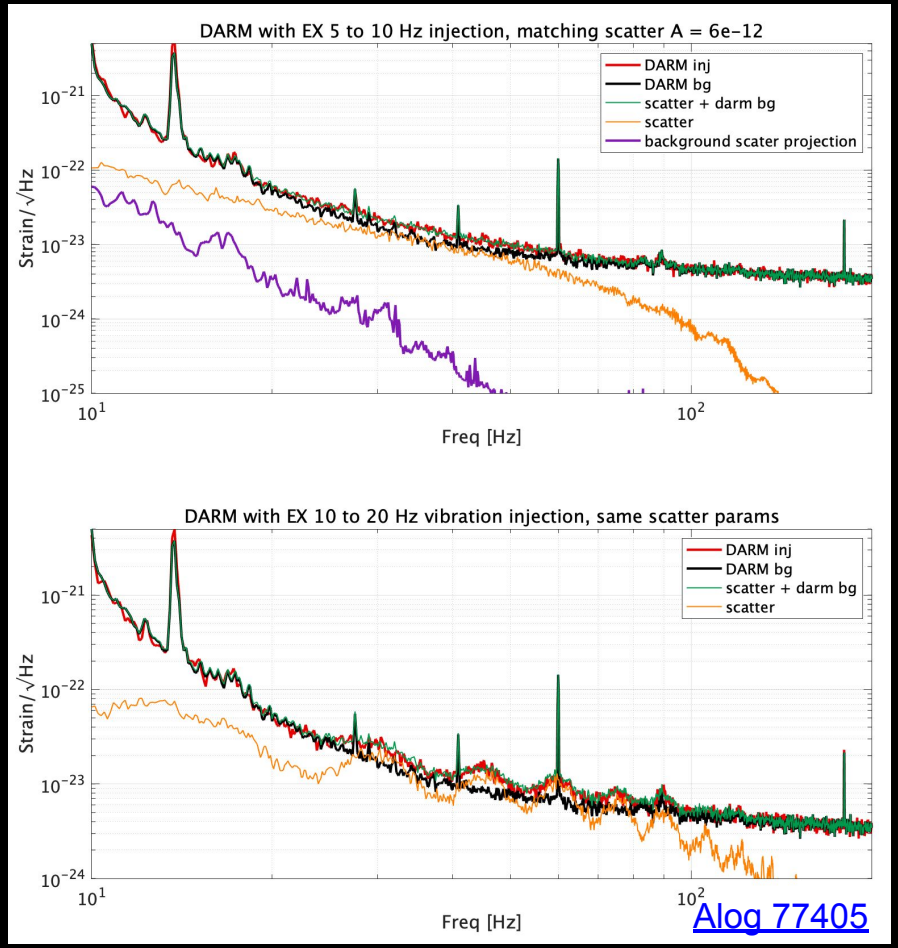
Ambient sources (PEM = physical environmental monitoring)

- Want **good coverage**: any noise source should make a larger signal in a sensor rather than DARM!
- Protection for data quality and vetoes
- Various measurements can point to noise sources and prioritize noise investigations

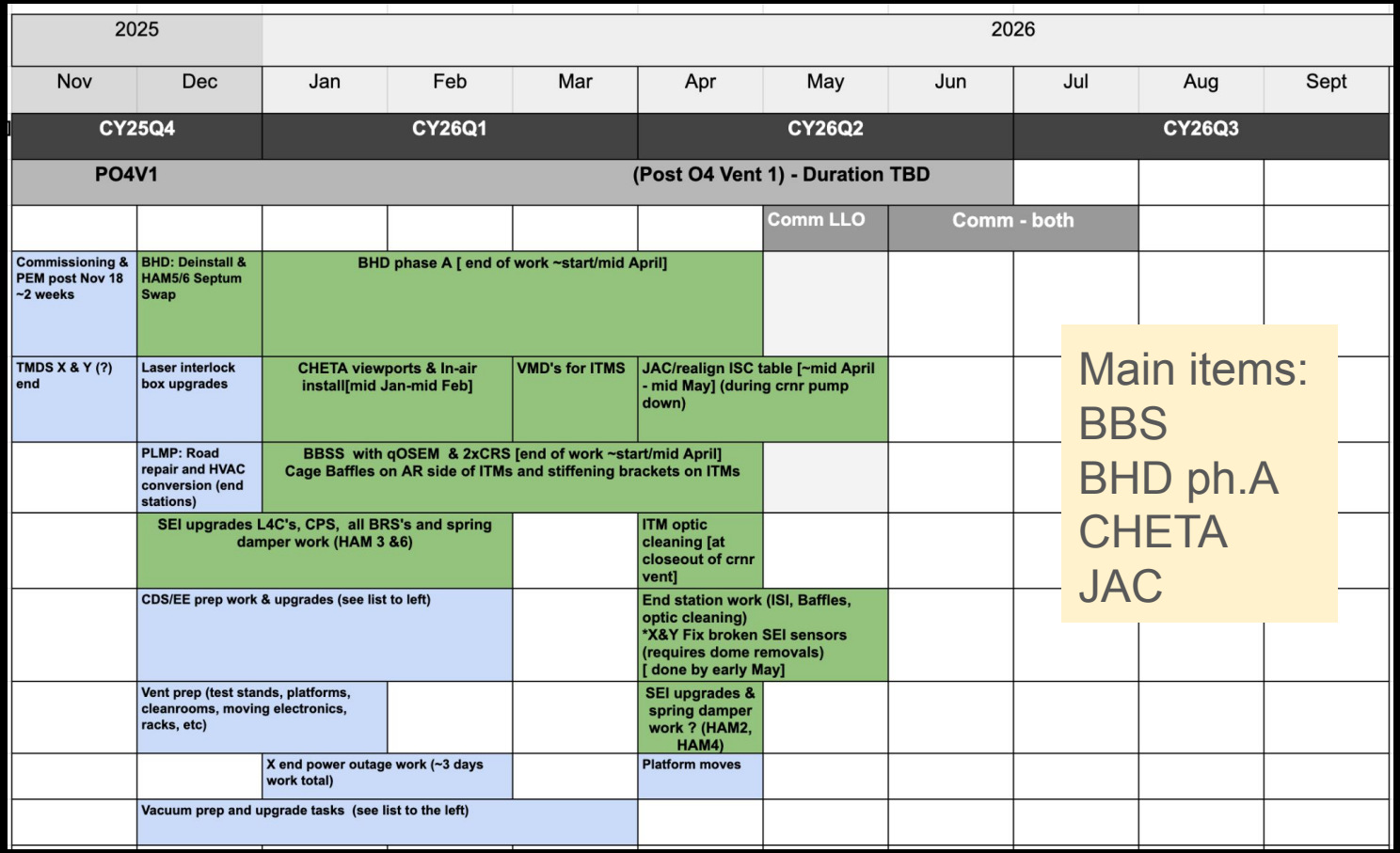


Upconverted noise example

- We can also model upconverted noise just fine as long as we have a physical model
- We can infer other parameters of the coupling (eg amount of light needed)



Current schedule (L1, but H1 similar)

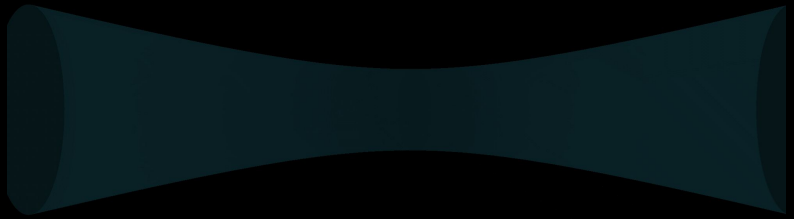


2025		2026								
Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
CY25Q4		CY26Q1			CY26Q2			CY26Q3		
PO4V1					(Post O4 Vent 1) - Duration TBD					
						Comm LLO	Comm - both			
Commissioning & PEM post Nov 18 ~2 weeks	BHD: Deinstall & HAM5/6 Septum Swap	BHD phase A [end of work ~start/mid April]								
TMDS X & Y (?) end	Laser interlock box upgrades	CHETA viewports & In-air install[mid Jan-mid Feb]		VMD's for ITMS	JAC/realign ISC table [~mid April - mid May] (during crnr pump down)					
	PLMP: Road repair and HVAC conversion (end stations)	BBSS with qOSEM & 2xCRS [end of work ~start/mid April] Cage Baffles on AR side of ITMs and stiffening brackets on ITMs								
	SEI upgrades L4C's, CPS, all BRS's and spring damper work (HAM 3 &6)				ITM optic cleaning [at closeout of crnr vent]					
	CDS/EE prep work & upgrades (see list to left)				End station work (ISI, Baffles, optic cleaning) *X&Y Fix broken SEI sensors (requires dome removals) [done by early May]					
	Vent prep (test stands, platforms, cleanrooms, moving electronics, racks, etc)				SEI upgrades & spring damper work ? (HAM2, HAM4)					
		X end power outage work (~3 days work total)			Platform moves					
	Vacuum prep and upgrade tasks (see list to the left)									

Main items:
BBS
BHD ph.A
CHETA
JAC

Nikhil from here on

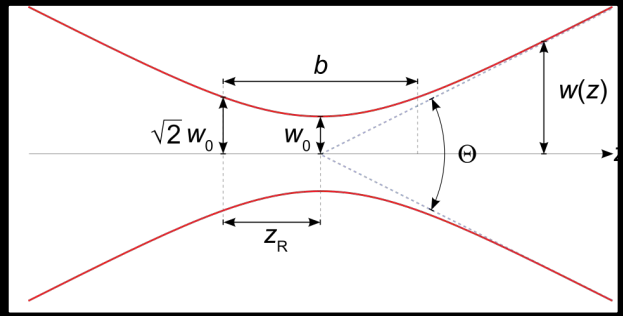
Gaussian Beam



Exact solutions to EM wave equation under paraxial approximation

Lowest-order, minimum-divergence solutions supported by stable optical resonators

Natural eigenmodes of paraxial propagation and stable optical cavities.

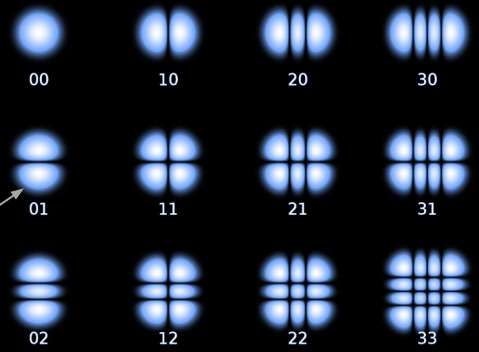


$$U(x,y,z,t) = U_0 \frac{w_0}{w(z)} \exp(-i\omega t) \exp\left[-\frac{x^2+y^2}{w^2(z)}\right] \exp\left[-i\left(kz + \frac{k(x^2+y^2)}{2R(z)} - \psi(z)\right)\right]$$

Laser Beam Quality

Paraxial approximation of laser beam model

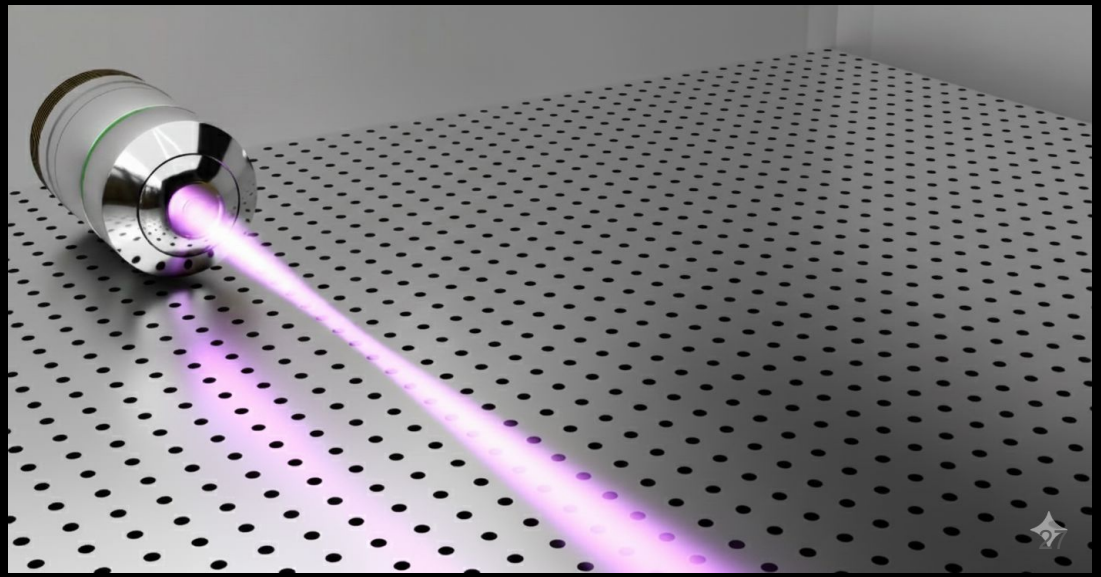
$$U(\vec{r},t) = U_0(t)\,\exp(2\pi i\,\nu(t)\,t)\sum_{l,m\geq 0} c_{lm}(t)\,\Phi_{lm}(\vec{r})$$



Complex amplitudes of Hermite-Gaussian modes TEM_{lm}

Fluctuations can occur in

- Power
- Frequency
- Beam quality
  - Spatial beam geometry
  - Beam pointing
  - Mode-matching
  - Astigmatism
  - Ellipticity



Relative Power Noise / Relative Intensity Noise

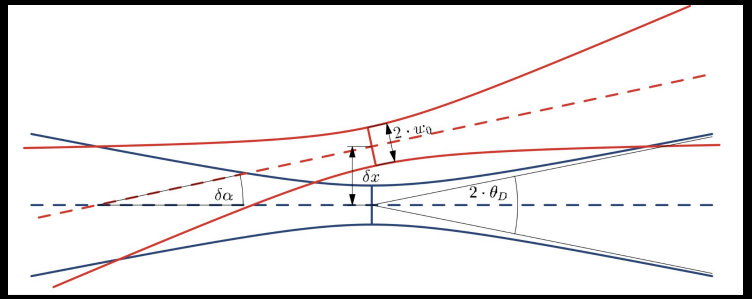
$$\frac{P(t)}{P_0} = \frac{|U_0(t)|^2}{\overline{|U_0(t)|^2}} \quad , \quad \overline{|U_0(t)|^2} = \frac{1}{T}\int_T dt\,|U_0(t)|^2$$

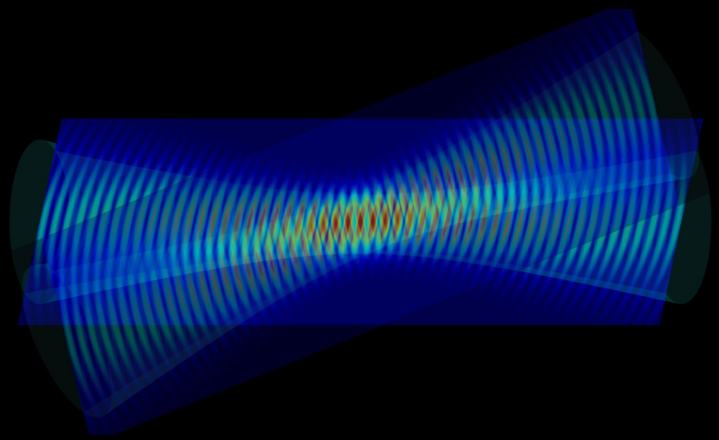
Beam Quality

Measured in terms of relative power in the fundamental TEM00 Mode

$$\frac{P_{\mathrm{fund}}}{P_{\mathrm{tot}}} = \frac{|c_{00}|^2}{\sum_{l,m}|c_{lm}|^2} = |c_{00}|^2$$

Beam Pointing Fluctuation Errors





$$\epsilon(t) = \frac{\delta x}{w_0} + i\frac{\delta \alpha}{\theta_D}$$

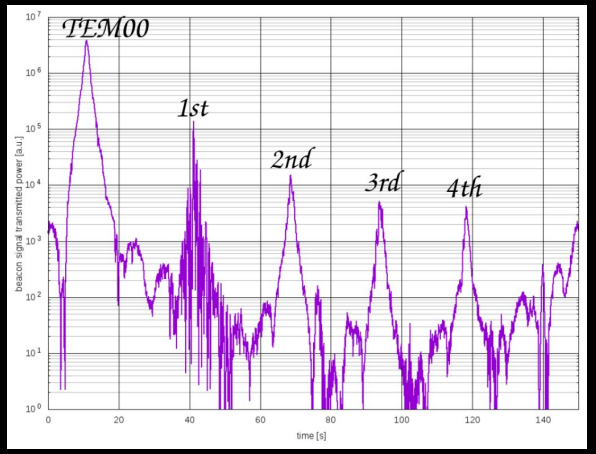
Fluctuation error, ε(t) of a shifted and tilted beam can be expanded Hermite-Gauss modes of the reference beam in terms of TEM10 & TEM01 relative amplitudes (ε << 1 limit)

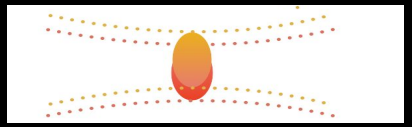
$$U(\epsilon_x, \epsilon_y) \approx \phi_{00} + \epsilon_x \phi_{10} + \epsilon_y \phi_{01}$$

where

$$\epsilon_x(t) \approx \frac{c_{10}}{c_{00}} \, , \, \epsilon_y(t) \approx \frac{c_{01}}{c_{00}}$$

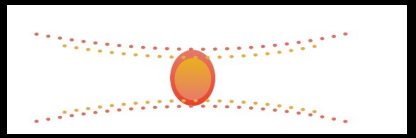
Detchar Example: Laser Beam Coupling to Cavity Eigen Modes





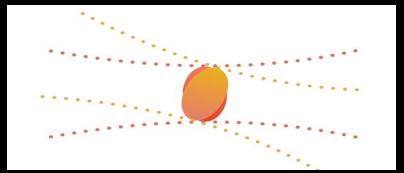
In phase coupling to 1st Order

(Beam Displacement)



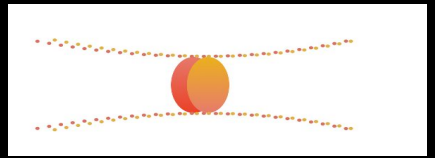
In phase coupling to 2nd Order

(Waist size mismatch)



Quadrature phase coupling to 1st Order

(Beam Tilt)

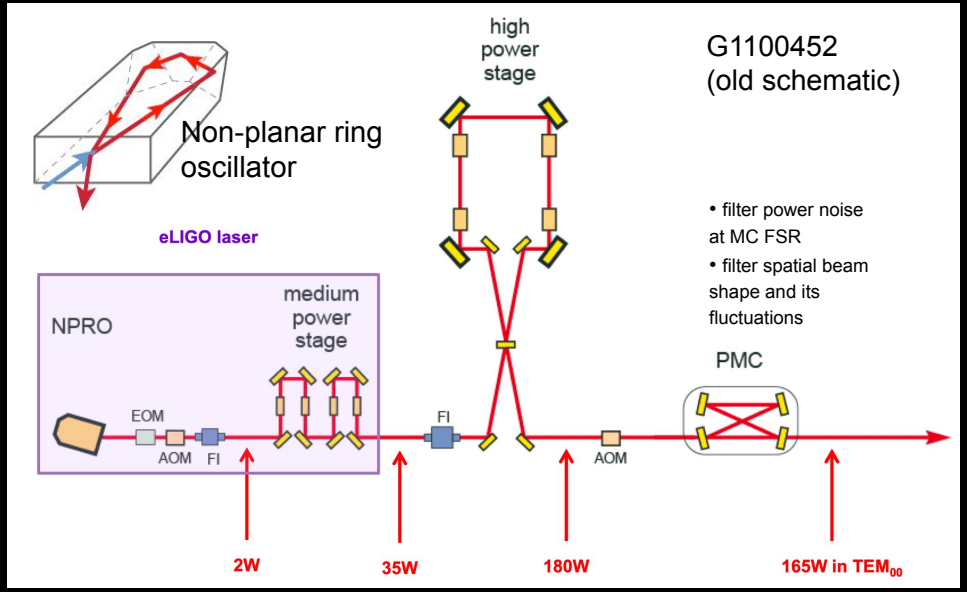


Quadrature Phase coupling to 2nd Order

(Waist position mismatch)

LIGO Pre-Stabilized Laser

LIGO Pre-Stabilized Laser



Philosophy
Stabilize first at low power → amplify later → clean again

<u>Requirements</u>

Frequency stability

Power stability

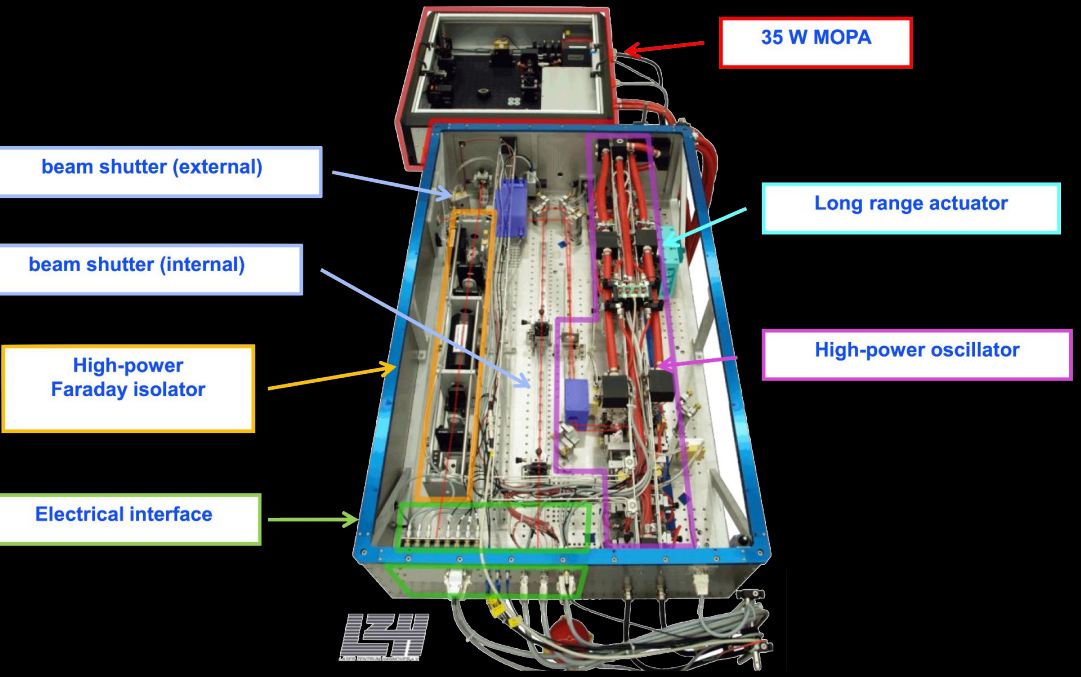
Pure spatial mode (TEM00)

High Power
(200W in TEM00, < 5W in higher non-TEM00)

Reliable & controllable

5% power drift over 24hrs
100 kHz frequency drift over 100s

LIGO Pre-Stabilized Laser

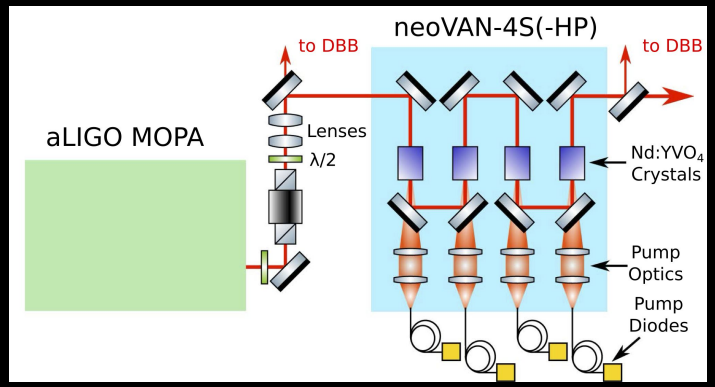


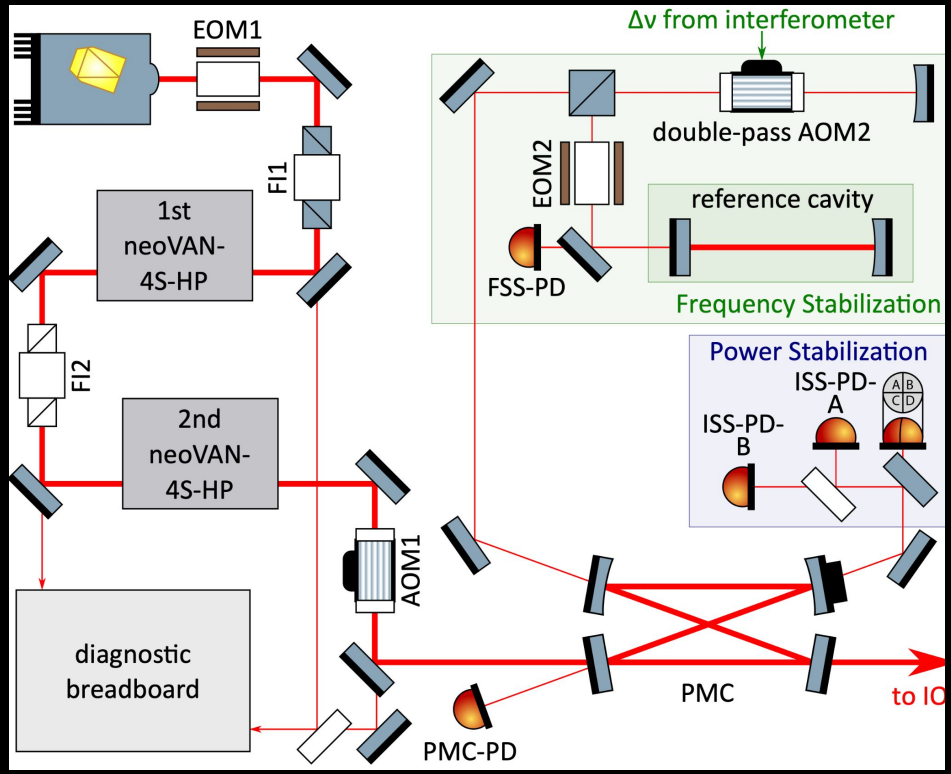
HPO requires strong water cooling, and cooling-driven vibrations creates beam pointing/size noise, which couples badly to the detector.

Can also suffer from cavity length noise, thermal noise etc.

LIGO PSL O4 Latest Schematic

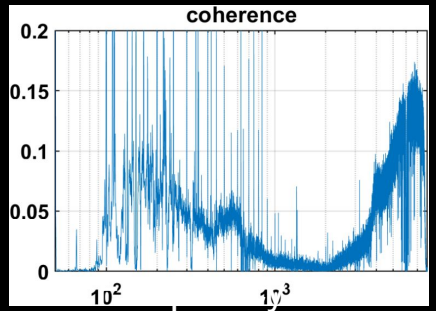
High power oscillator
replaced with amplifier stage.

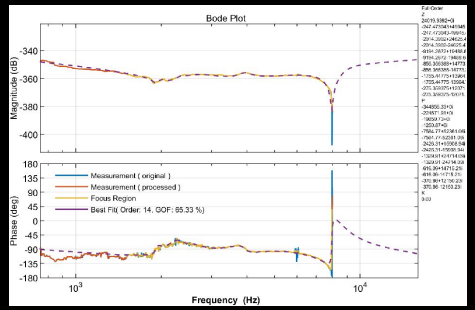


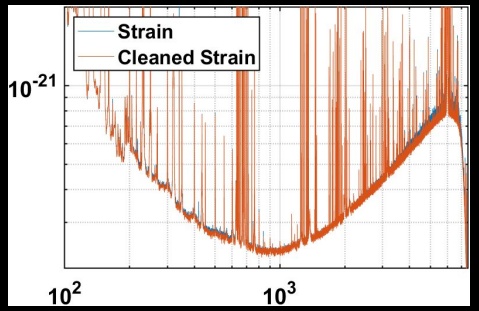


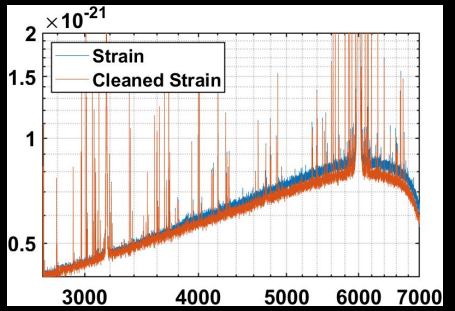
Output power : 140W

Detchar Example: Laser Amplitude Noise Subtraction









Step 1.
Measure coherence with strain

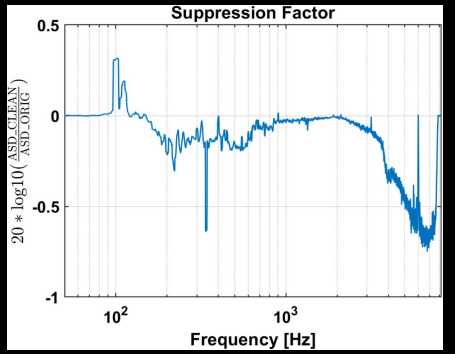
Identify coupling

Step 2.
Measure transfer function from witness to GW strain channel

Do system identification.
Fit IIR/FIR filter

Step 3.
Do time domain subtraction

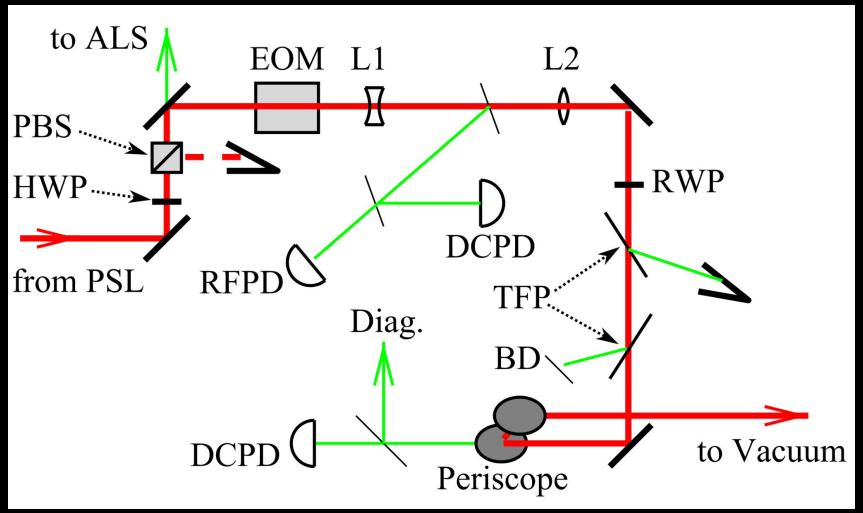
Check suppression/ residual coherence

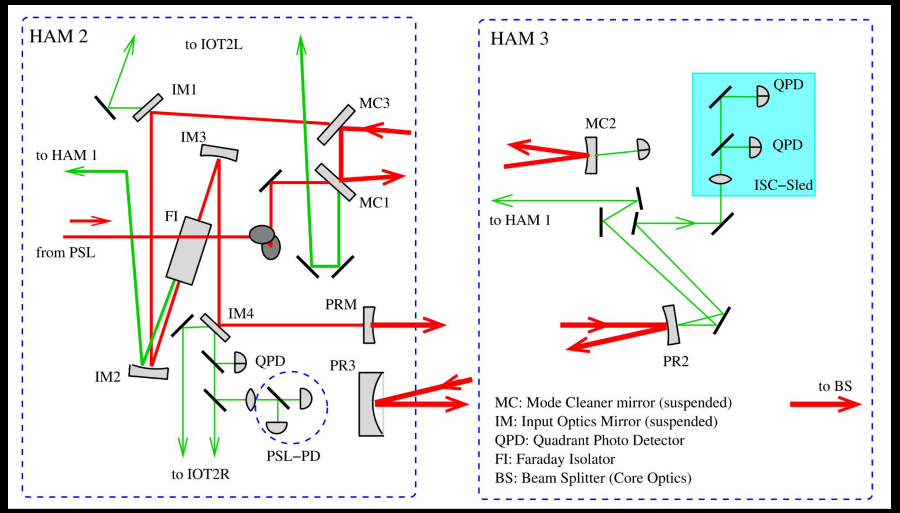


Input Optics

Input Optics

Main task: Take the beam from PSL, prepare it and inject it to main interferometer.



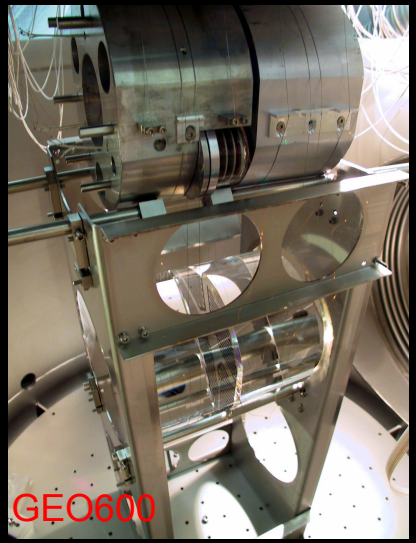


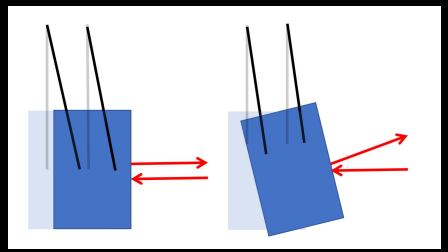
Outside vacuum, co-located with PSL

In vacuum, seismically isolated

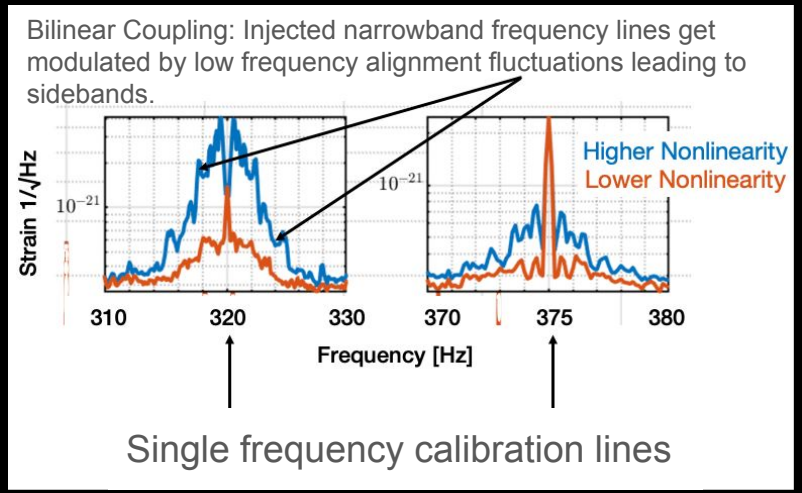
Alignment Sensing & Control (ASC)

Misalignments affect strain sensitivity

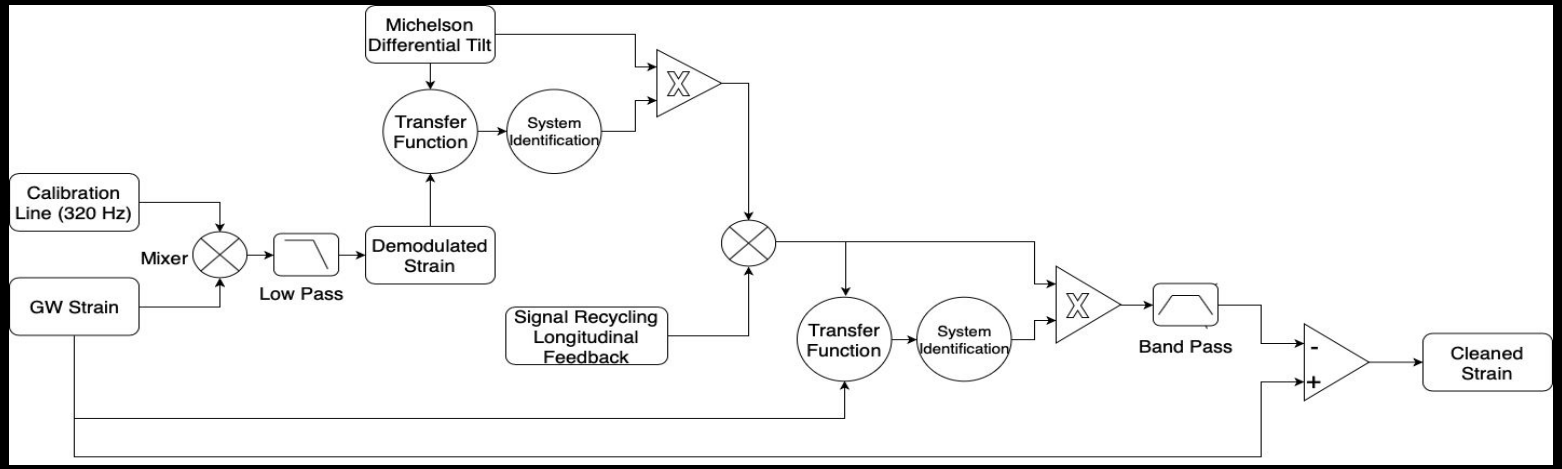


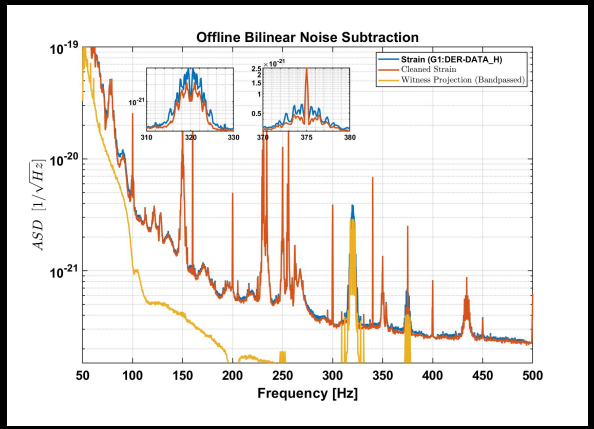


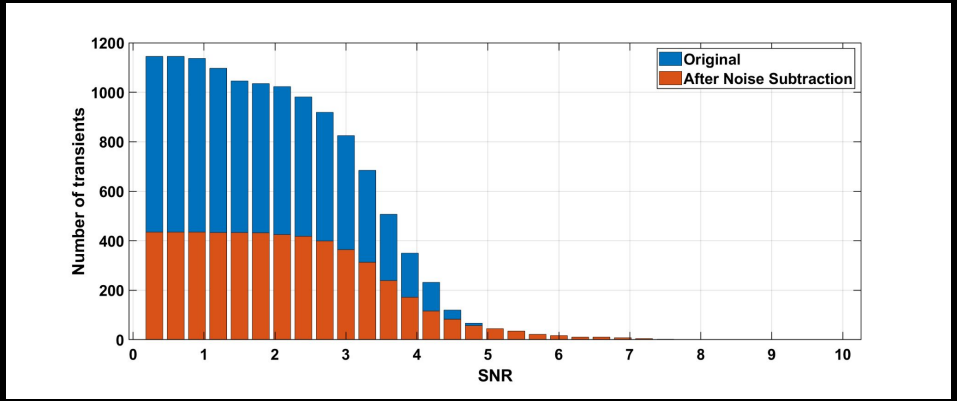
- Angular Motion is imprinted in the strain signal in a broadband sense.
- Increases the number of transients -> false GW triggers
- Persistent sidebands also effect continuous wave searches



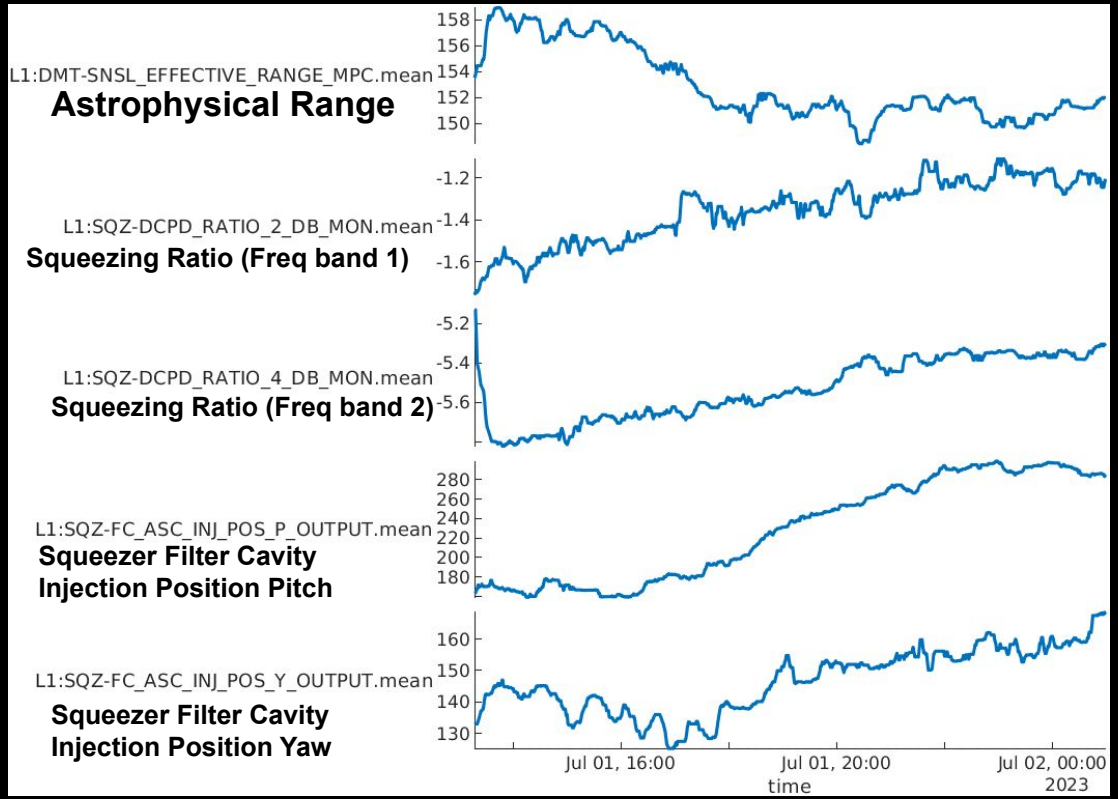
DetChar Example: Removing Bilinear Coupling





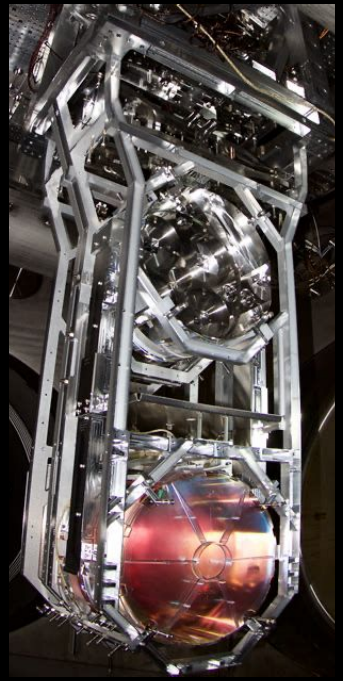


DetChar Example: Squeezer Filter Cavity Misalignment Correlates with Astrophysical Sensitivity Degradation

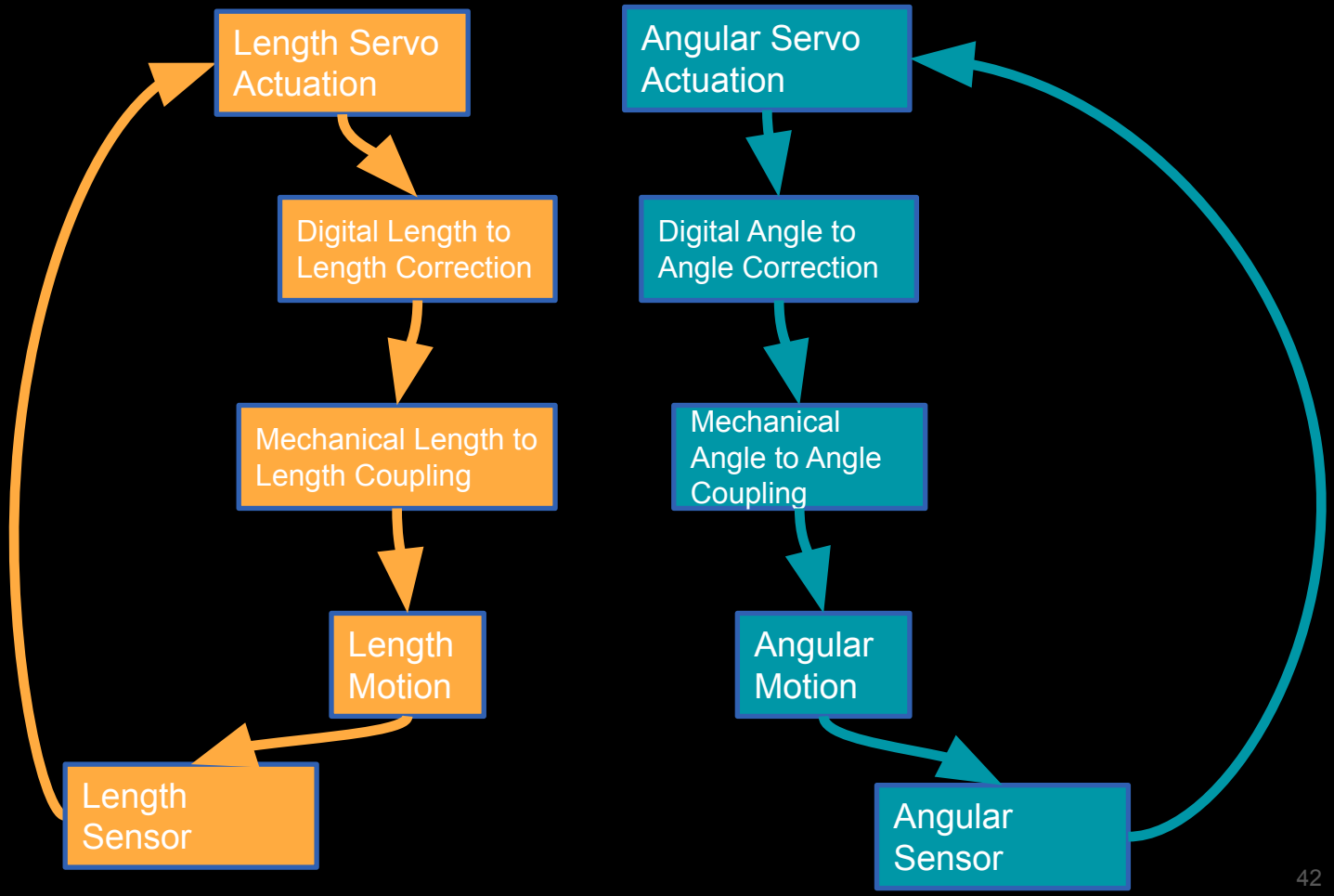


Ideal

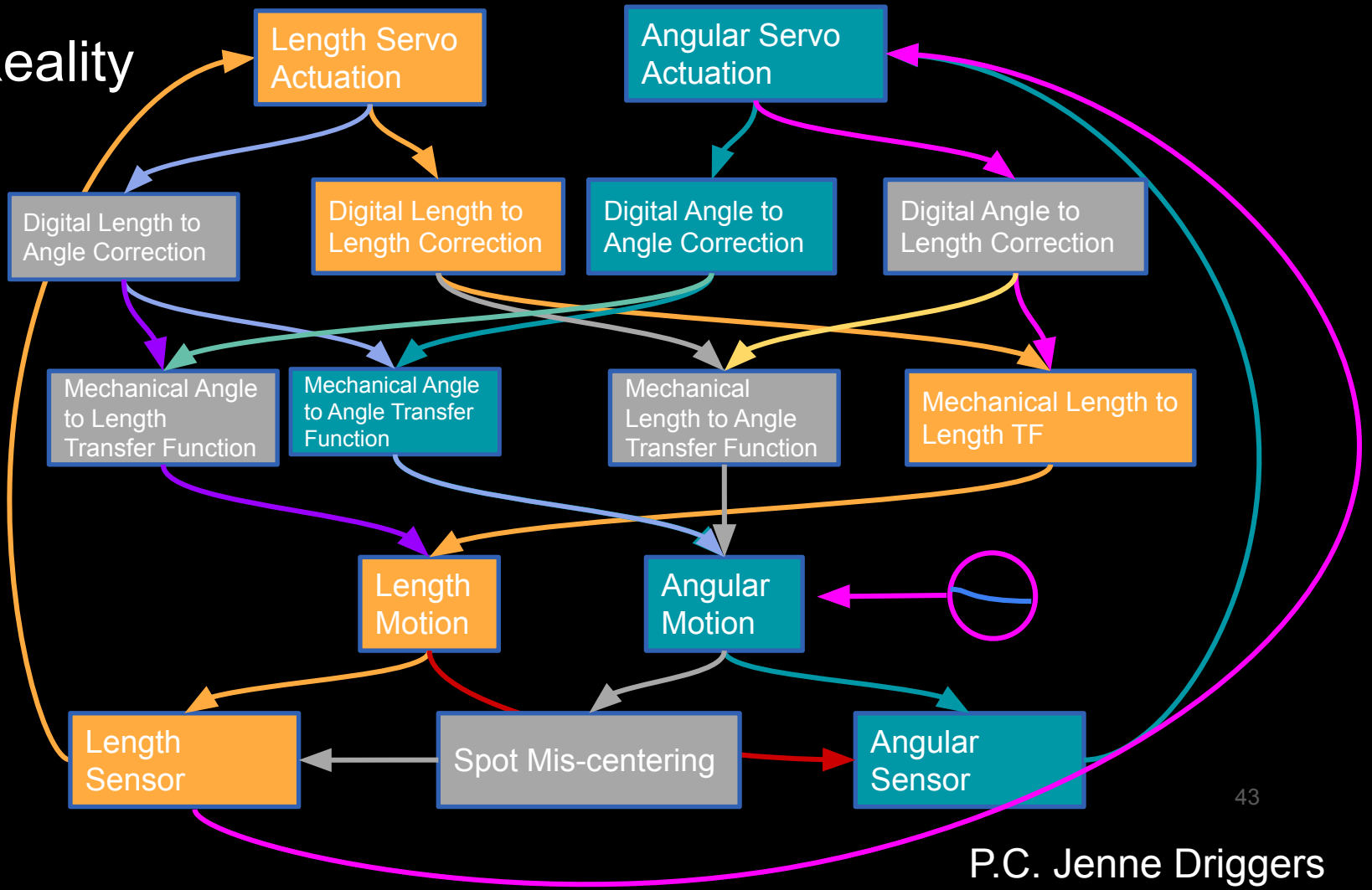
Controlling Suspended Optics



Advanced LIGO 40kg test mass

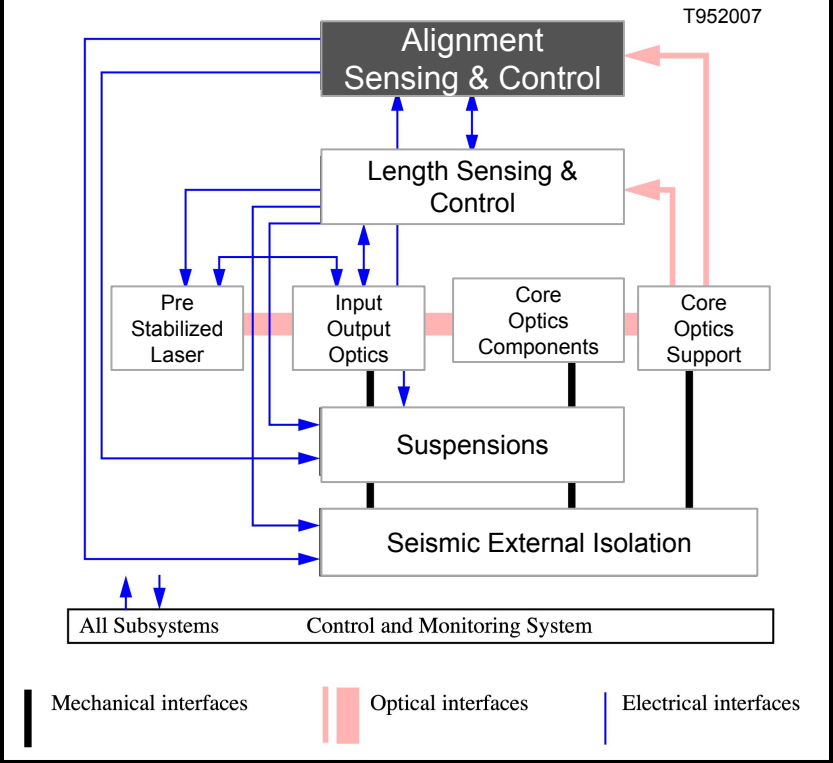


Reality



P.C. Jenne Driggers

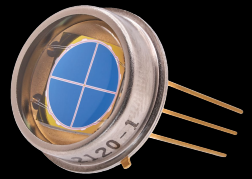
Alignment Sensing & Control (ASC)



Any hardware and/or algorithms used for

- Determination of initial interferometer optical axes
- Initial alignment of input-output optics and suspended core-optics
- Determination and control of beam position on the suspended core-optics

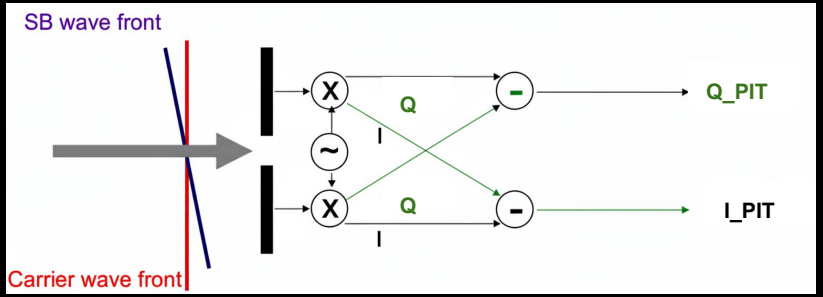
ASC Sensors : QPD & WFS



Quadrant Photodiode

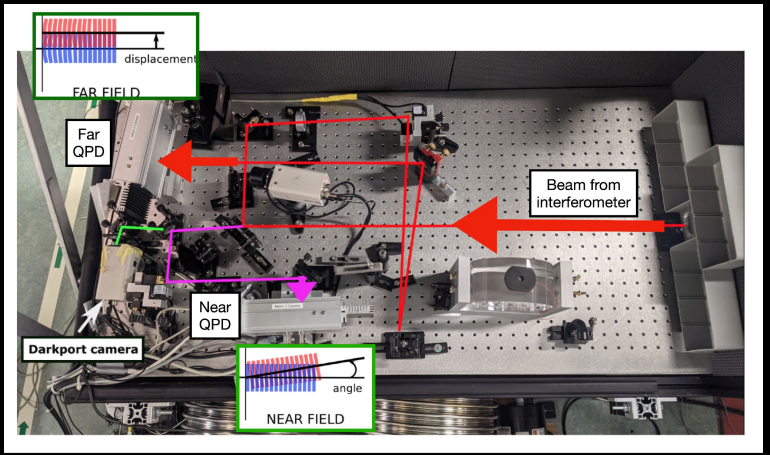
Gives info about the beam position of the QPD (good for pointing/drift control)

Pitch = (top-bottom)/sum
Yaw = (left-right)/sum

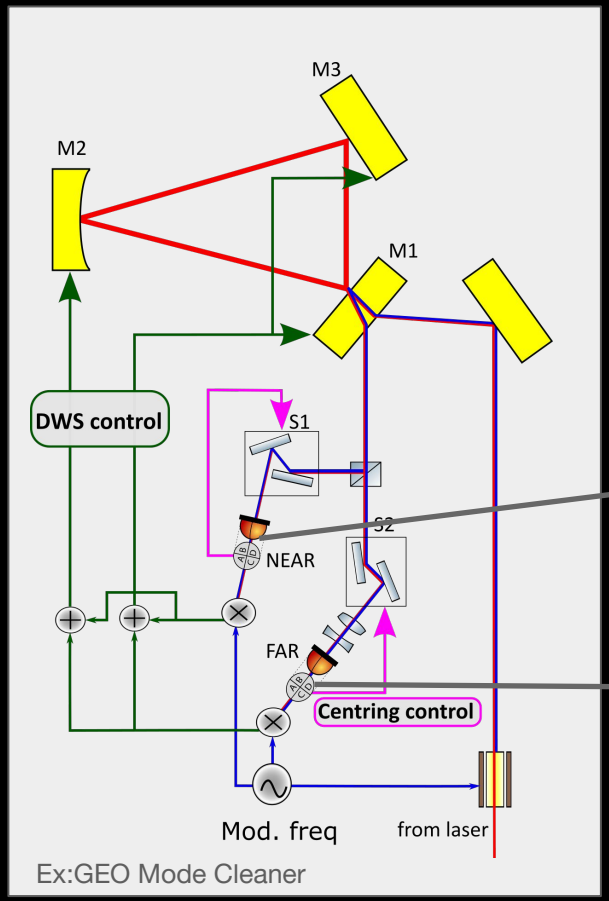


Wave Front Sensor

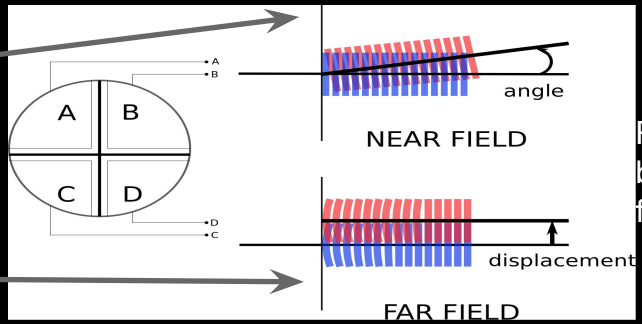
- Relative alignment info btw two laser fields at two frequencies (carrier & sideband)
- Each sensor head is a Radio Freq QPD
- Each quadrants get demodulated by Cos & Sin (I & Q)
- 8 initial signals combined to 4 (Pitch/Yaw, I/Q) per WFS



Differential Wavefront Sensing (DWS)



- Mark the incident field to a cavity with a reference frequency, which is promptly reflected
- Demodulate the "near" and "far" quadrant photodetector signals at the reference frequency



Relative Gouy phase between the near and far QPD is 90°

- DWS can sense four misalignments in total (horizontal, vertical) x (angle, displacement)

Hard and Soft Modes

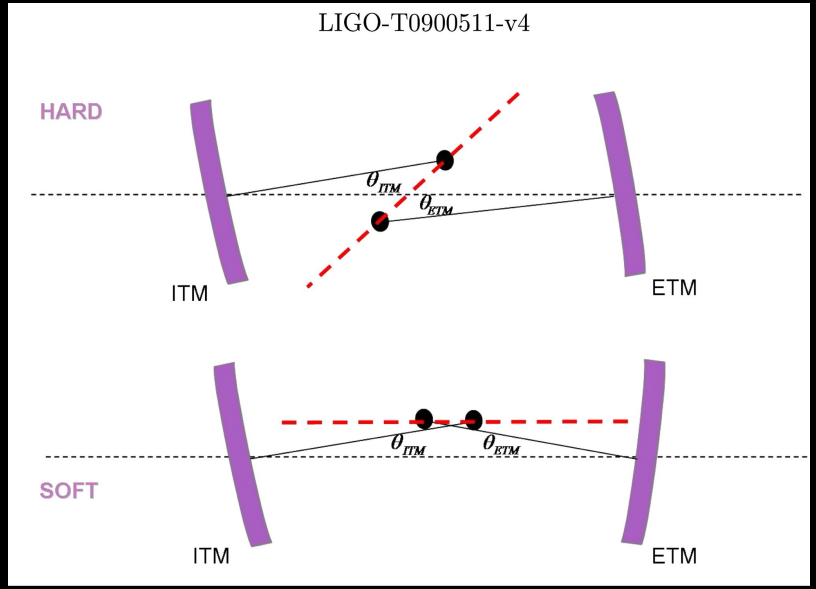
- At high power, radiation pressure from the laser couples to the cavity mirrors

- Laser acts like a rotatory spring along pitch (yaw) axis

$$\vec{\tau}_{\mathrm{opt}} = \begin{bmatrix} T_i \\ T_e \end{bmatrix} = \mathbf{K}_{\mathrm{opt}} \begin{bmatrix} \theta_i \\ \theta_e \end{bmatrix}$$

$$\mathbf{S}^{-1} \begin{bmatrix} k_{\mathrm{soft}} & 0 \\ 0 & k_{\mathrm{hard}} \end{bmatrix} \mathbf{S} = \mathbf{K}_{\mathrm{opt}}$$

- Hard (soft) modes have higher (lower) frequency than individual suspensions

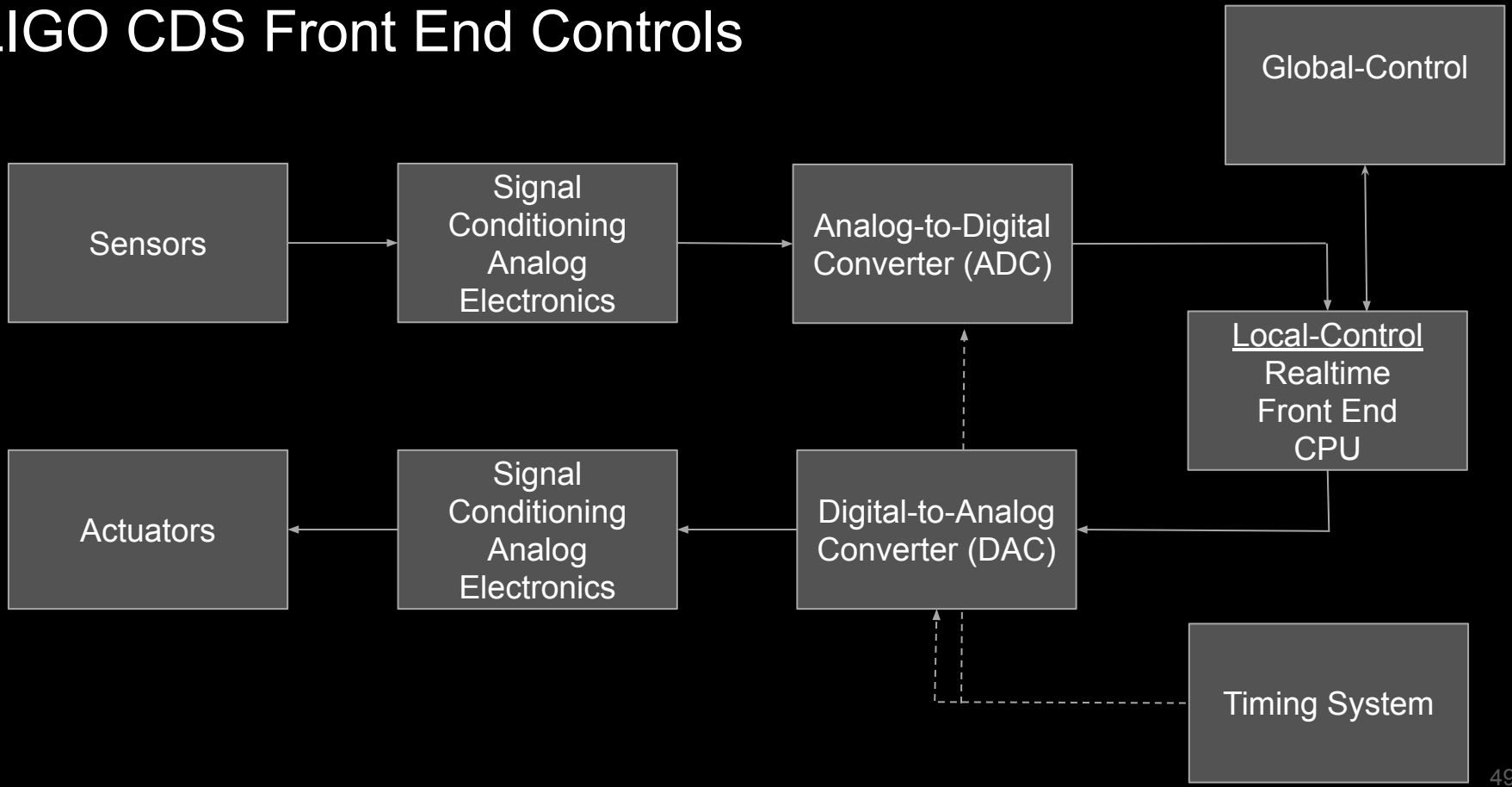


- Hard mode -> higher g-factor->higher sensitivity -> damped at higher bandwidth using ETMs

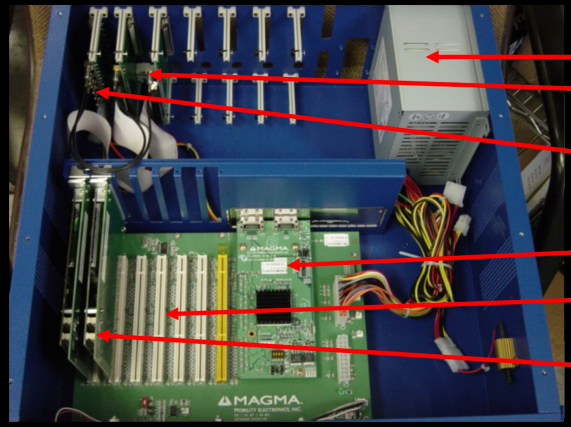
- Soft mode -> lower g-factor->higher sensitivity -> damped at lower bandwidth using ITMs

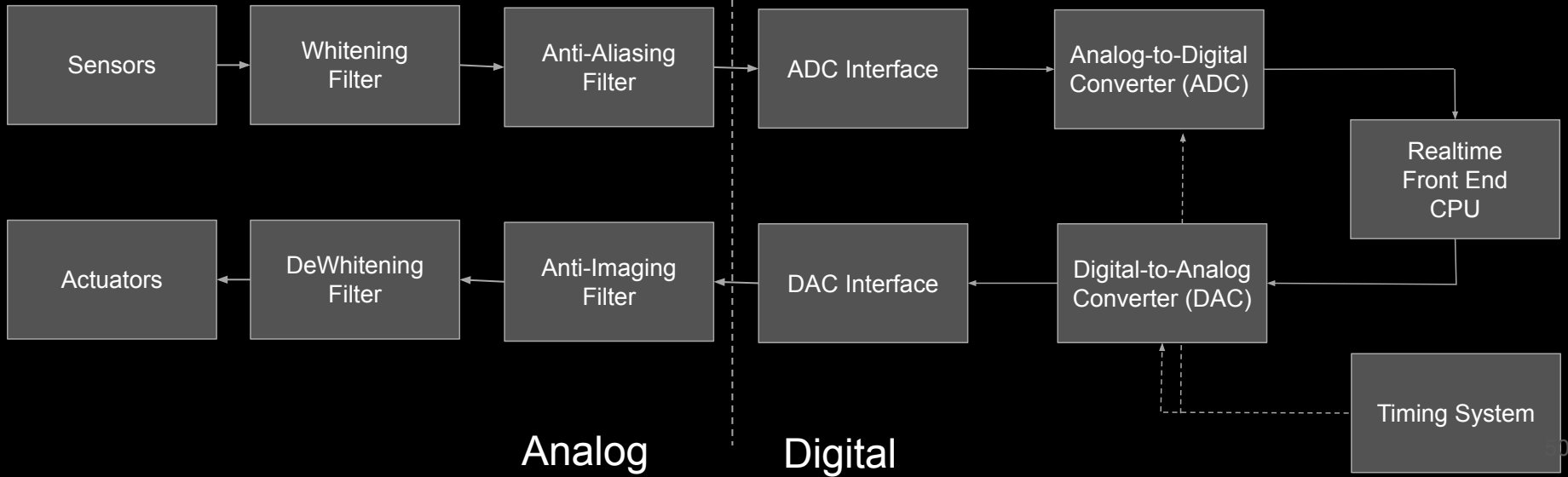
Controls & Data Systems (CDS)

LIGO CDS Front End Controls



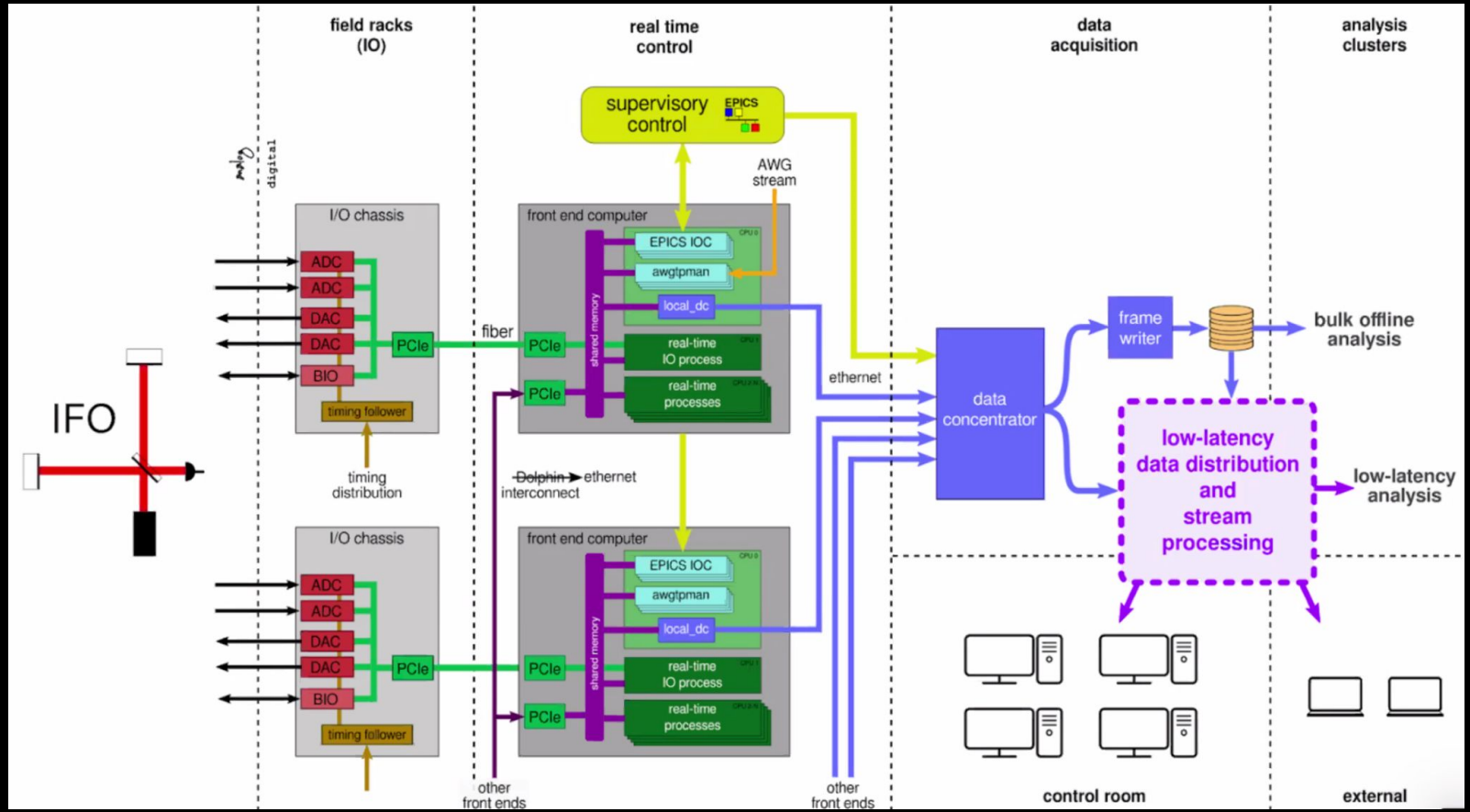
LIGO CDS Front End Controls





LIGO CDS Front End Controls

Jamie Rollins



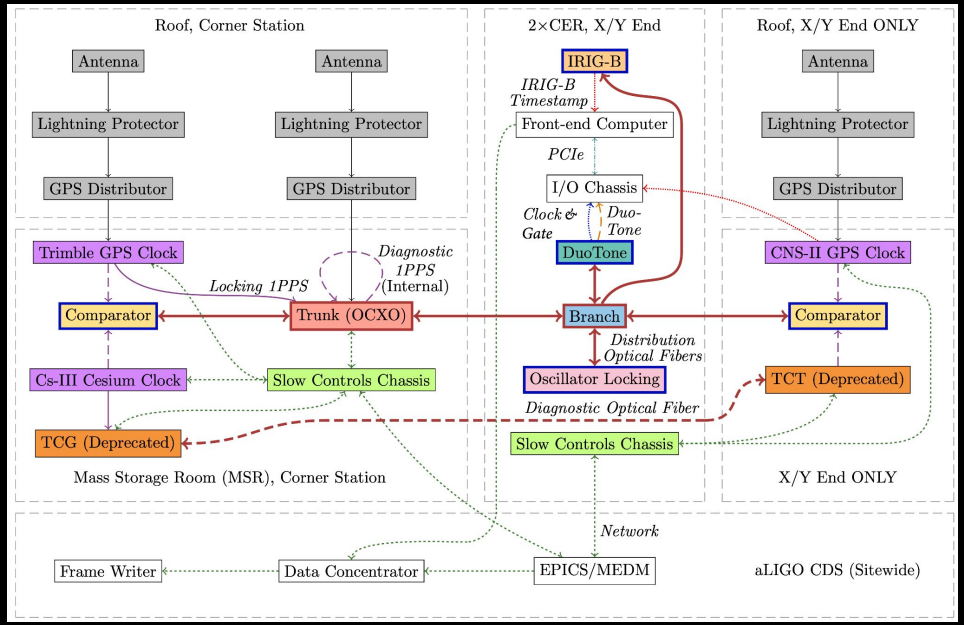
Advanced LIGO Timing System

Needed for

- Coherent GW detection
- Source localization
- Skymap creation
- Realtime controls
- RF signal sampling (digital demodulation)

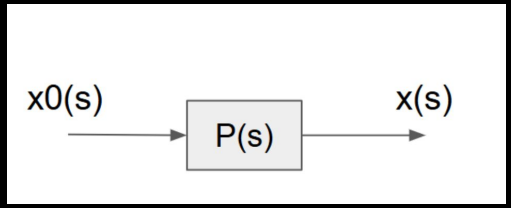
The Advanced LIGO Timing System is required to provide timing information with uncertainty below $1\mu s$

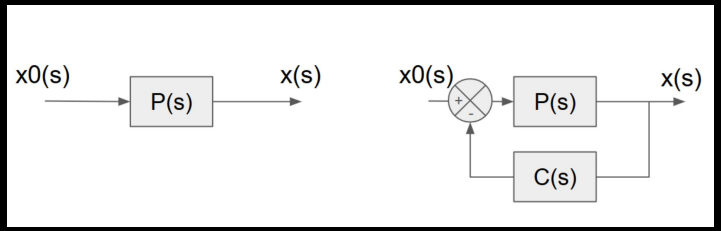
Synced to Coordinated Universal Time (UTC) from GPS satellite system, which has a nominal accuracy of ~O(100ns)



ArXiv: 2304.01188

Control Loops





How a GW interferometer listens to GWs…

Seismic Noise

Acoustic Noise

Feedback Actuator

Coil Magnets

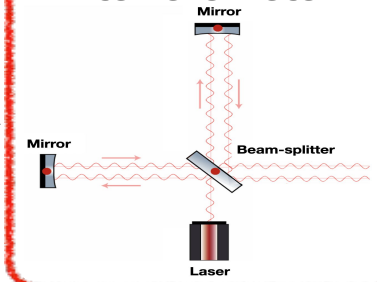
Electrostatic Drive

Actuator Noise

Calibration Lines

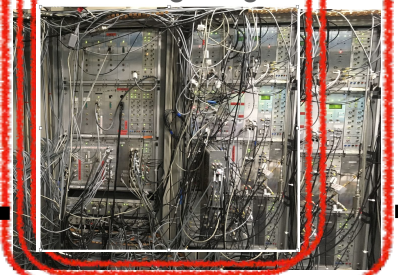
Data Storage

Interferometer



"High frequency sensing
Low frequency actuation"

Servo Controller
Analog + Digital

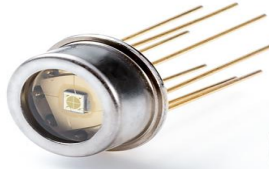


Low Pass

Readout Noise
Photon Shot Noise

Scattered light

Photodiode Readout
Low Noise Electronics

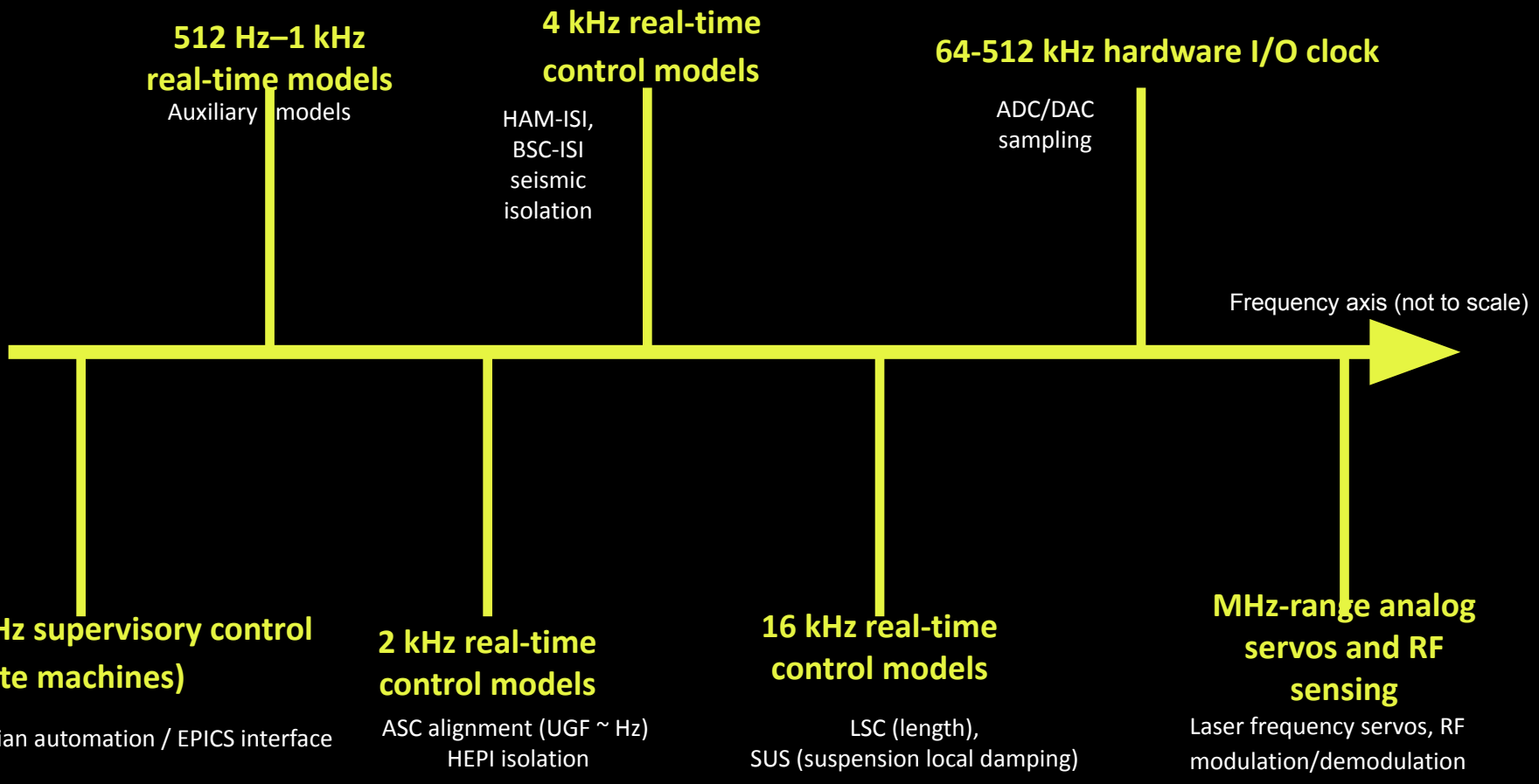


Data Storage

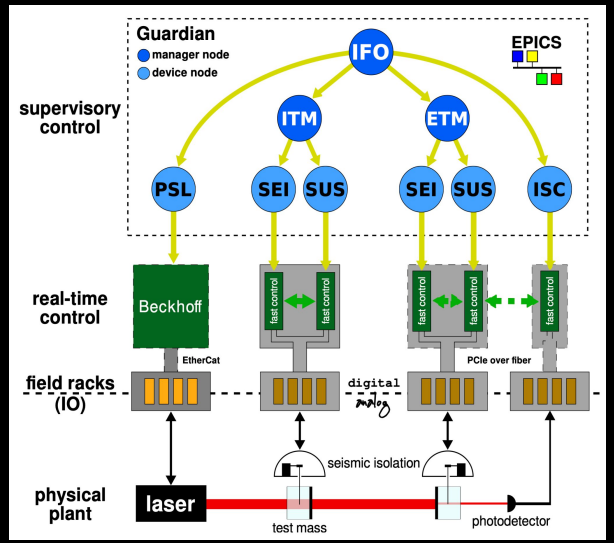
Controller Noise

Control Frequency Hierarchy

Model rate = digital controller execution rate
UGF = closed-loop control bandwidth



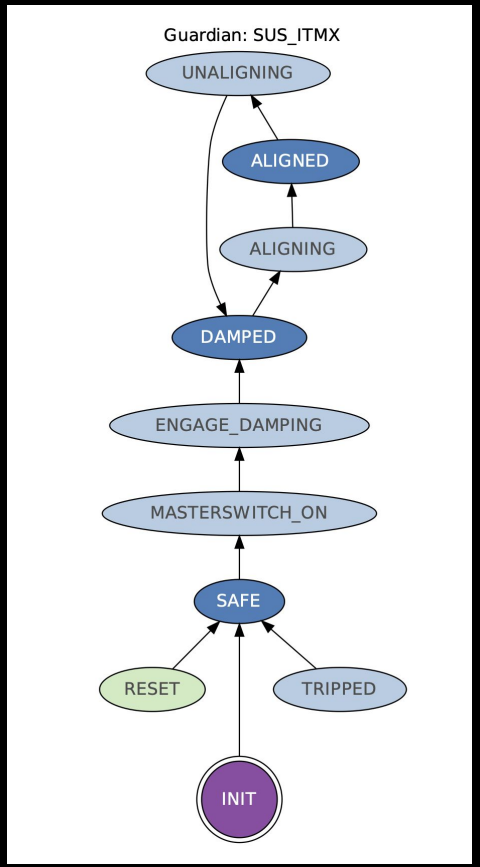
GUARDIAN: Hierarchical State Machine



ArXiv: 1604.01456v1

Manages the global state of the interferometer by coordinating subsystem states

Each node loads a directed state graph: states are executable code blocks; edges define allowed transitions.



Control Loop Bands in Advanced LIGO

MHz range (analog):

PSL and IMC frequency-stabilization loops; PDH servos.
Unity-gain bandwidth roughly 0.8–1 MHz for laser-frequency loops.
RF phase modulation and demodulation at approximately 10–50 MHz.

64 kHz hardware clock:

ADC and DAC timing; front-end I/O processors.

16 kHz fast digital models:

LSC : global longitudinal control (DARM, CARM, etc.). LSC model runs at 16 kHz.
Core suspension (SUS) models : QUAD suspension local damping and actuator interface.
DARM servo unity-gain typically 40–100 Hz.

4 kHz band:

HAM-ISI and BSC-ISI in-vacuum seismic-isolation controllers. Sensor inputs are digitized at 64 kHz then decimated to 4 kHz.

2 kHz band:

HEPI external seismic-isolation platforms.
Many ASC and angular-control front-end models run at 2 kHz or 4 kHz; typical alignment loop unity-gain around 1–3 Hz.

512 Hz–1 kHz band:

Various other fast digital models (thermal-compensation systems, auxiliary controls), depending on site and configuration.

16 Hz slow control:

Guardian automation state machines for lock acquisition and recovery.
EPICS “slow” operator-monitoring channels.

https://gwosc.org/detector_status/

GWOSC Calendar Today Yesterday O4 summary Previous Observing Runs

Gravitational-Wave Observatory Status

Please select a date from the calendar above to see archived or current status.

Information is available for dates after November 30, 2016. The Advanced LIGO and Virgo detectors have begun the third part of the fourth observing run, known as O4c, as of January 28, 2024. The entry of the KAGRA detector into O4c has been postponed in order to continue detector commissioning activities and further increase the sensitivity of the detector. All detectors are planned to rejoin O4 by the end of the run. Summaries of the current observing run and previous observing runs a the menu above. For overviews of LIGO, Virgo, and KAGRA observing runs, see the arXiv:1304.0670.

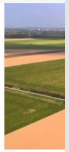
- **Today's Summary Page**
- Current Status (GWISTAT)
- LIGO/Virgo Alerts (GraceDB)
- Hanford alog – Livingston alog – Virgo logbook – KAGRA klog
- LIGO Laboratory – Virgo – KAGRA Observatory – GEO600

LIGO Hanford

LIGO Livingston

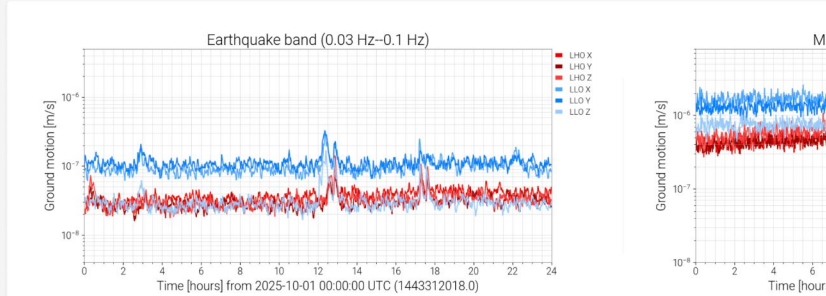
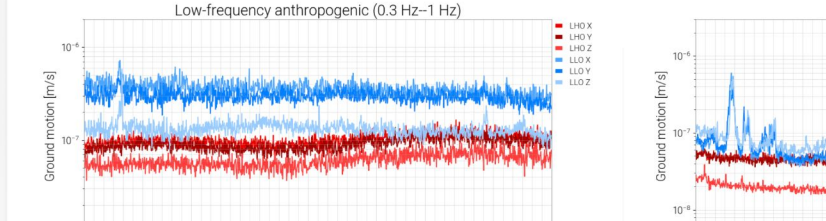
Virgo

KAGRA


GEO600

https://gwosc.org/detector_status/day/20251001/environment/ground_motion/

« October 1 2025 » Home Summary Environment Instrument performance

Environment : Ground motion

These plots display the ground motion at the LIGO Livingston and LIGO Hanford Observatories as measured by Streckeisen STS-2 s
Each plot shows the root-mean-square ground motion in a different frequency band, which capture independent ground motion beha