Commissioning Pedagogy

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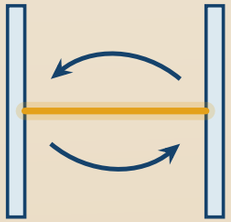
LIGO-INDIA · 5 DAYS · IUCAA

Everything is a feedback loop.

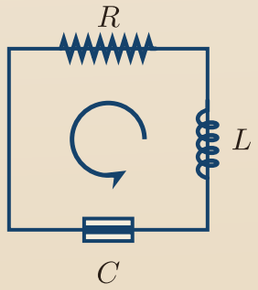
The one idea

Everything is a **feedback loop.**



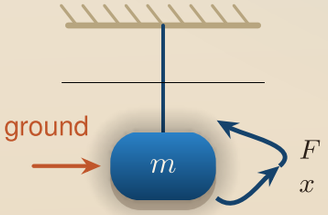
cavity

light re-enters itself



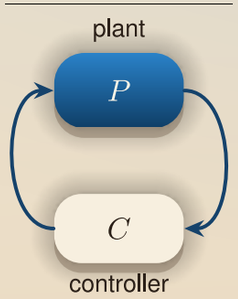
circuit

current re-enters itself



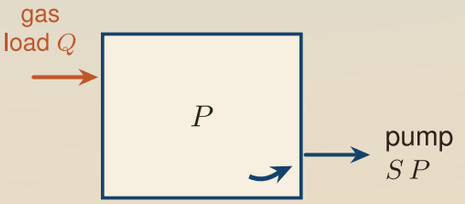
suspension

force sets x, x sets force



control system

the loop you draw on purpose



vacuum

settles where $S\,P = Q$

The same feedback structure in five different systems. Commissioning is populating, closing, and budgeting these loops.

Loops all the way down

DARM — the gravitational-wave readout loop

the interferometer **is** this one loop: differential arm length, sensed at the dark port, fed back to the test masses

its plant is four more length loops, running in parallel

- **CARM** — common arm length
- **MICH** — Michelson
- **PRCL** — power recycling
- **SRCL** — signal recycling

. . . and the plant of every one of those is built from loops

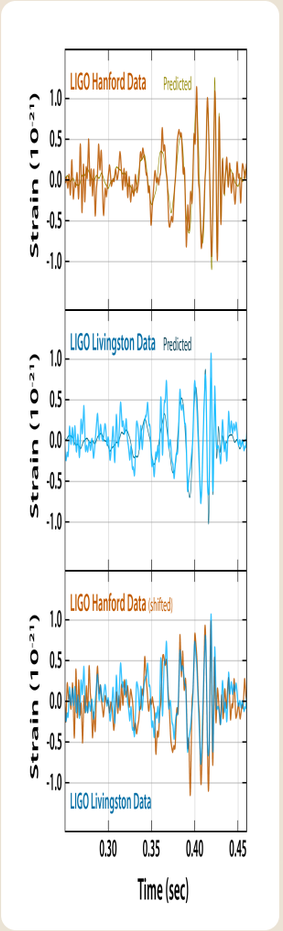
- **PRC** — optical
- **SRC** — optical
- **arm cavities** — optical
- **SUS** — suspension damping
- **ISI** — seismic isolation

every box on this slide is itself a closed feedback loop

What it’s for

Two black holes merge a billion light-years away and ring spacetime. A well-commissioned detector turns that ripple into **this** →

GW150914 — the first detection. Everything this week serves one goal: a detector quiet enough to hear the next one.



What you will do this week

01

Tune up damping

Knock down high-Q suspension resonances — and keep the loop stable.

02

Understand ISC-loop noise

Read where a sensor's noise enters and what it costs you.

03

Design control loops

Gain, phase, stability, loop shaping.

04

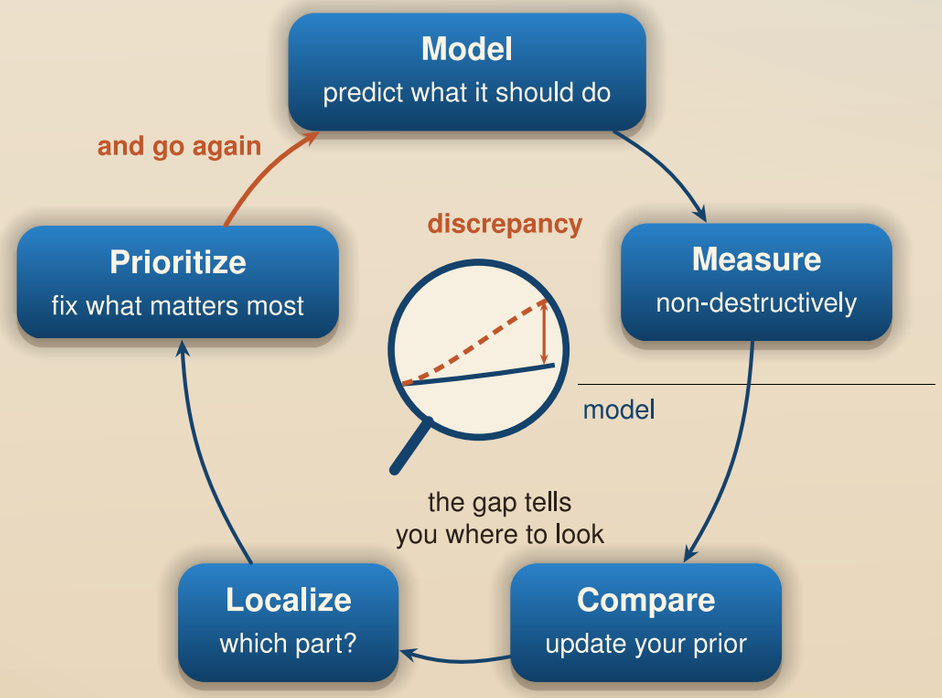
Build noise budgets

Enumerate, propagate through S/T, sum, find the limiting term.

Four operations on one feedback loop: **damp** it · **design** it · **account for** its noise · **budget** it.

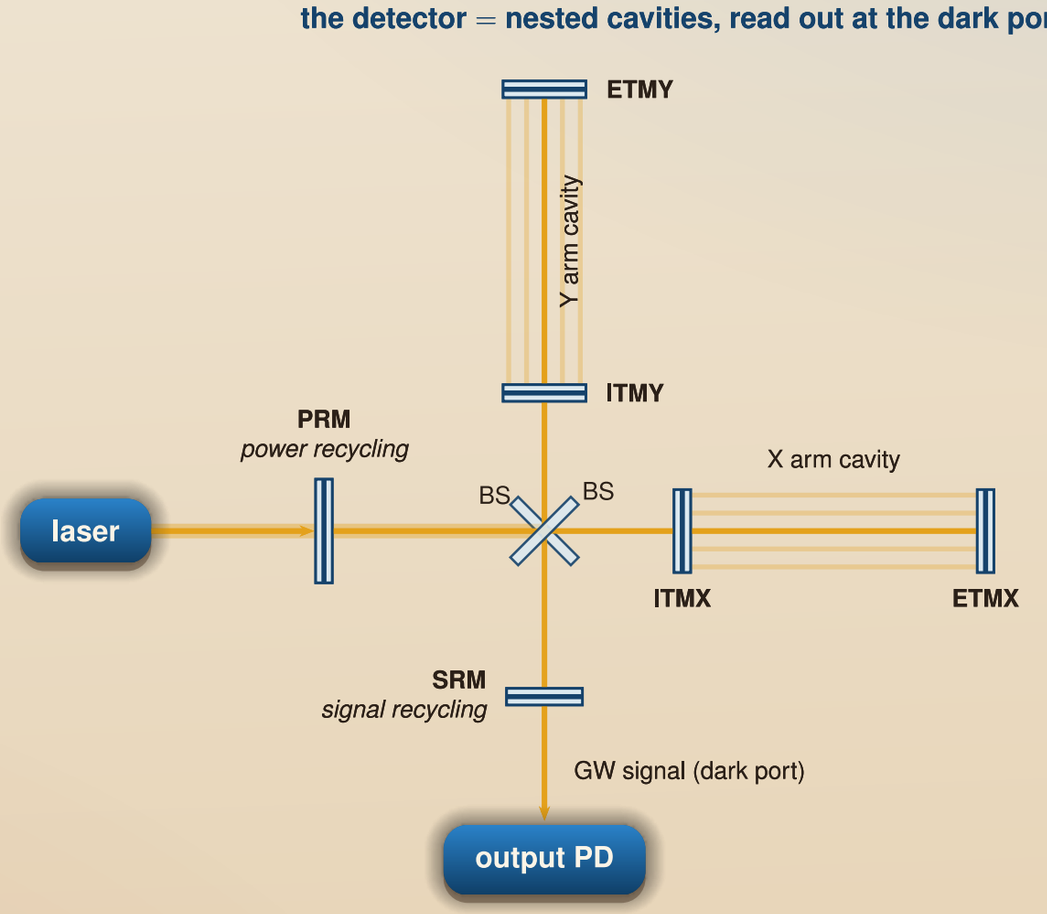
The commissioning method

the method: model → measure → compare → localize → prioritize → repeat



The whole toolkit serves this cycle: the **adjacency matrix** is the model, S/T is the non-destructive measurement, the **noise budget** is the triage.

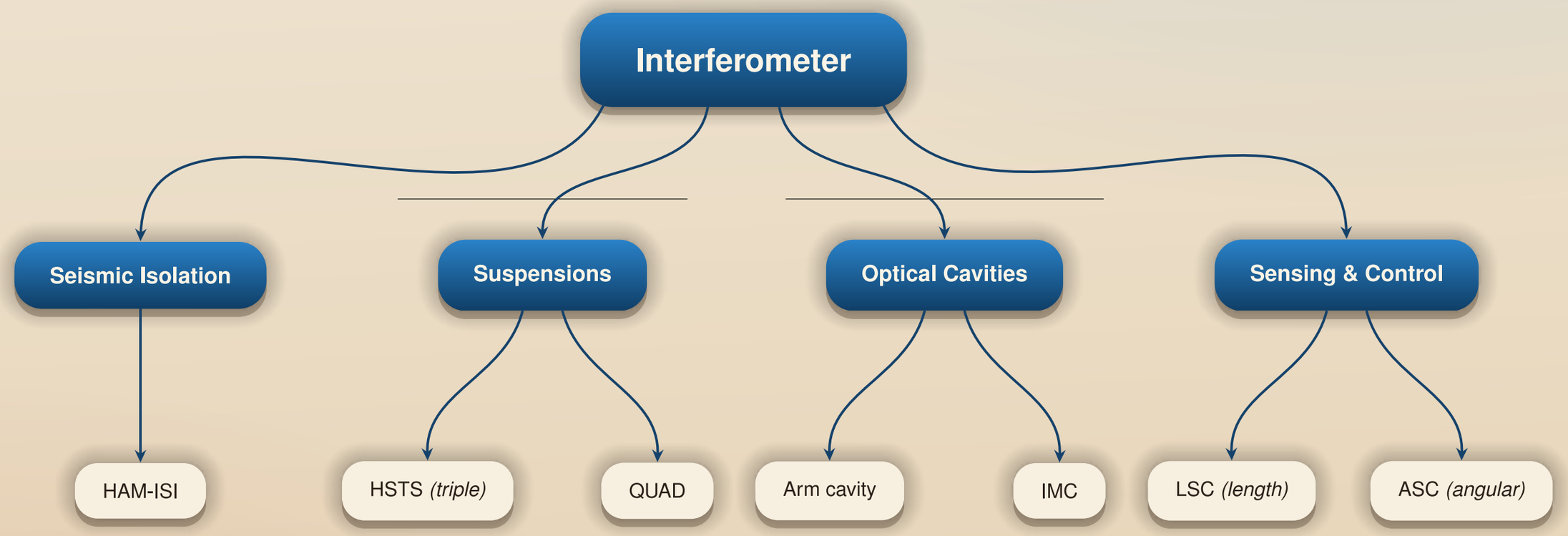
What’s wrong with this diagram?



The **beamsplitter** was at the wrong angle. Rotated 90°, it splits the laser into *both* arms and sends the recombined signal to the dark port.

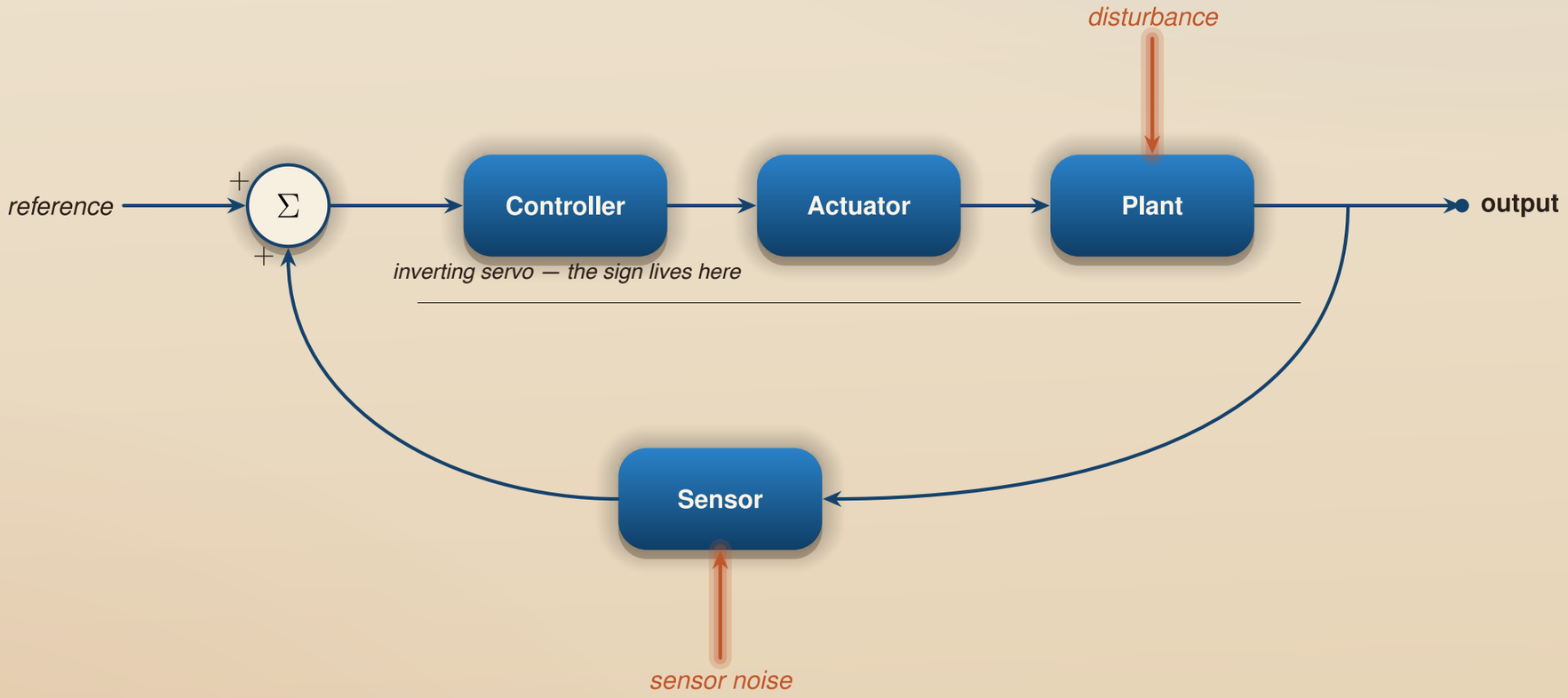
It decomposes

The detector is not a monolith. It is a hierarchy you can hold in your head.



And it repeats

Every sub-system is the **same loop** — plant · sensor · controller · actuator, with noise coming in. Only the plant, sensor, and actuator change.



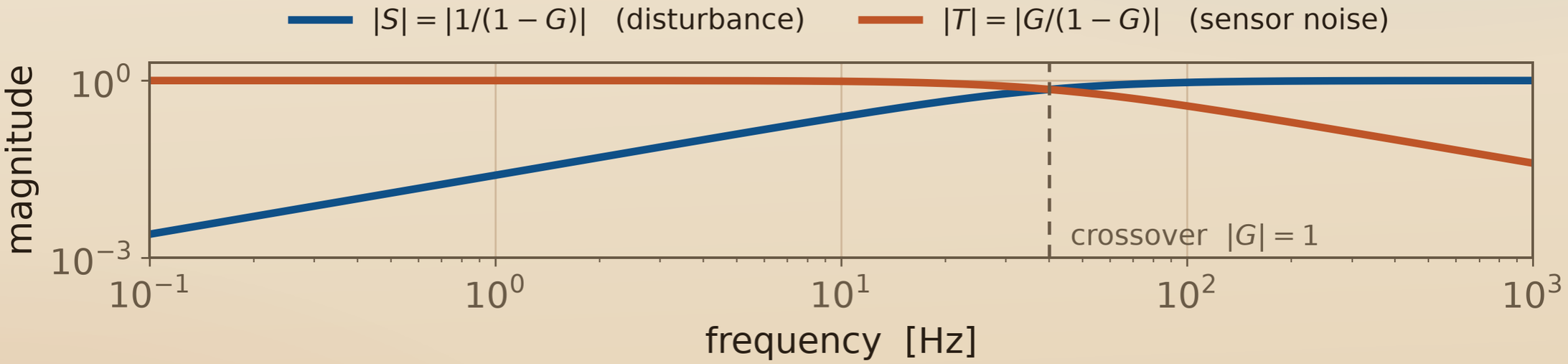
One loop, two inputs

$$x = \underbrace{S}_{\text{on disturbance}} d + \underbrace{T}_{\text{on sensor noise}} n$$

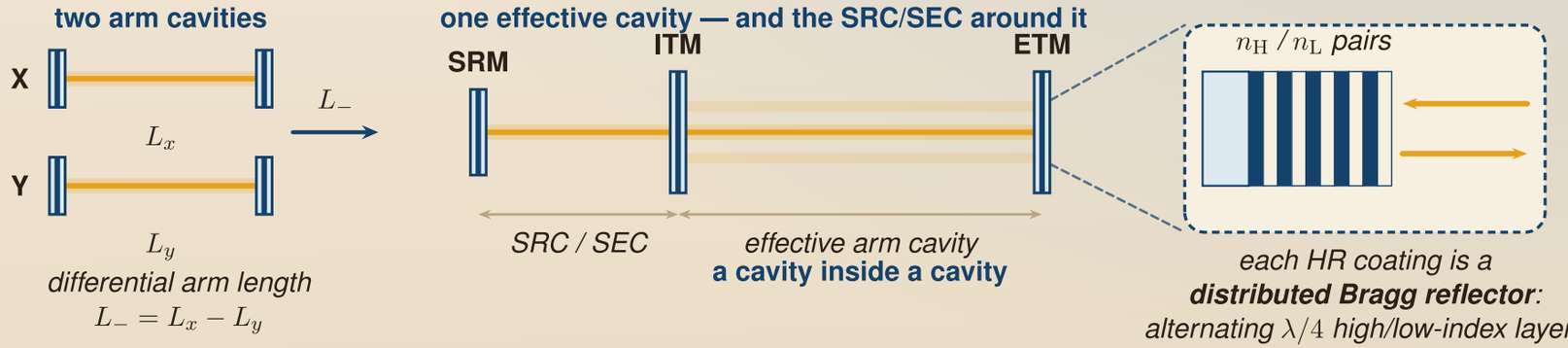
One loop, two inputs

$$x = S\,d + T\,n, \qquad S = \frac{1}{1-G}, \qquad T = \frac{G}{1-G}$$

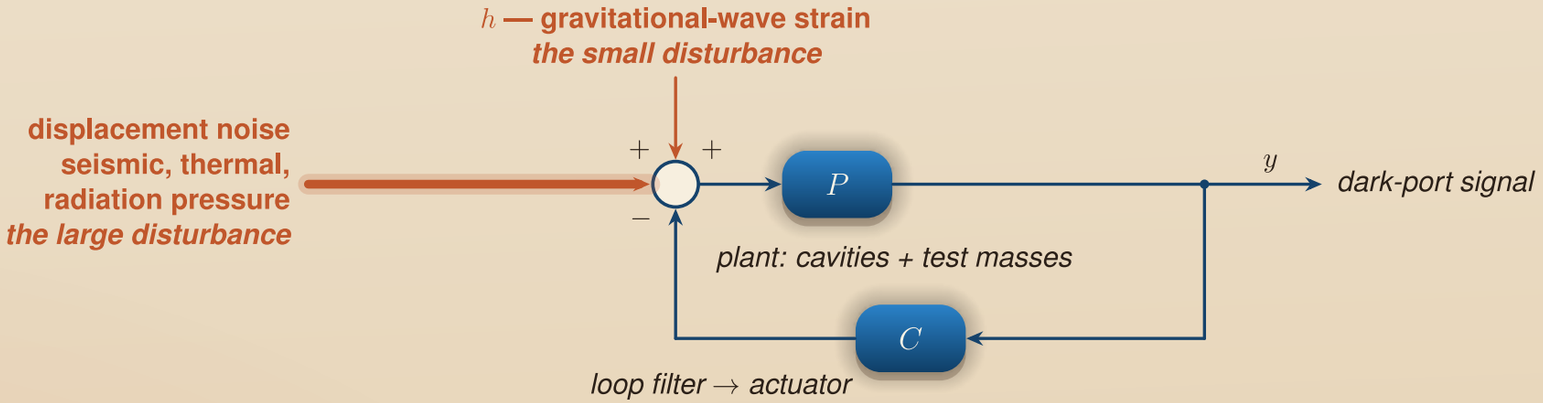
The mirror motion x is the disturbance d filtered by S, plus the sensor noise n filtered by T. Push S down where you fight the world; you pay in T where the sensor is noisy.



DARM — the loop the wave arrives on



the gravitational wave enters this loop as a *disturbance* — nearly, but not quite, like a mirror displacement

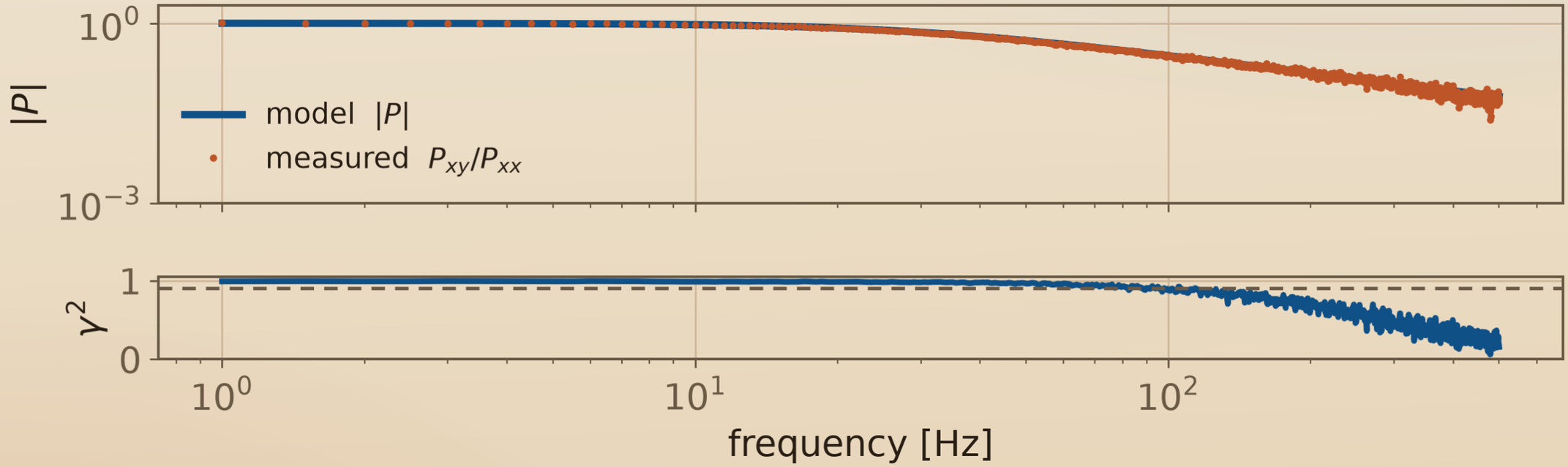


detecting a gravitational wave is sensing a *small* disturbance in the presence of a *large* one — at the same port

Coating design: Venugopalan, Salces-Cárcoba, Arai & Adhikari, *Opt. Express* **32**, 11751 (2024). · Displacement-noise-free: Gefen, Tarafder, Adhikari & Chen, *Phys. Rev. Lett.* **132**, 020801 (2024).

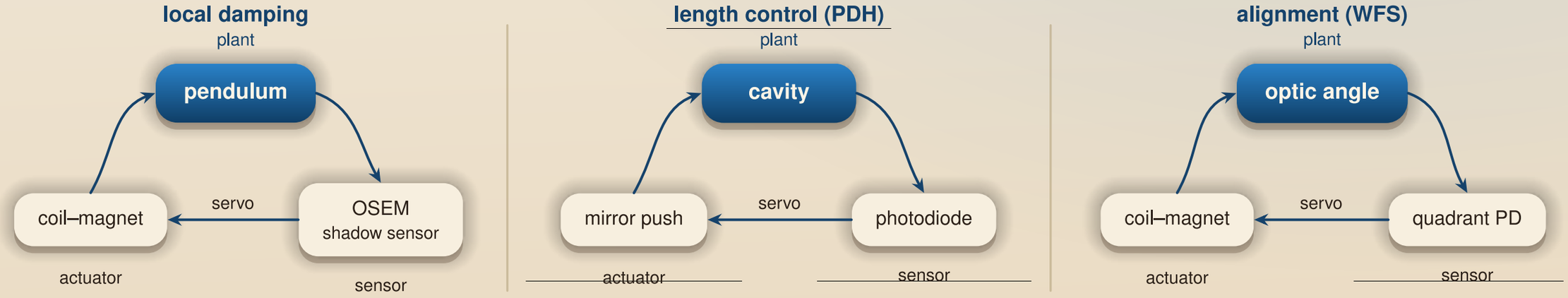
System identification (M1)

Nobody hands you the transfer function of the hardware. You **measure** it: drive an input, record the output, and estimate $H(f)$ — this is **system identification**, and you do it before you touch anything. There are several methods (swept sine, broadband noise + CSD, chirps, and more); the one thing they share is a **trust metric**, the coherence γ^2 — near 1, believe the point.



The measured $|P|$ tracks the model until the plant rolls off; then readout noise wins and the **coherence drops there first**. This is “measure gently” — build it in M1, reuse it all week.

Same loop, different hardware



every subsystem is the *same* feedback loop — only the hardware changes

Same loop, three physical systems — suspension + OSEM + coil · cavity + PDH + mirror · optic + WFS + coil. Each is plant · sensor · actuator.

One loop, three physical systems

	Suspension damping	Cavity lock	Alignment (ASC)
Plant	pendulum	optical cavity	optic angle
Sensor	OSEM	PDH photodiode	WFS / QPD
Actuator	coil	mirror / PZT	coil
Controller	damping filter	length servo	ASC servo
Noise in	OSEM readout	shot noise	WFS shot noise

One loop structure; only the plant, sensor and actuator change. The week fills in one column per day.

How the pre-work feeds the week