Building a Detector

Build-a-Detector Workshop
University of Glasgow – LIGO India Partnership
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Thanks to…

- The many colleagues from whom I have borrowed slides
- The LIGO Lab – MIT, Caltech, Hanford and Livingston Observatories
- The LIGO Scientific Collaboration; Virgo and KAGRA; Cosmic Explorer
- The US National Science Foundation for extraordinary support and perseverance for LIGO

References

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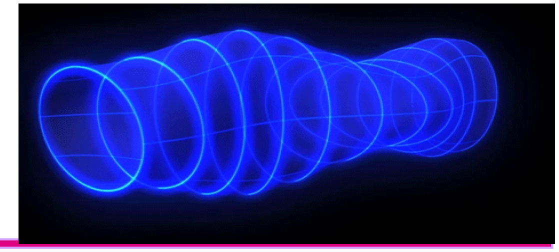
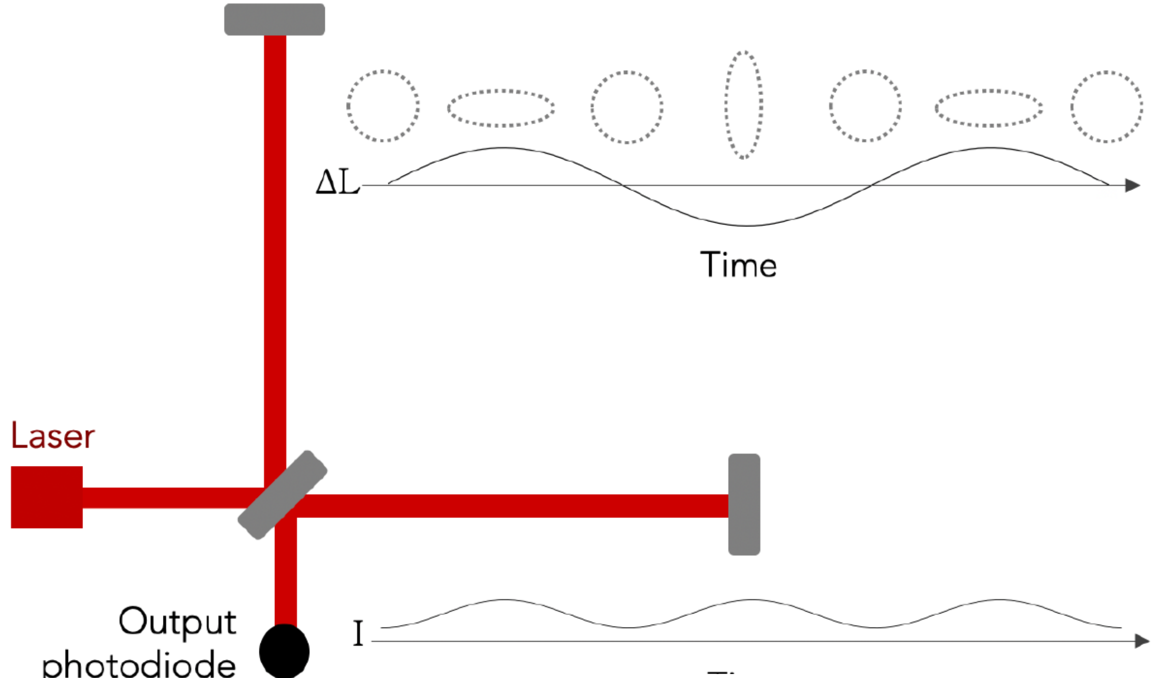
Scope

- Already heard of the ‘fundamental’ noise sources
- **This talk:**
  - **Detector design overview**
  - **A couple of additional limits to sensitivity**
  - **System engineering to move from theory to practice**
- Coming soon:
  - Jamie Rollins: pygwinc, a software tool to show graphically the sensitivity of a GW detector design
- Kevin Kuns:
  - examples of how to actually implement design choices in pygwinc
  - how you can use them to actually make the design choices and what some of the constraints on those choices are

What is our measurement technique?

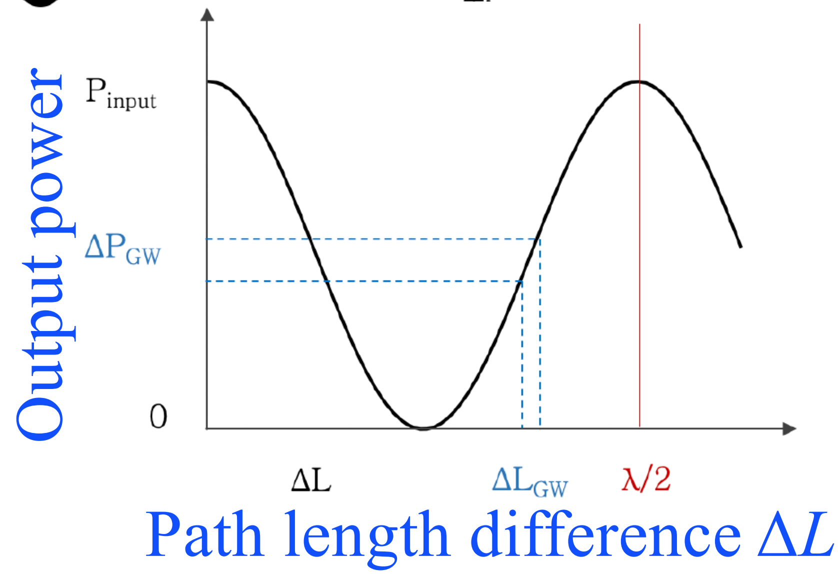


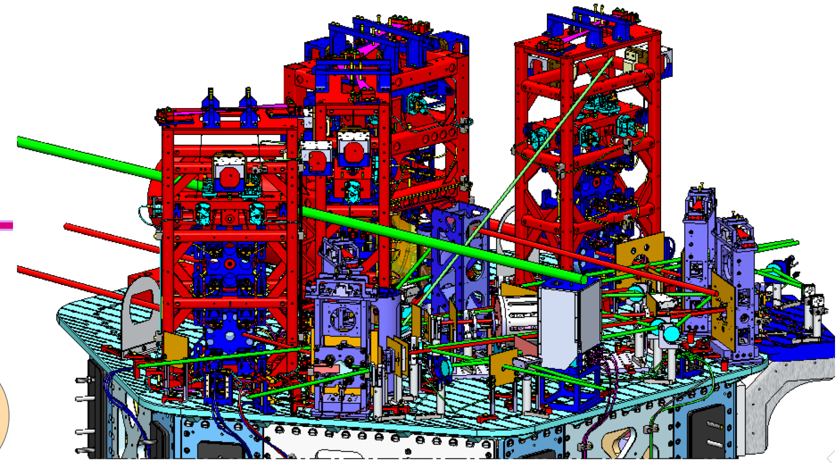
- Enhanced **Michelson interferometers**
- GWs modulate the distance between the end test mass optic and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude

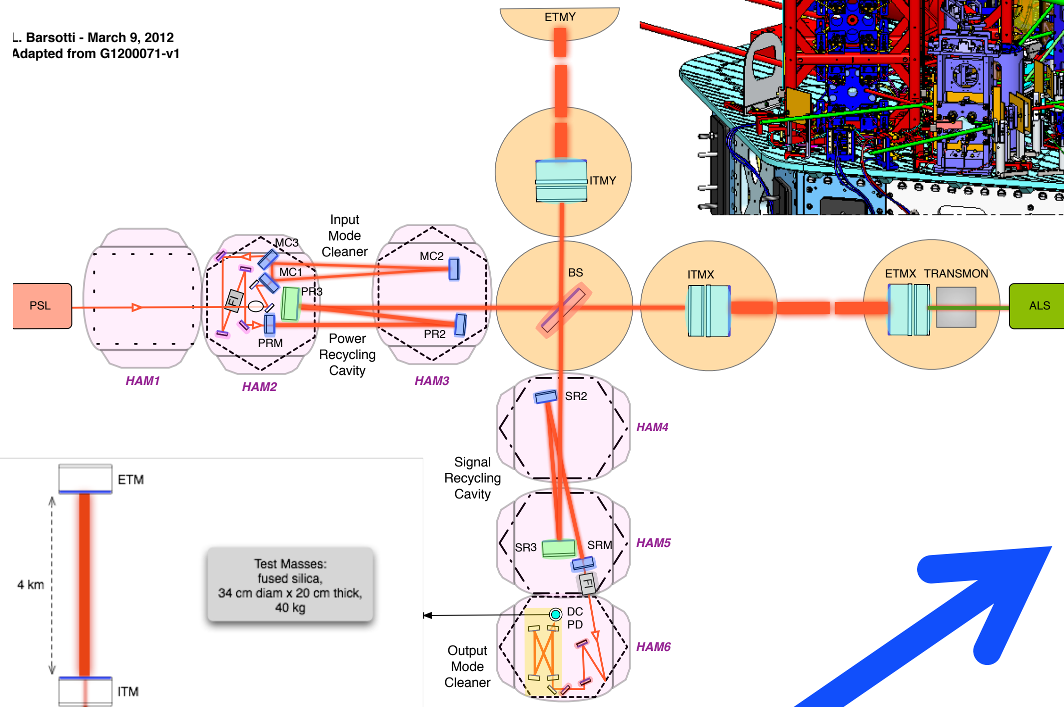


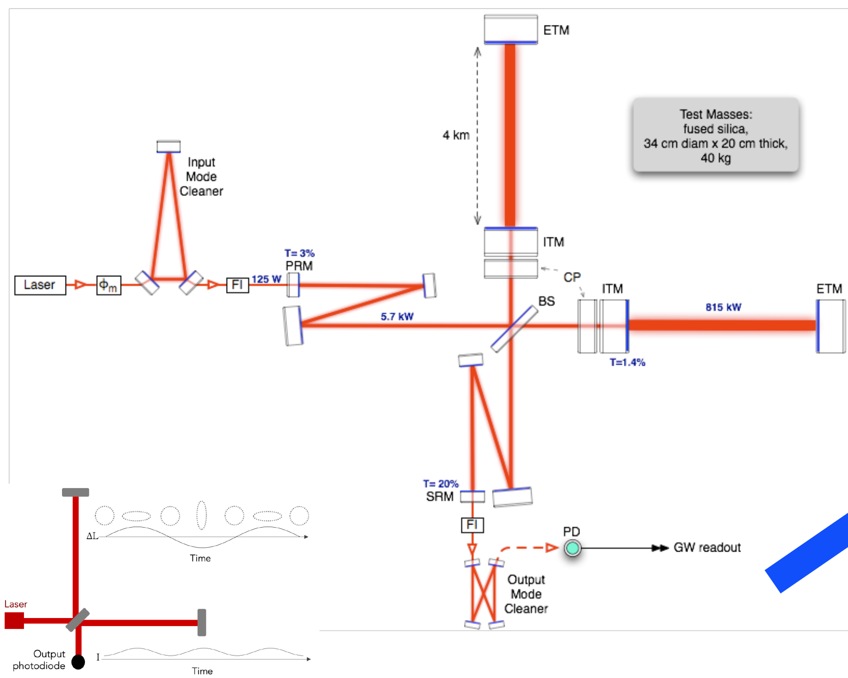
- For a given strain $h = \Delta L/L$,

$$\Delta P_{\mathrm{GW}} \sim hLP_{\mathrm{laser}}/\lambda_{\mathrm{laser}}$$









Reality axis

The real instrument is far more complex than a simple Michelson…

Useful paradigm in considering limits to detector sensitivity

- **Ability to measure** the position of our test mass
  - **Quantum noise**
  - Scattered light
  - Laser light defects – intensity, position, mode shape, frequency noise
  - Laser path noise fluctuations, apparent or real
  - Electronics noise

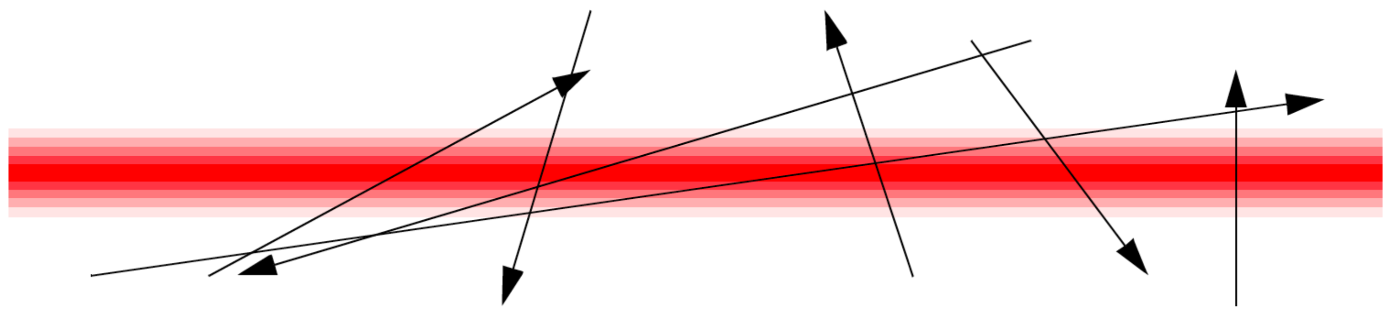
- **True noise motions** of the reference surface on our 'free test mass' which can mask GWs
  - **Thermal noise**
  - Radiation pressure
  - Environmental mechanical forces – seismic, anthropogenic, weather
  - Stray electric, magnetic fields
  - Accidental noise forces from our control systems and sensors

In the school so far…

- An in-depth review of the ‘fundamental’ noise sources:
  - » Quantum noise, and interferometer topologies; squeezing
  - » Thermal noise, and low-mechanical-loss construction methods
  - » Coating Brownian noise, choice of materials, coating processes
  - » Newtonian noise – environment around test masses; sensing
  - » Seismic noise – active and passive attenuation
- I’ll now add to that a couple of others:
  - » Path-length fluctuations due to residual gas in arms
  - » Scattered light
  - » Taxpayer noise

Vacuum System

- The 3 or 4km (or 15 or 40km…) path of the laser from beam splitter to end mirror must be in an excellent vacuum

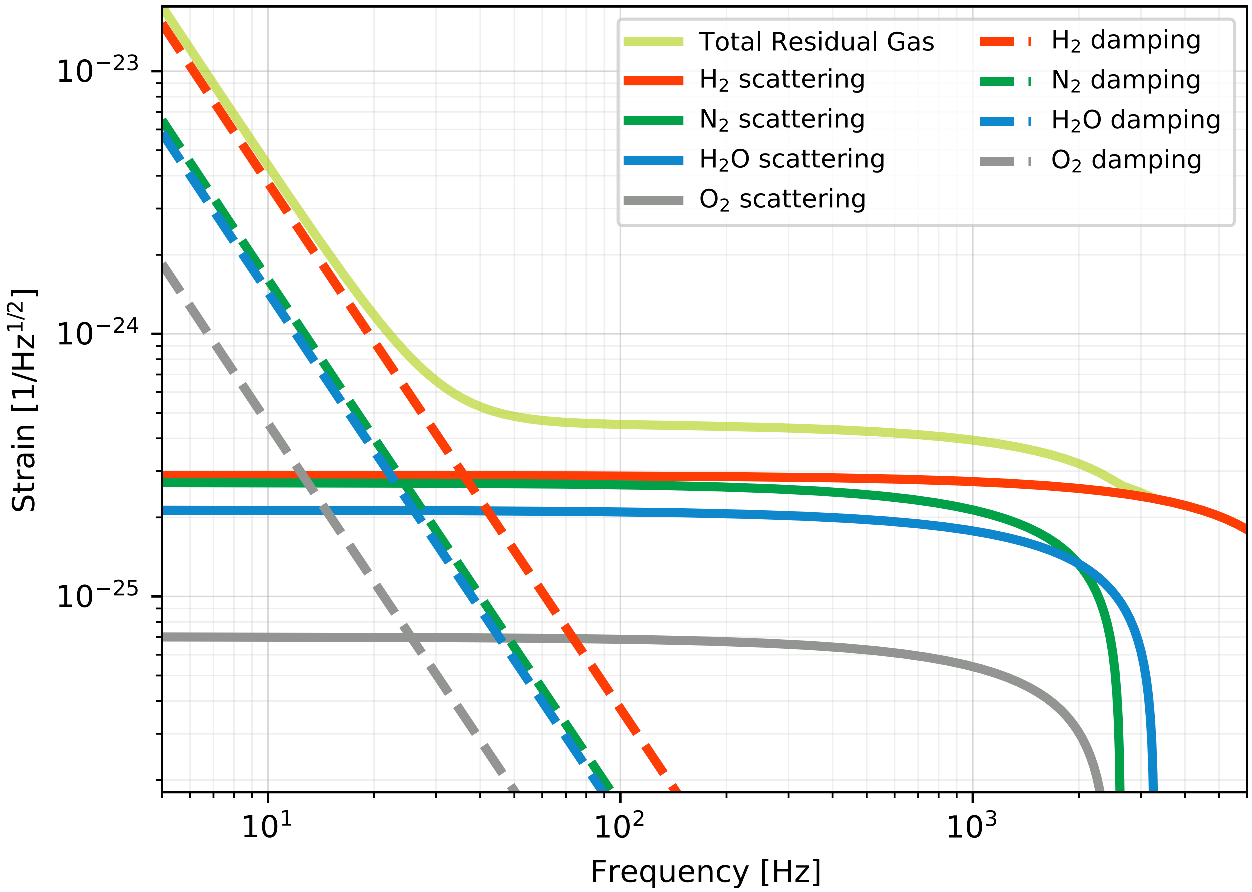


- Polarizability α of the remaining gas molecules induces path-length fluctuations; Poisson Statistics, and an effect proportional to square root of density $\rho^{1/2}$ along the path

$$h(f) \approx 4\pi\alpha\left(\frac{2\rho}{v_0 w_0 L}\right)^{\frac{1}{2}}$$

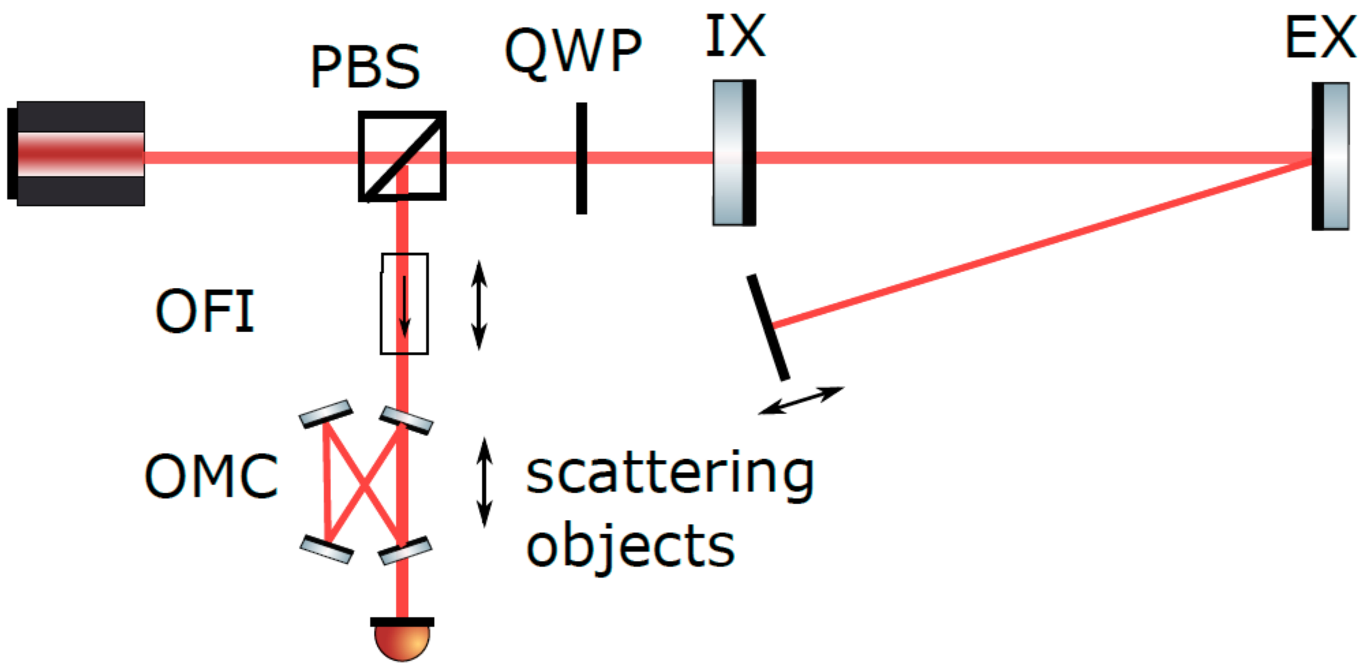
Residual gas: path-length fluctuations, pendulum damping

- Pygwinc model for residual gas, for
  - The path length fluctuations for gas along the n*km path
  - Pendulum suspension thermal noise due to transfer of momentum to/from gas molecules from/to test mass



Scattered light

- Light scattered out of the main beam by a defect on e.g., a mirror
- …to a moving object like baffles or chamber walls
- …and back into the main beam (via the same or a different defect)



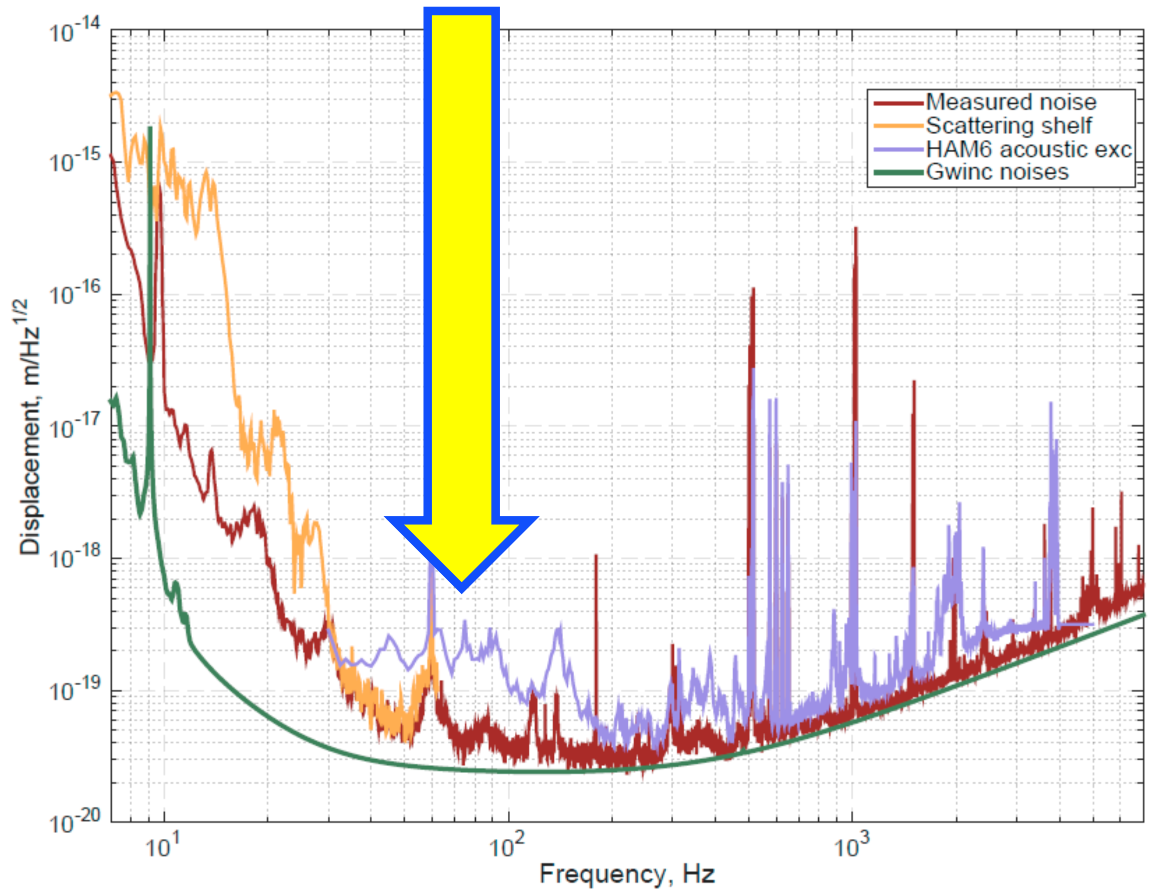
- Scattered light noise is seen in the frequency range 10-200 Hz.
- Significant noise source, difficult to track down and mitigate
  - » …reduction in motion (isolation) of chambers, or better baffling

REF: Denis Martynov thesis: https://dcc.ligo.org/DocDB/0119/P1500087/001/DenisMartynovThesis.pdf

Finding coupling to scattered light

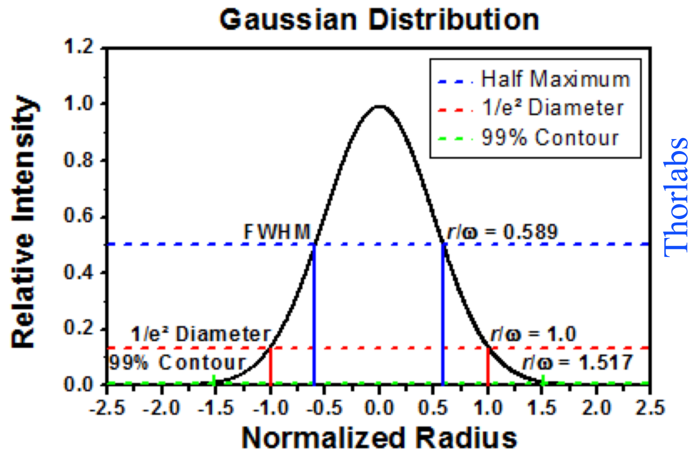
How do we determine that at least some of the excess noise is related to scattering?

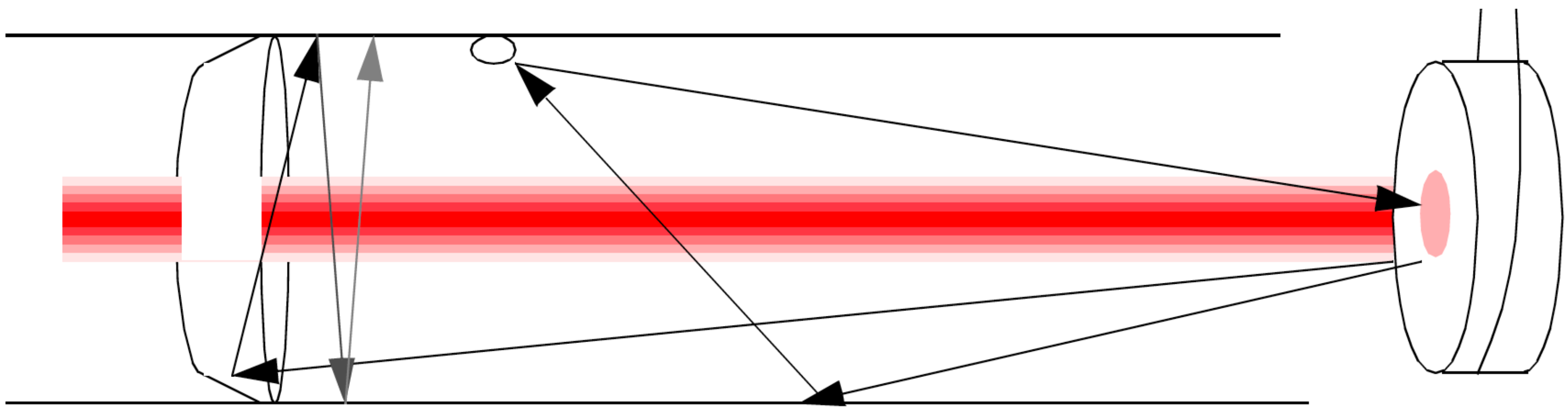
- Scattering from chamber walls is measured via acoustic excitation, then measuring response in GW strain output.
- If clean room fans (in ceiling above chambers) are turned on, motion of chamber walls increases by factor of 30-100 above 40Hz.
- Plot shown shows acoustic coupling to detector output via scattered light
- **→ add baffles, acoustic isolation**



Beam Tube Scattered Light

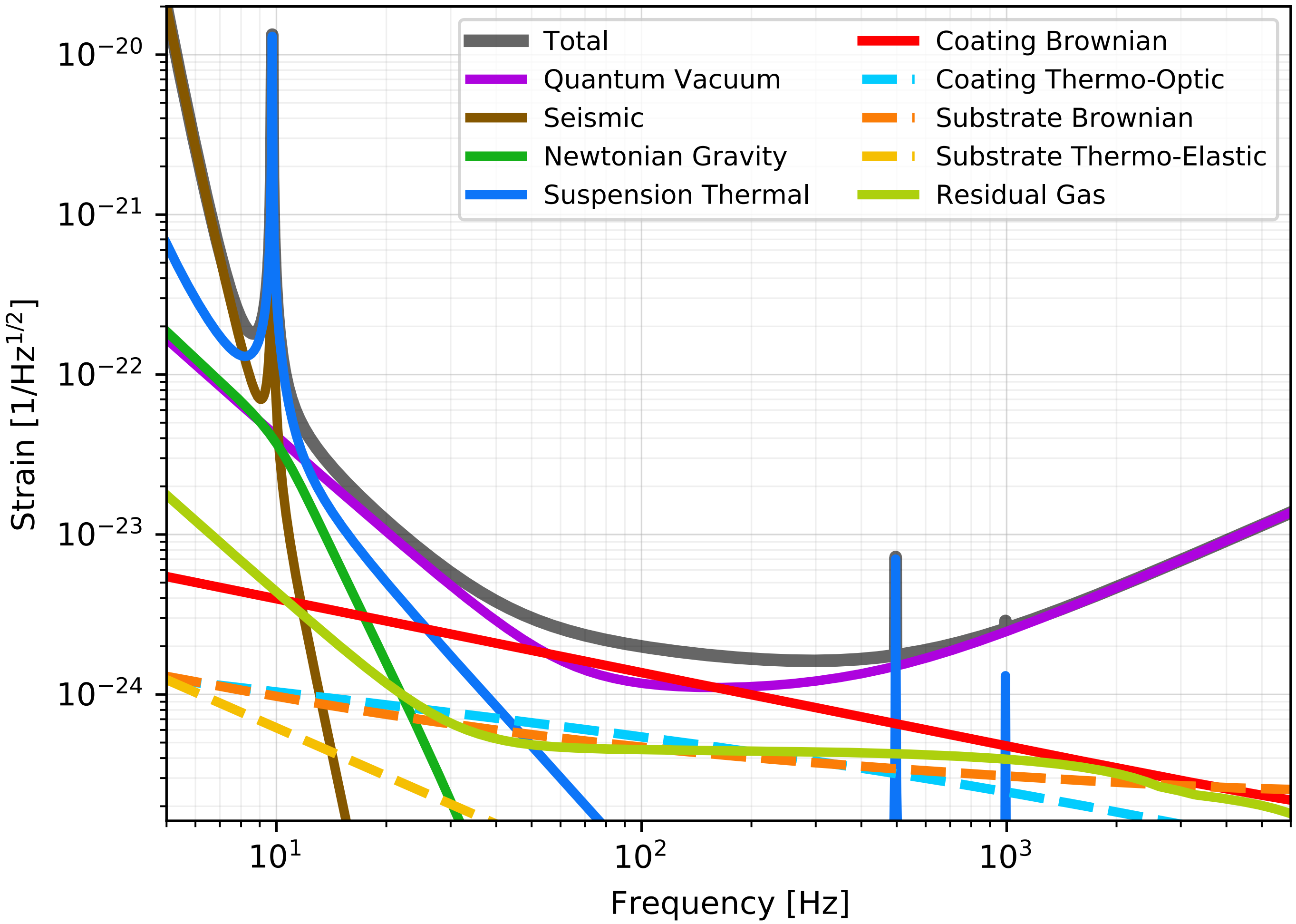
- Laser wavelength determines the minimum beam size after 4km propagation – for 1064nm Nd:YAG, this leads to 10-12cm diameter for $1/e^2$ – but in fact mirrors must be much further in the tails of Gaussian, ~10^{-6} loss per bounce
- In addition, the mirrors are not perfect
  - ‘dust’ and point defects
  - Large-scale ‘waviness’ (~10 nm over 1 cm)
- → very low scatter mirrors
- → 1.2m diameter beam tube
- → baffles to catch scattered light



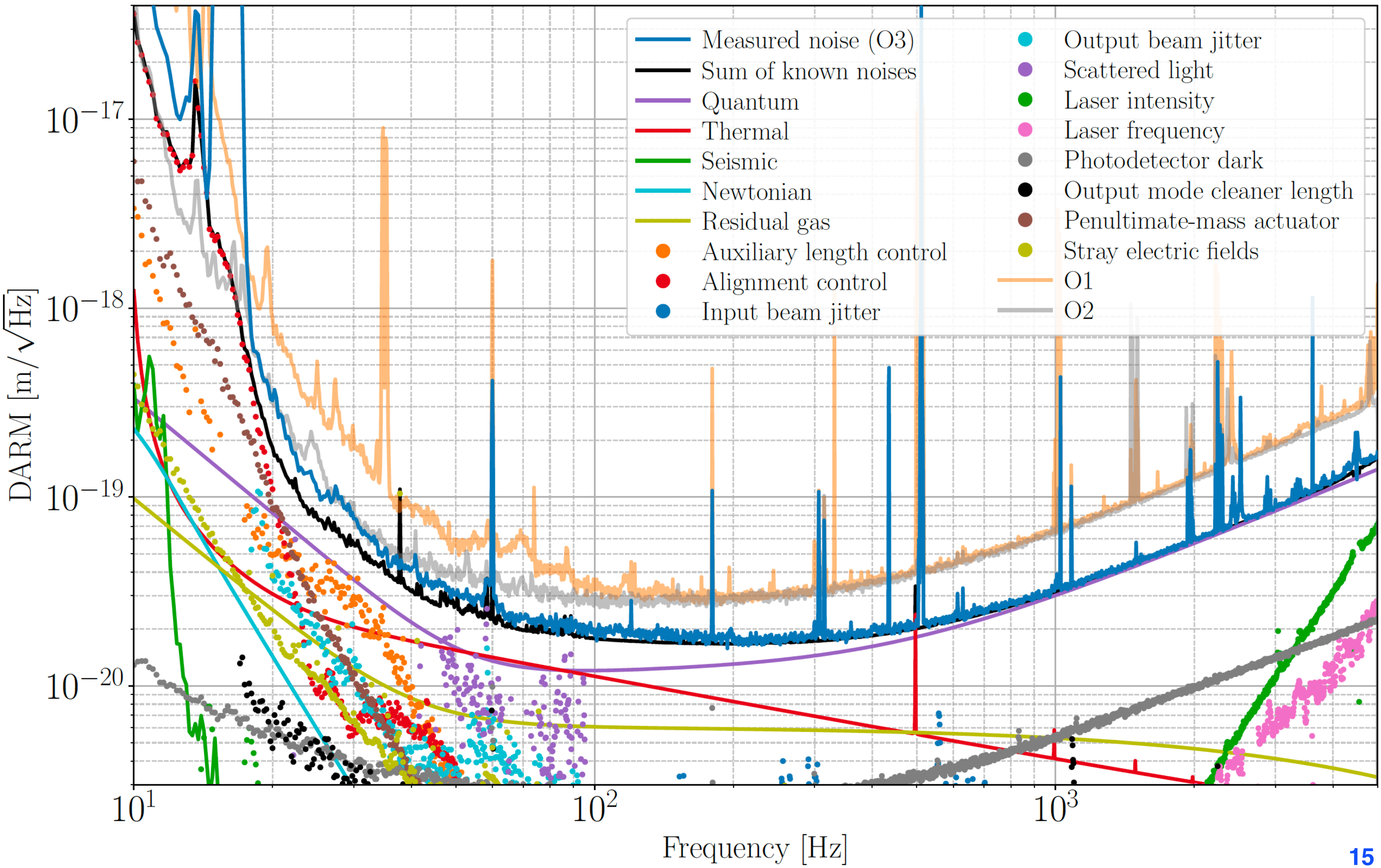


A+ noise model

- The pygwinc model for a set of analytically calculable noise sources
  - Kevin and Jamie will show you how to make these models
  - Scattered light not here…can't calculate ab initio



Scattered light as measured, along with a few other additional terms….



One more noise term…

Taxpayer noise

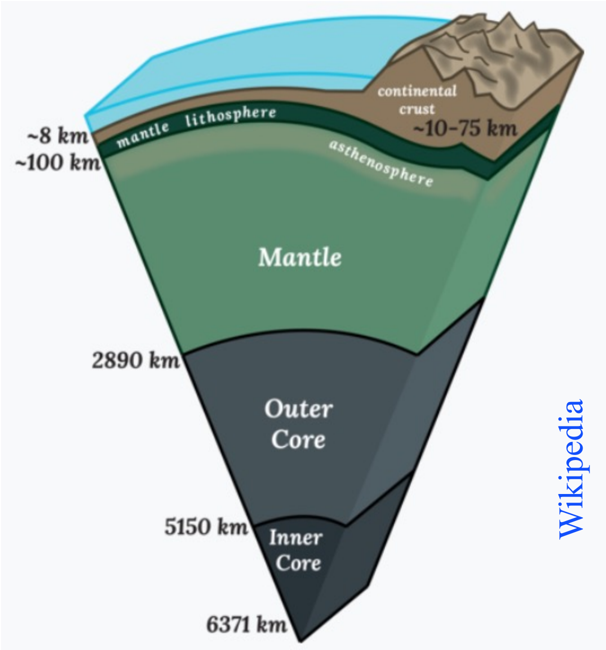
- I promised a page on this noise source!
  - Finding equilibrium with funding is a crucial 'system engineering' trade
- The length of the detector is the most significant scale factor
  - Length of vacuum pipe, support and protection structures
  - Diameter grows as sqrt(length) due to diffraction of the beam
- Vacuum system
  - Order of 45% of the cost for 40-km-long Cosmic Explorer (CE)
- Earthmoving and civil construction more generally
  - If on the surface, need to deal with spherical earth and linear laser
    - Finding a 'bowl' == truly flat site can help significantly
  - If underground, tunneling
  - Order of 30% of the cost for CE
- Detector
  - *Order of (only) 20% of the cost for CE*
- Legally spending billions of Dollars/Euros in an efficient way -- management
  - Order of 5% of the cost of CE; order of one hundred million dollars.

Observatory Infrastructure; LIGO as an example

Civil Construction

- Light travels in straight lines (when far from black holes)
  - The Earth is not flat (whatever some political partisans may say)
  - Sagitta for 4km is some 0.3m – some earthmoving needed
  - For 40km more like 30m – need to find a truly flat (not spherical) site
- Also need stable foundation to support 1.2m beam tube (aligned to ~1mm)
- And some weather protection for the beam tube
  - Turns out that there are are stainless-steel eating microbes
  - Also wasps and black-widow spiders
  - And rodents
  - …and, worst of all, humans

fantasticpestcontrol.co.uk, terro.com



Wikipedia

Civil Construction:
Beam Tube cover, foundation, earthmoving

…and worst of all, humans

Length

- Length is great for sensitivity! Technically *much* easier than lowering noises
  - Signals get larger, noises tend not – until one is comparable to λ/2
  - Optimum for coalescence of BNS around 20km
- Increases the GW signal size, but reduces thermal noise, quantum limits, Newtonian background, seismic noise, electronics/control noise…

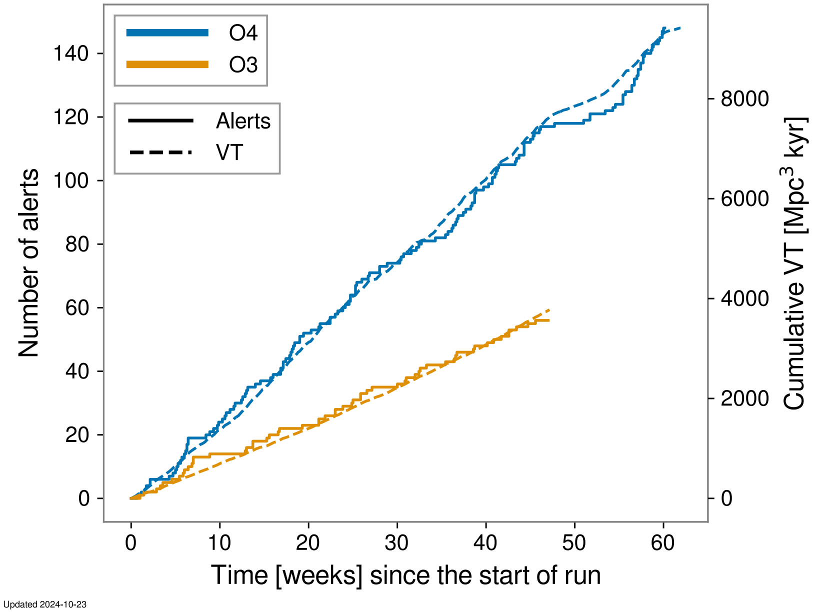
- **Length scaling dominates the cost for a detector**

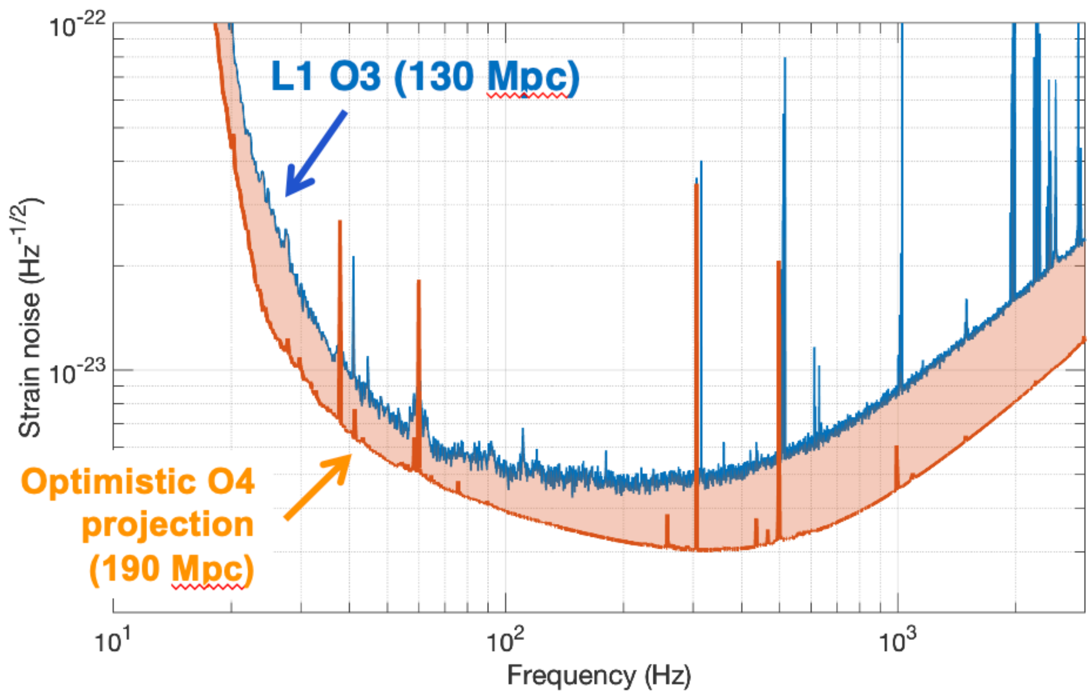
Noise	Scaling
Coating Brownian	$1/L^{3/2}$
Substrate Thermo-Refractive	$1/L^2$
Suspension Thermal	$1/L, 1$
Seismic	$1/L, 1$
Newtonian	$1/L$
Residual Gas Scattering	$1/L^{3/4}$
Residual Gas Damping	$1/L$
*Quantum Shot Noise	$1/L^{1/2}$
*Quantum Radiation pressure	$1/L^{3/2}$

Strain sensitivity as function of length L

Sensitivity improvements are *very* well rewarded

- LIGO 'A+' – Incremental changes to the Advanced LIGO design; 2 x improvement
  - Similar changes planned for Virgo
- Rough doubling of reach
  - $2^3 = 8$ greater volume
  - 8x higher rate
  - 17-300 BBH/month
  - 1-13 BNS/month
  - 2-11 BNS x SGRB coincidences/year
- Population studies
- Hubble Constant
- …higher SNR for e.g., tests of GR





- O4 used some A+ technology

Surface or Underground?

- Burying the detector has clear advantages (see talk on Newtonian background) to improve the low-frequency sensitivity
- The Science Case should drive the design decision here
- Asking for both an optimal length **and** and a buried detector is probably unrealistic from a cost standpoint
- Next-generation detectors are a wonderful illustration of this ‘trade’
  - » Cosmic Explorer: 40km, surface detector, best reach
  - » Einstein Telescope: 10km, underground, best low-frequency
- Also considerations beyond simple sensitivity/cost questions:
  - » Working underground, safely, is hard! Can expect slower progress in activities leading up to observation (see: KAGRA)
  - » On the surface, Blocking migratory paths, occupying land belonging to indigenous peoples present challenges

Risk

- Different projects can adopt different risk levels
- GEO-600 is a great example on where risks can be taken
- Also different cultures, funding agencies, collaborations have different levels of tolerable risk
- More ambitious designs require more R&D to be successful to be realized, and may
  - » Make more significant steps forward in measurement science
  - » Lead to a more sensitive detector
  - » BUT: Take more time to get working
  - » May not work as well as hoped
  - » May even simply fail.
- Safety
  - » A different kind of risk, but human safety is very important
  - » One person seriously injured or worse is not only a human tragedy – it can also kill a project

System Engineering

- To find solutions which meet the observational science goals, manage risk, and meet cost and schedule constraints
- Can require compromises both in the initial design, and dynamically as the project advances
- Constant modeling of the sensitivity is crucial, along with modeling of schedule and cost
- A mixture of engineering, instrument science, observational science, and project management is needed to succeed
- **All** decisions will be made with partial information, but waiting for better data has a significant cost and risk

- The next two talks will put the sensitivity modeling tools in your hands to allow that part of the challenge to be explored
- Just keep in mind that a full design process has a great deal of richness!

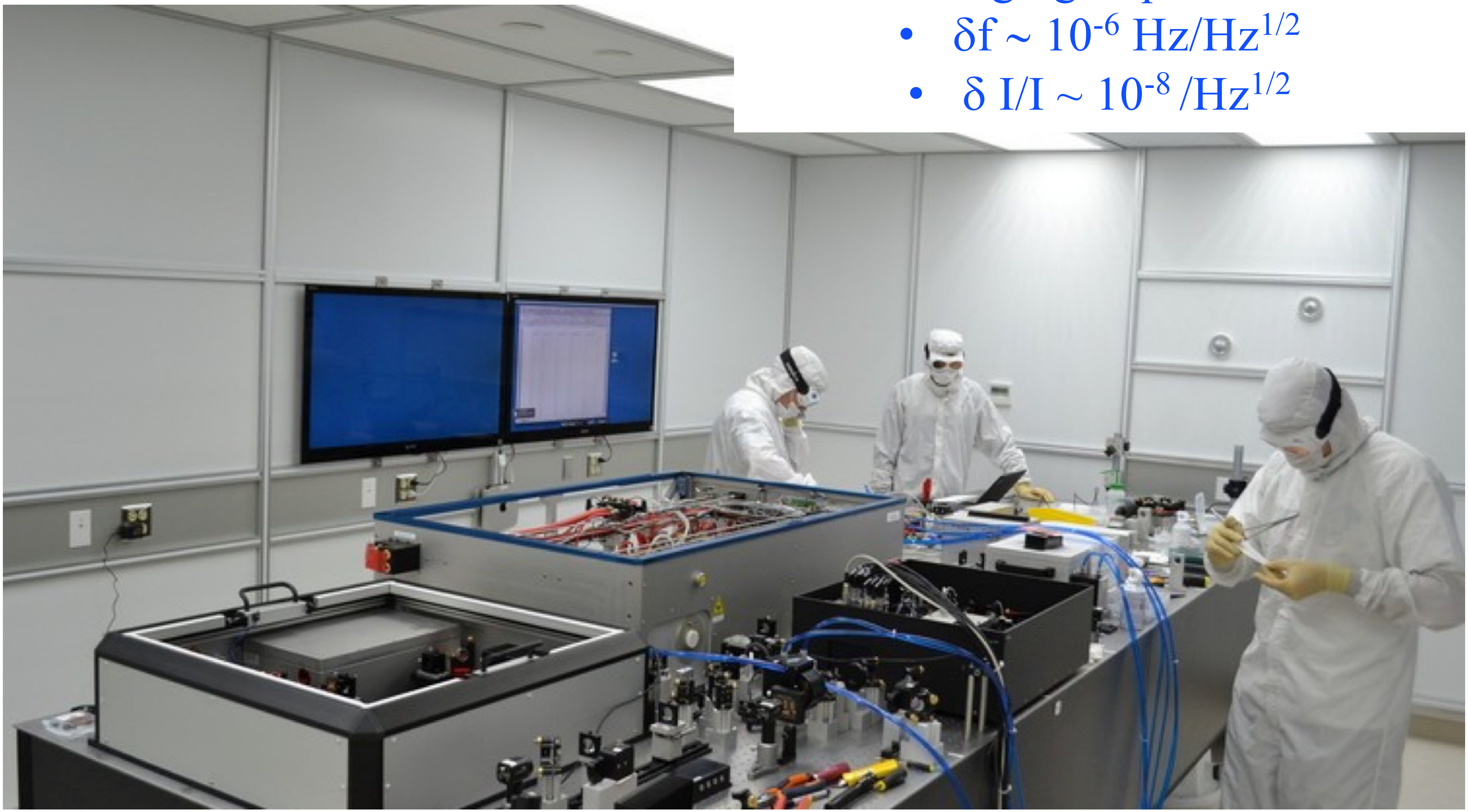
An Example:
Let’s look at the actual LIGO layout and hardware

Laser Clean Room; extraterrestrials for scale

200 W, single frequency, single mode, Nd:YAG laser

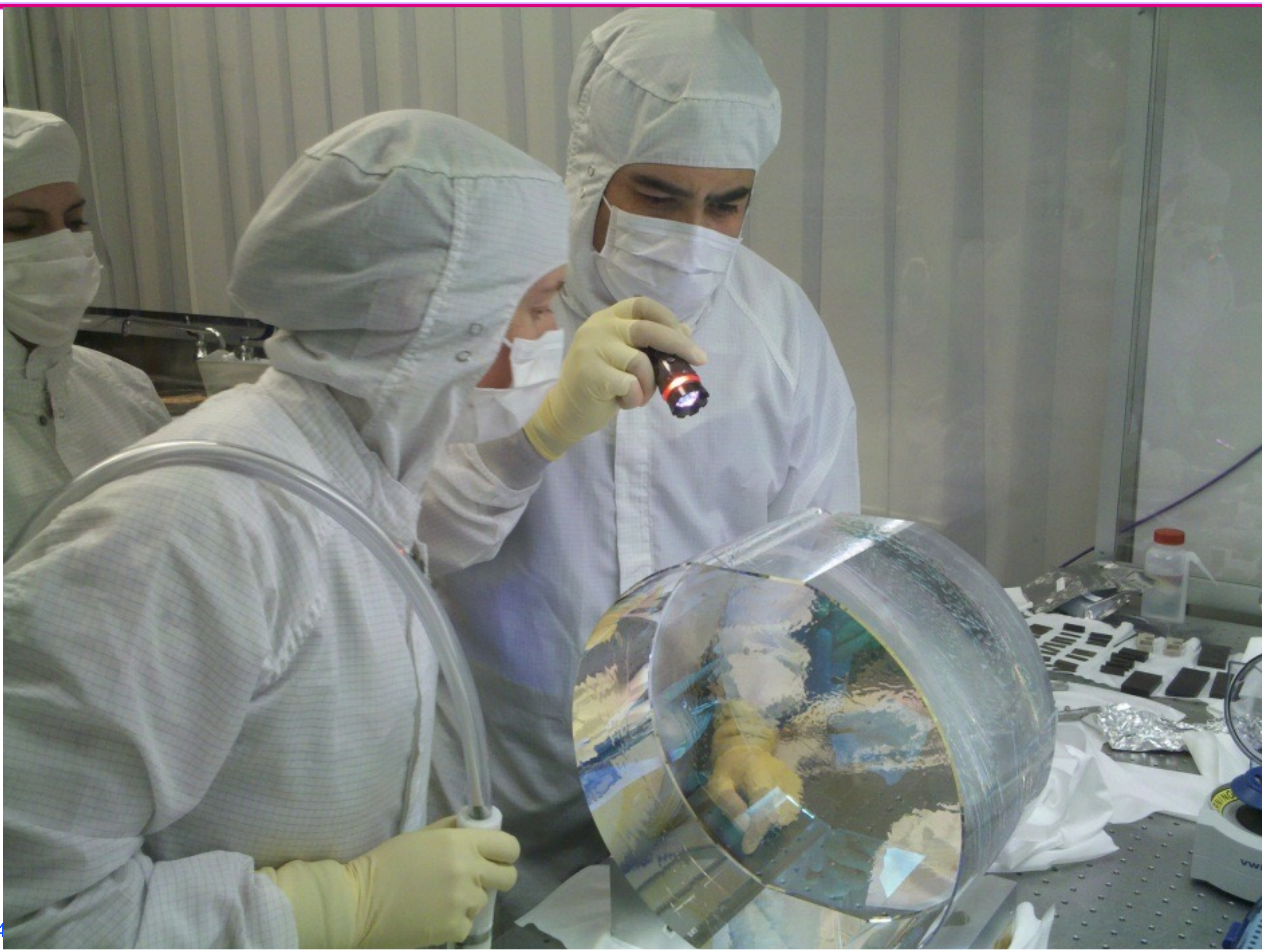
Challenging requirements:

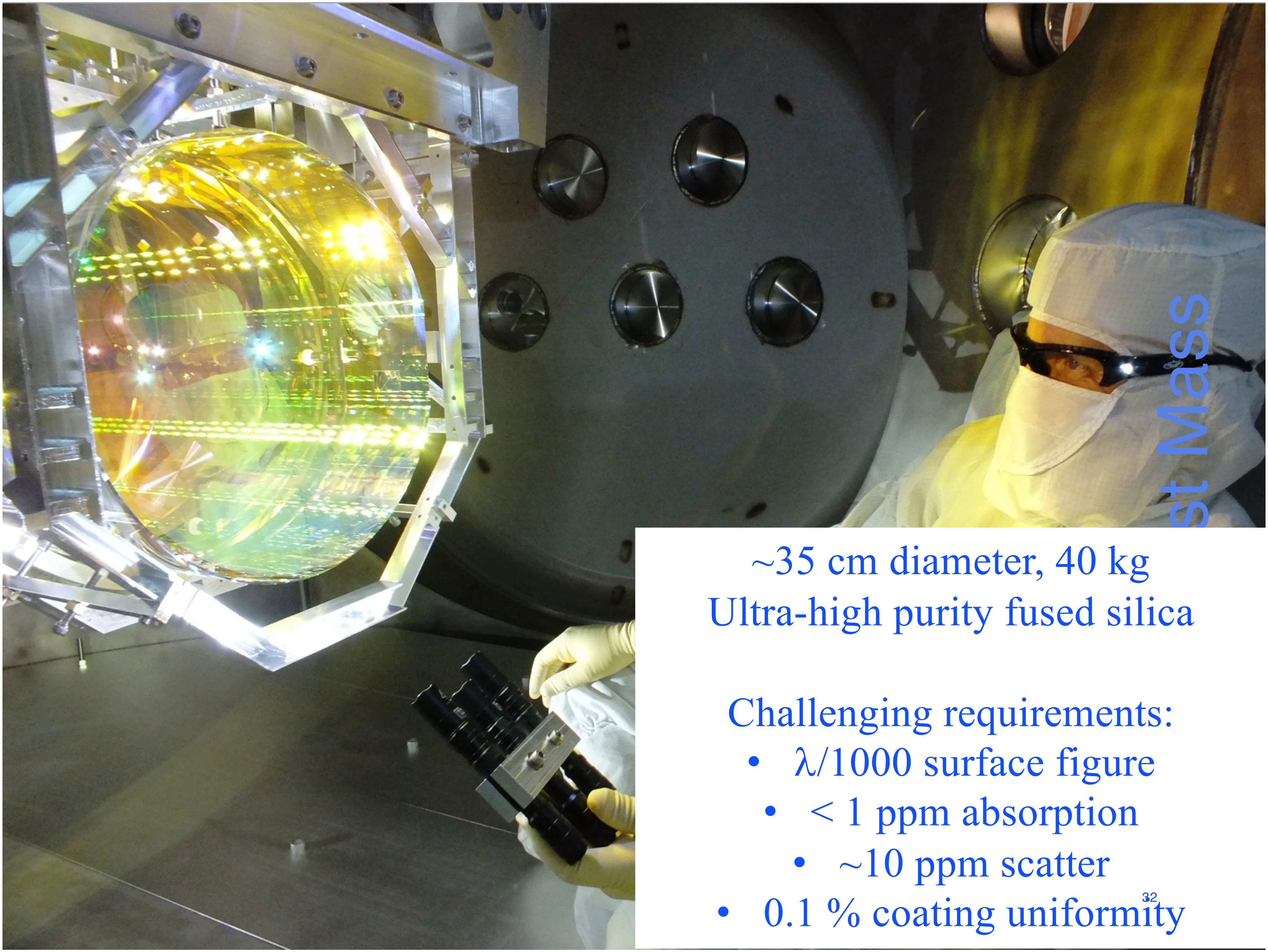
- $\delta f \sim 10^{-6}$ Hz/Hz$^{1/2}$
- $\delta I/I \sim 10^{-8}$ /Hz$^{1/2}$



Vacuum chambers to protect and isolate optics

Inspecting mirror during fabrication



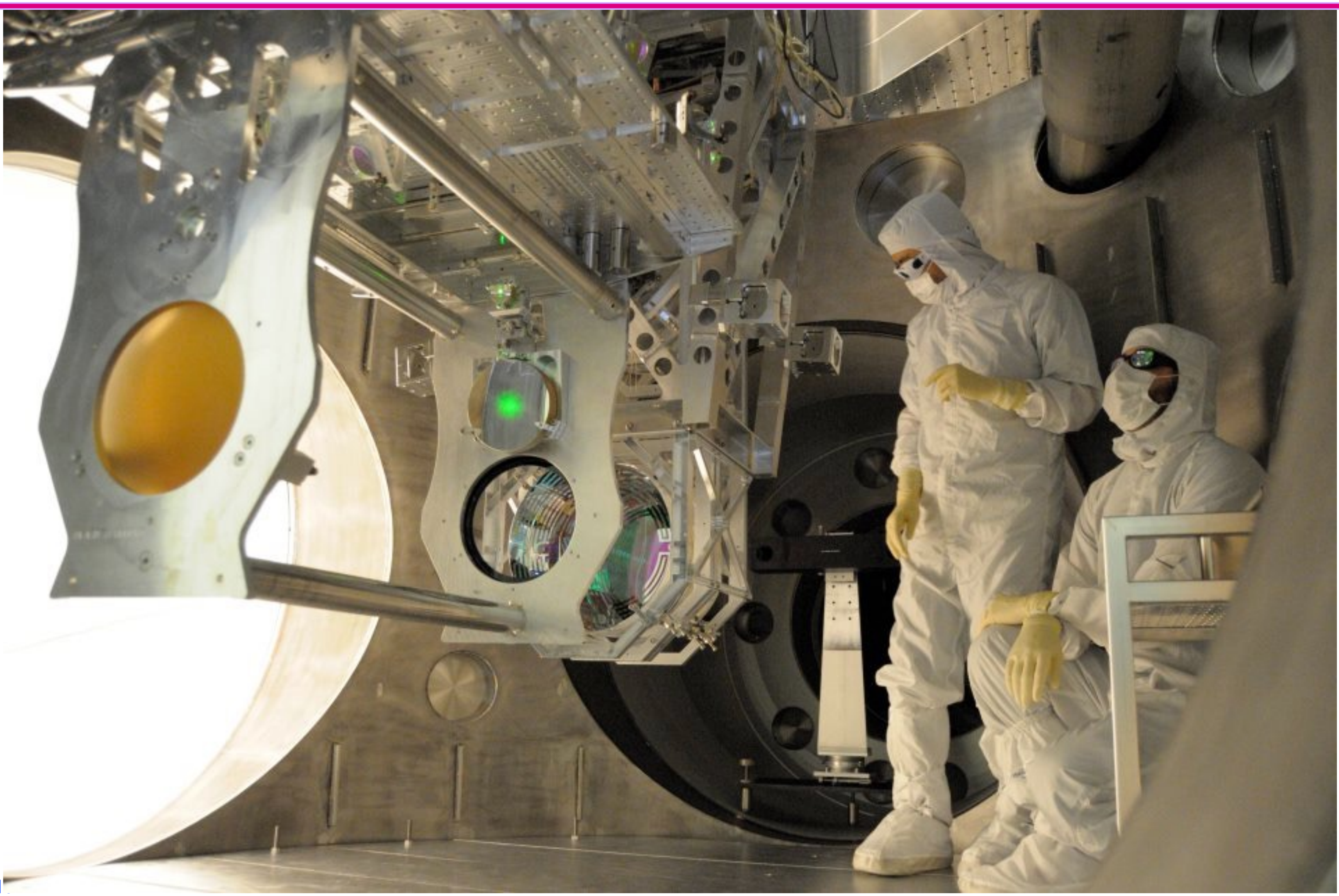


~35 cm diameter, 40 kg
Ultra-high purity fused silica

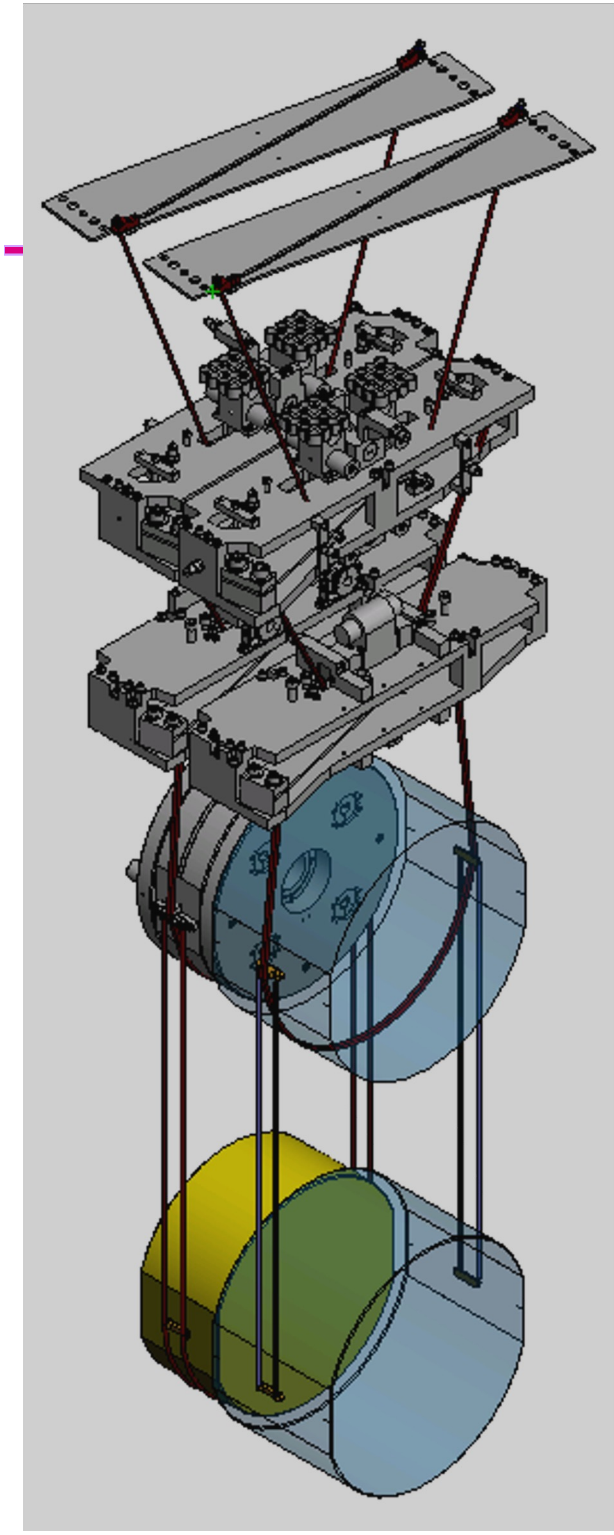
Challenging requirements:

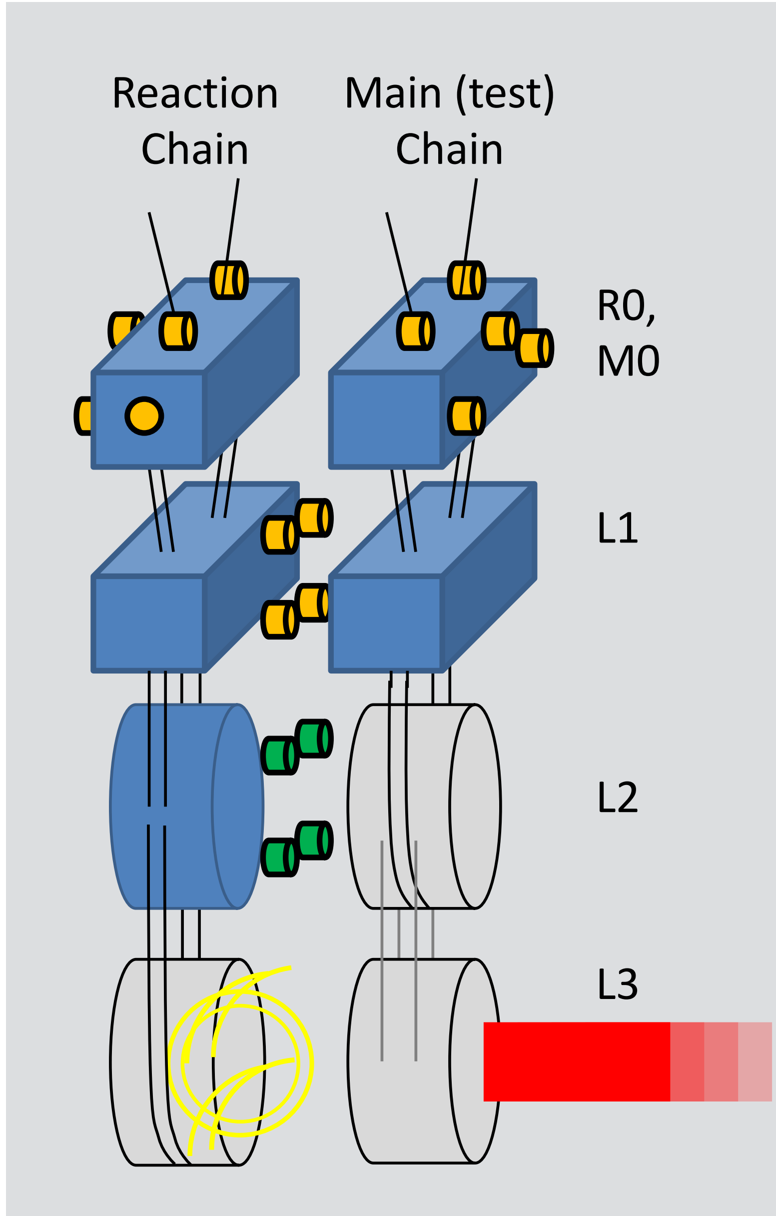
- $\lambda/1000$ surface figure
- < 1 ppm absorption
- ~10 ppm scatter
- 0.1 % coating uniformity

End-mirror assembly
(humans removed before pumpdown)



Optic Suspensions



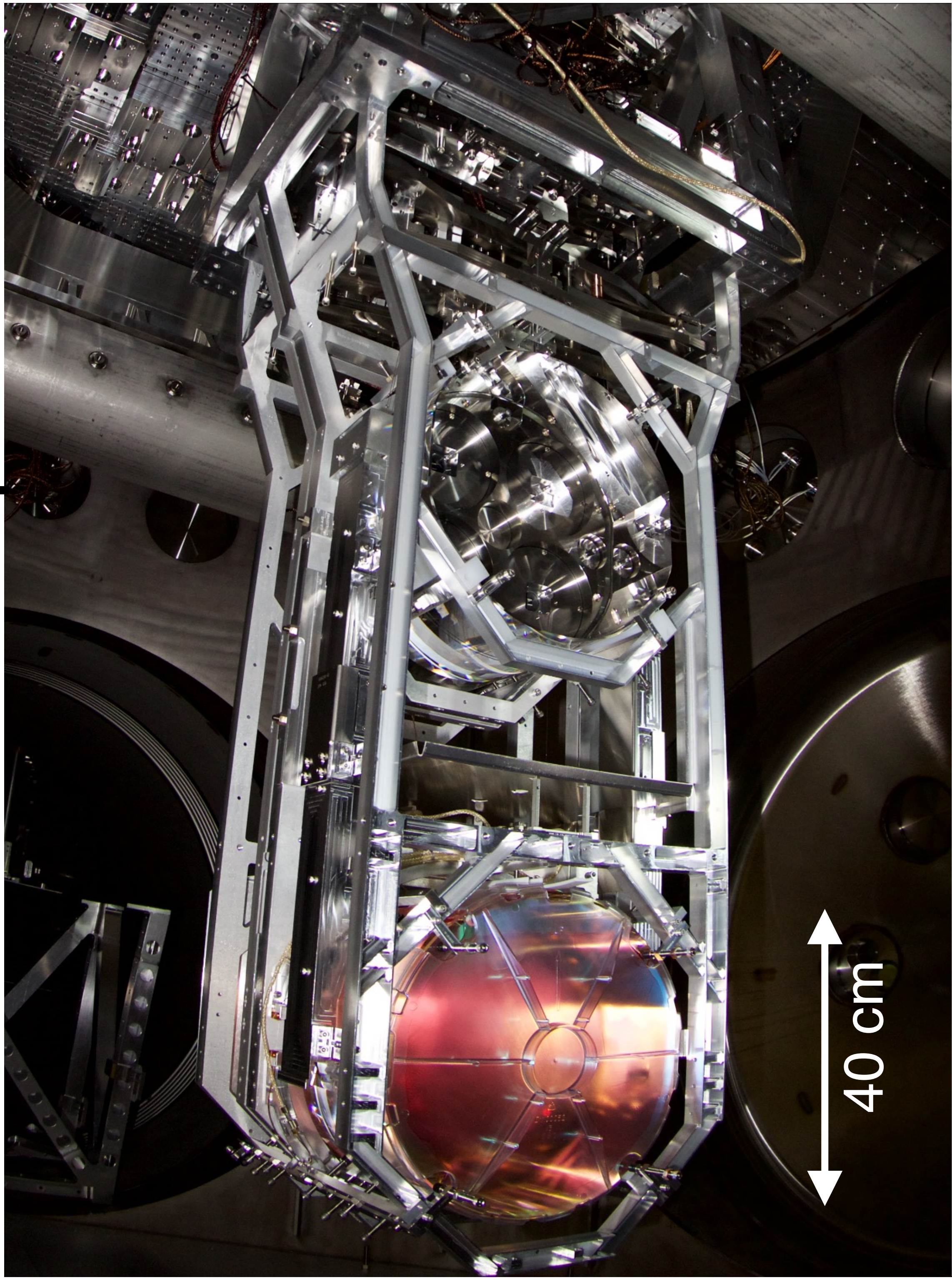


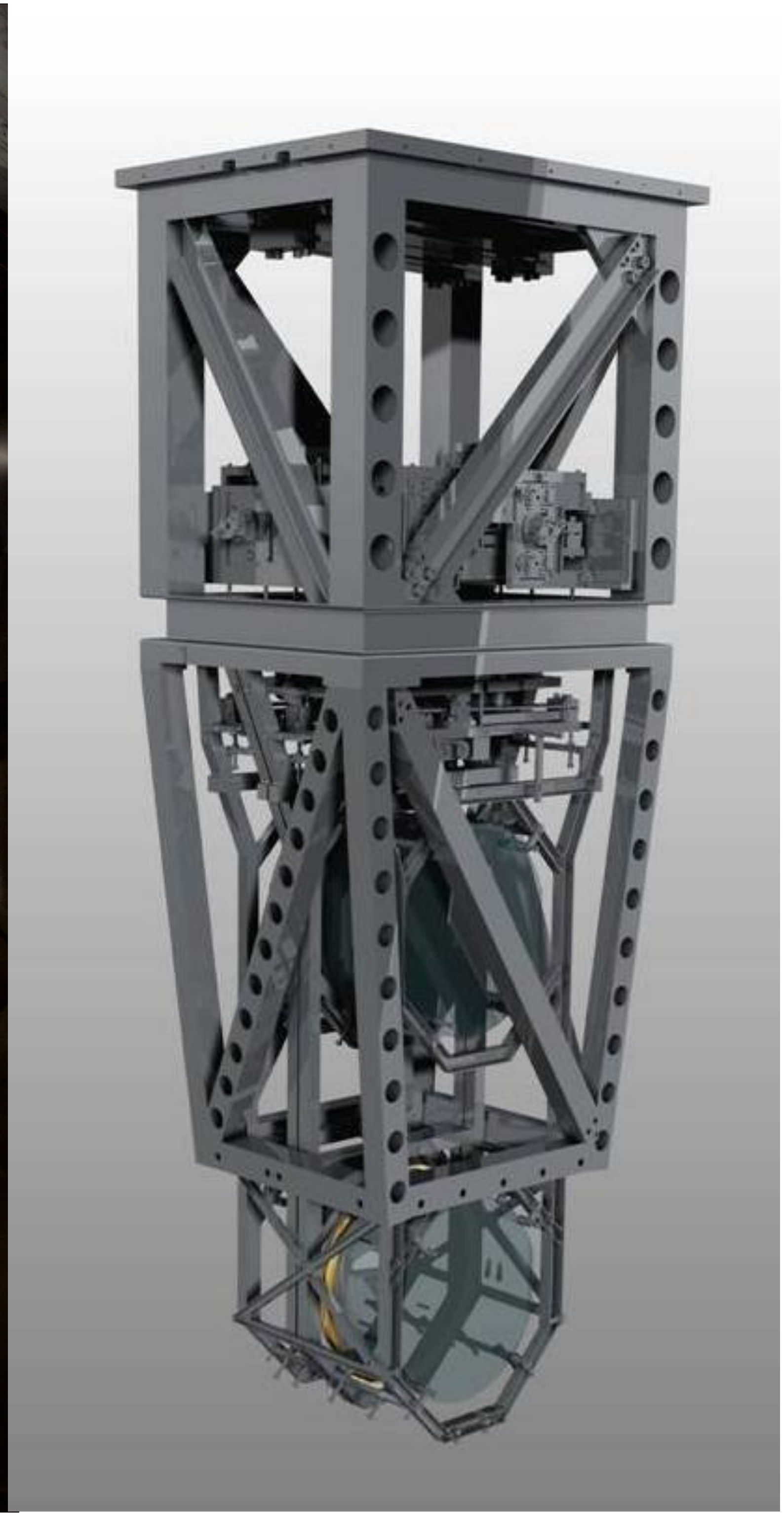
Electromagnetic sensors/actuators measure position relative to a reaction chain that is also passively isolated

Lower stage actuators used to control/maintain optic cavity length and alignment

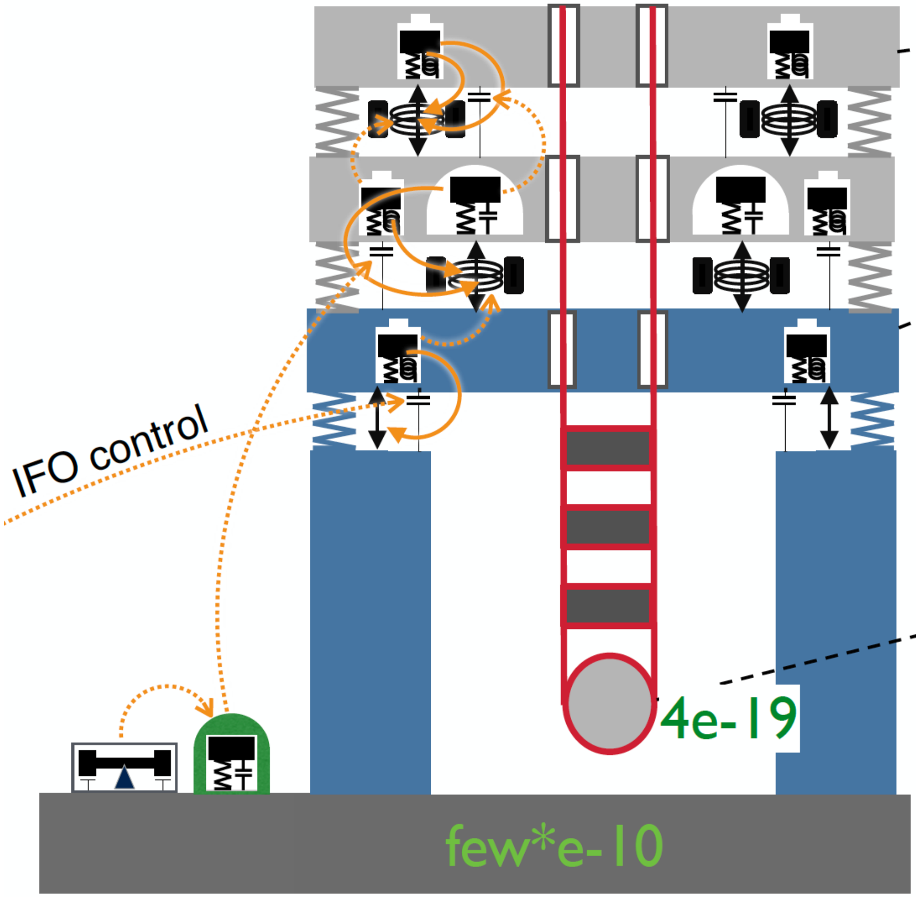
‘Monolithic’ – optic, penultimate mass, and suspension fibers welded together

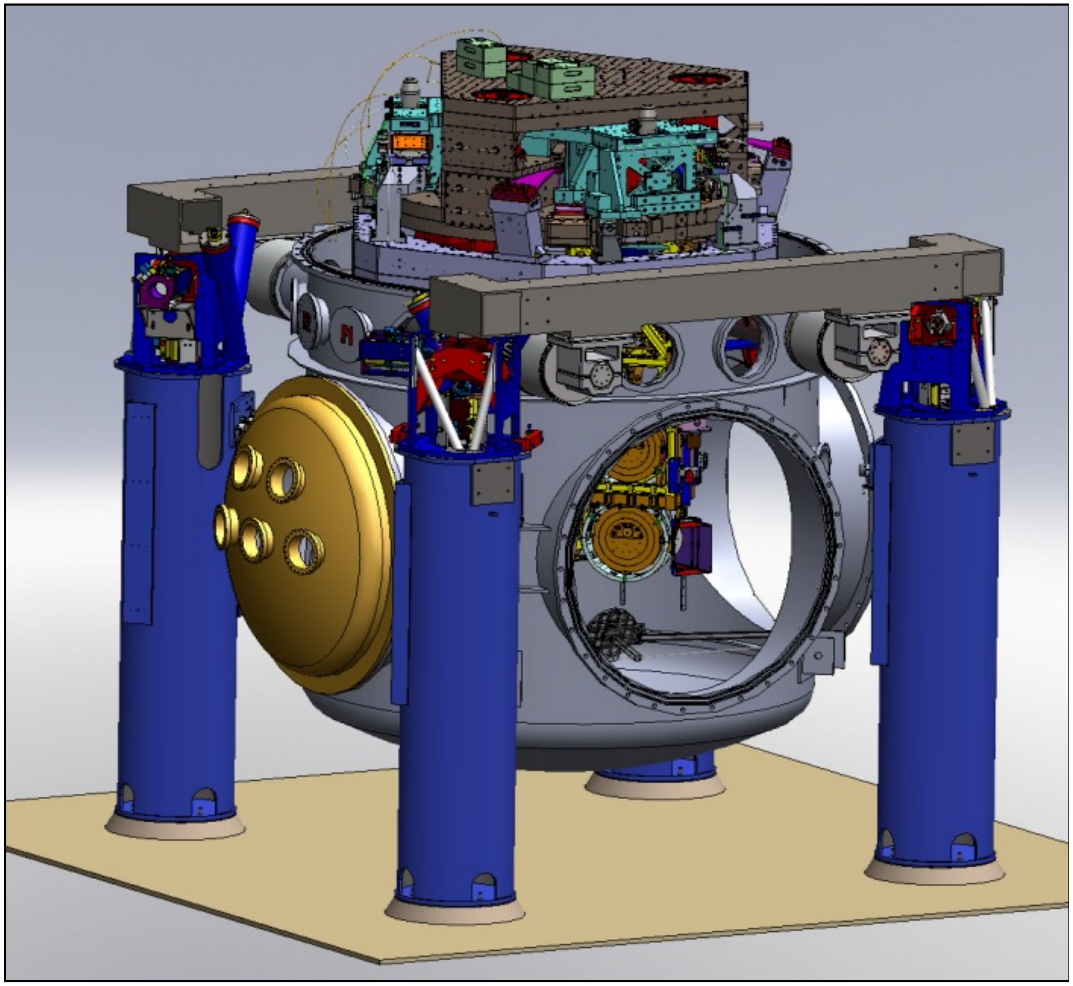
Test Mass Suspension

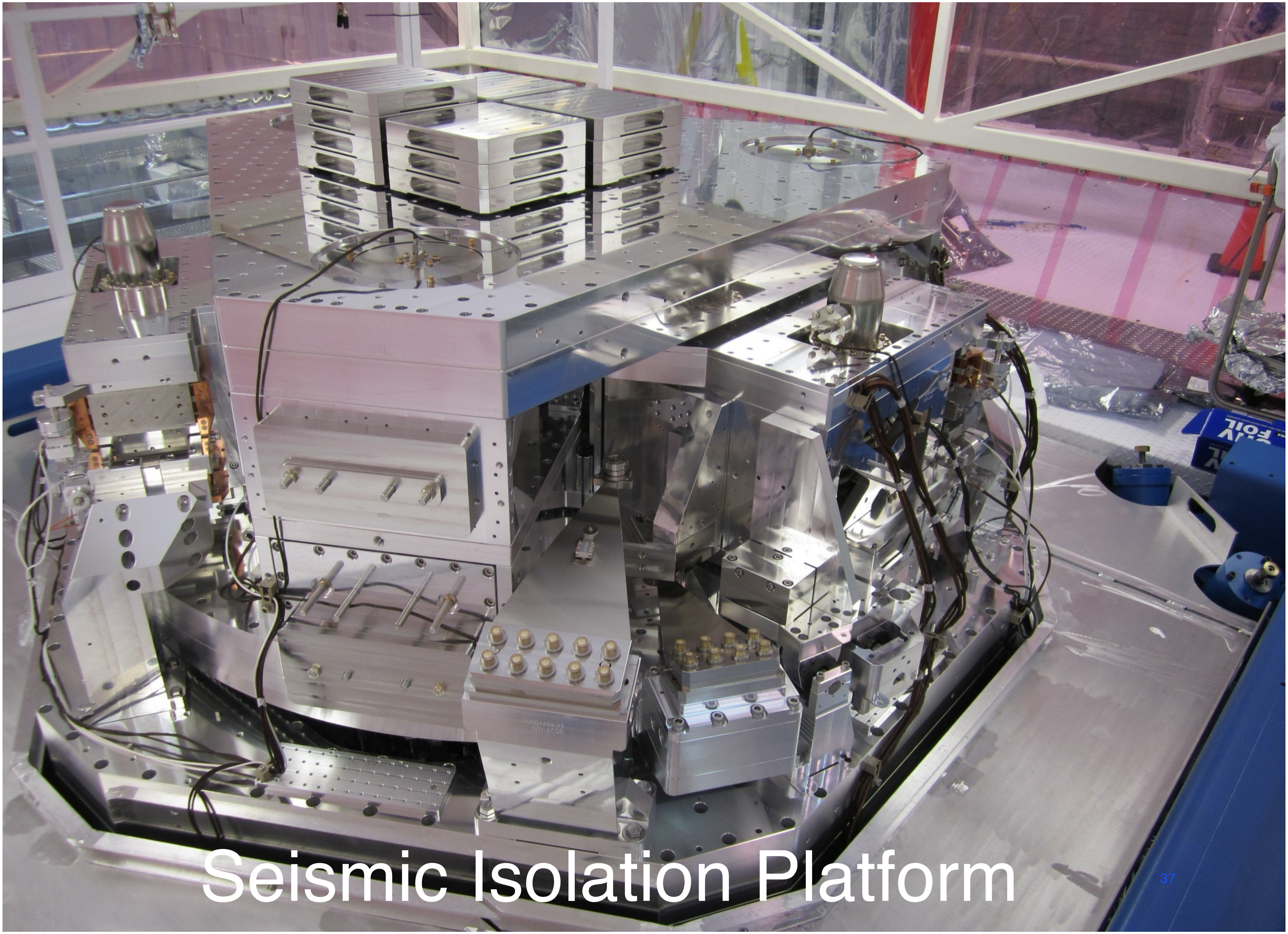




Active and passive seismic isolation







Seismic Isolation Platform

Another crucial element for success: Collaboration

- Table-top scientists – precision measurement, laser, atomic – started the field; tradition of small groups, small projects, and some competition
- Early general relativists, theorists, astrophysicists much the same
- Transformation when High Energy Physics types got involved
  - Engineering, project organization, computing, analysis
- Funding agencies also saw a need for a shift
  - There is a real skill in spending hundreds of millions of Euros!
- Goal pre-discovery was crystal-clear: Make a detection
- After the Collaborations formed and were stable, meta-collaborations: 'The LVK' – KAGRA, Virgo, and LIGO Scientific Collaborations all sharing data → IGWN
  - The science that is possible is qualitatively greater
  - The sociology of a (mostly) non-competitive environment nurturing and supportive
- LISA and Pulsar Timing also in collaborations/consortia
- Now perhaps 3000 persons worldwide

Last Page

Hope to have given a view of the
'Meta-design' concepts and processes

Good luck, and:

Have fun with your design experiment!