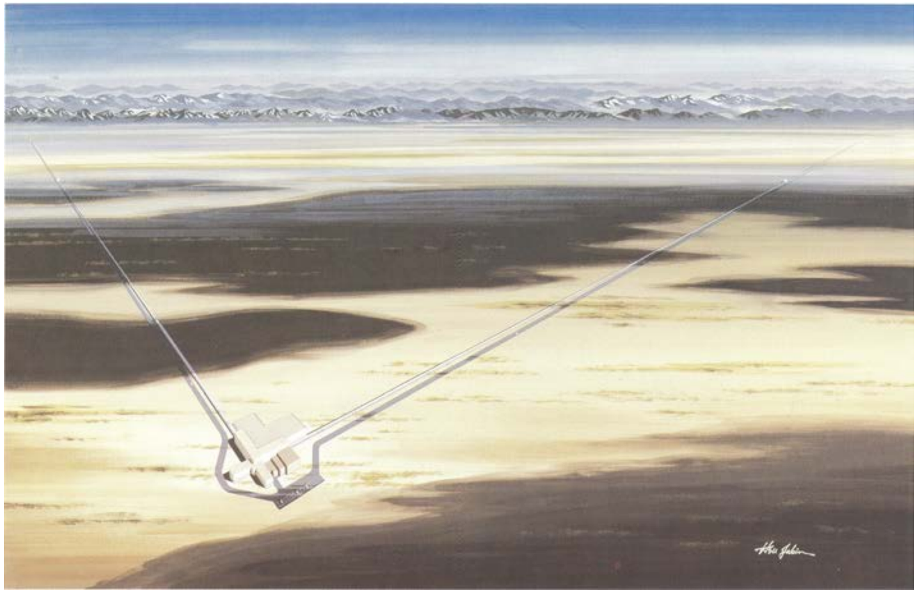
Gravitational Waves and LIGO: A Technical History



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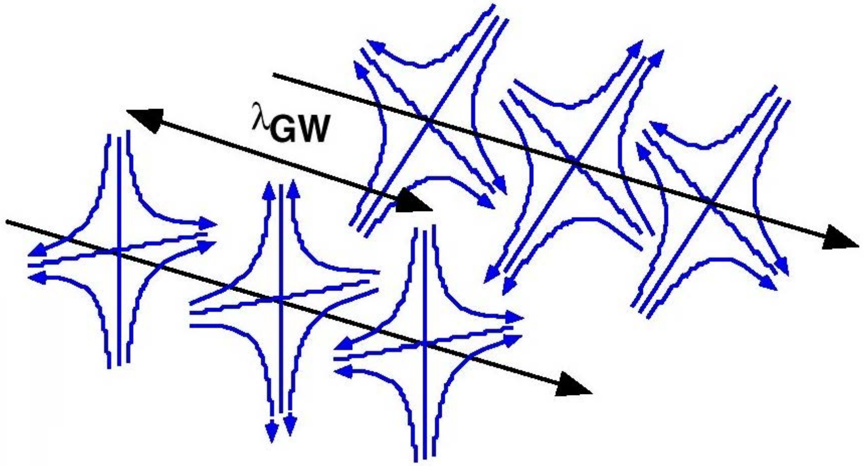
Goal of Talk

- Review a few of the technical developments that enabled LIGO, with emphasis on pre-1995 era
  - » Residual Gas Noise (Vacuum requirement)
  - » Thermal noise
  - » Mirror figure requirements

- Disclaimer: LIGO has an equally “rich” political history—NOT covered in this talk
  - » See e.g., Janna Levin, *Black Hole Blues*
  - » Caltech Archives--search for “LIGO Oral Histories” at http://archives.caltech.edu/search/index.html

Gravitational Wave Basics

- Einstein (in 1916) recognized gravitational waves in his theory of General Relativity
  - » Necessary consequence of Special Relativity with its finite speed for information transfer
  - » Most distinctive departure from Newtonian theory
- Time-dependent distortions of space-time created by the acceleration of masses
  - » Propagate away from the sources at the speed of light
  - » Pure transverse waves
  - » Two orthogonal polarizations



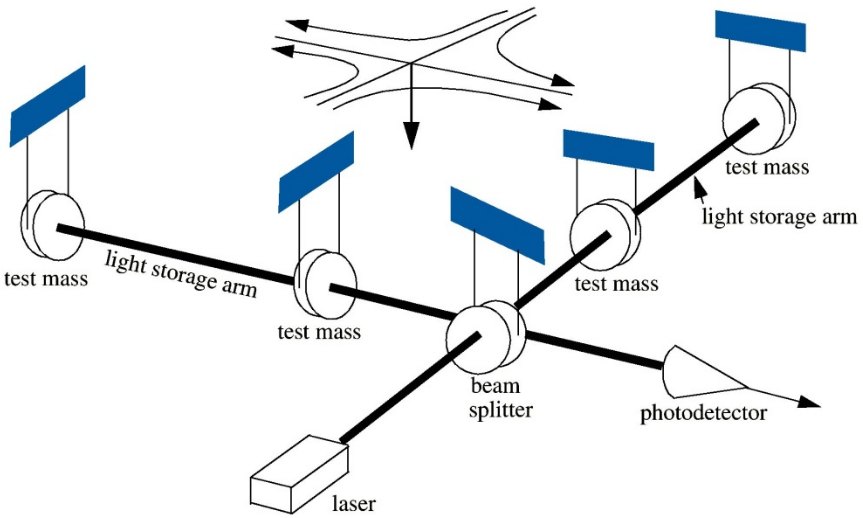
$$h = 2\Delta L / L$$

~10^{-21} for plausible astrophysical sources

Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses in horizontal plane for frequencies $f \gg f_{pend}$

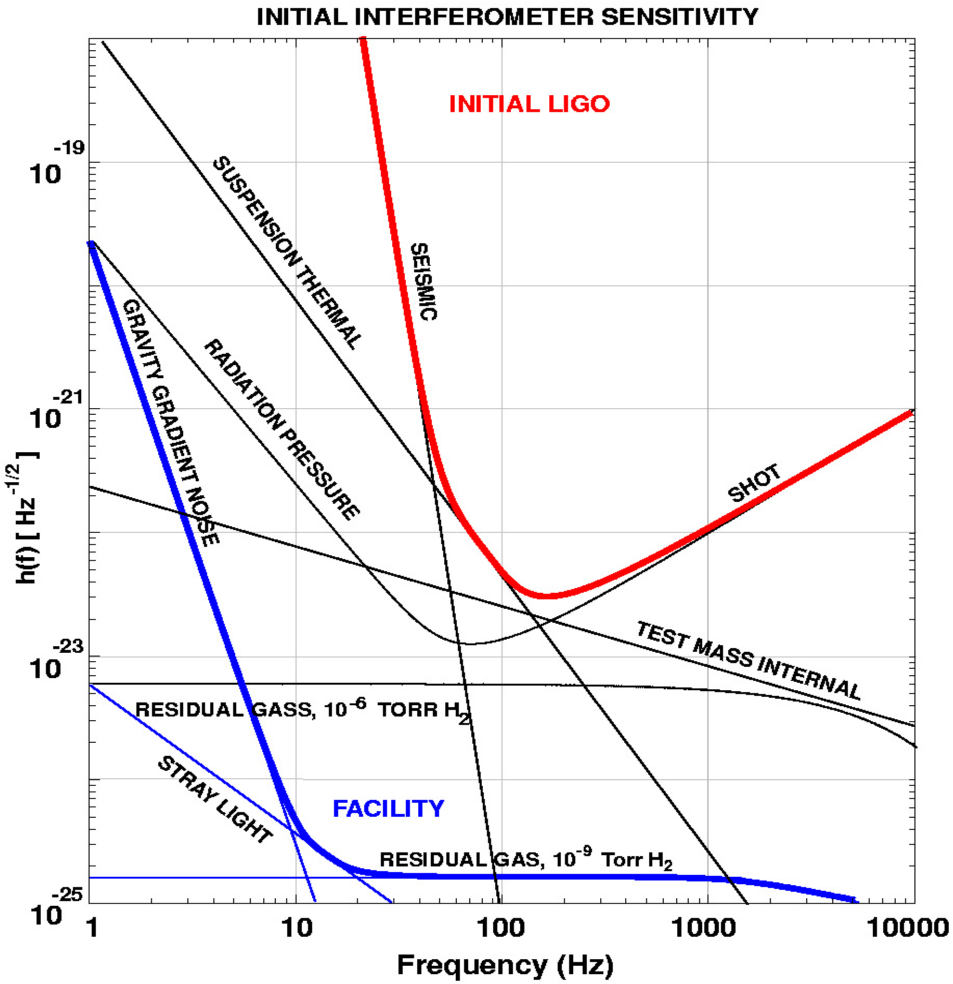
$$\Delta L = hL/2$$



For a LIGO detector,
$L \sim 4$ km, $h \sim 10^{-21}$
$\Delta L \sim 10^{-18}$ m

Laser Interferometer Gravitational-wave Observatory (LIGO)

The Core Principle Driving LIGO: Noise



- Sensing Noise
  - Photon Shot Noise
  - Residual Gas
- Displacement Noise
  - Seismic motion
  - Thermal Noise
  - Radiation Pressure
- Noise sources add
  - All noise sources have to be identified, understood and controlled

Reference Documents

Three documents so central to the technical history of LIGO that they must be introduced immediately

- "Rai's RLE paper"
  - » "Electromagnetically Coupled Broadband Gravitational Antenna" R. Weiss, Quarterly Reports of the Research Laboratory of Electronics MIT **105**, p. 54 (1973).
  - » Paper "… grew out of an undergraduate seminar that I ran at M.I.T. several years ago…"
- The "Blue Book"
  - » "A Study of a Long Baseline Gravitational Wave Antenna System"
  - » Authors: Paul Linsay, Peter Saulson, Rai Weiss
  - » Dated October 1983, but not really published
- NSF Proposal for LIGO Construction ('89 proposal)
  - » Proposal team: Robbie Vogt, Ron Drever, Rai Weiss, Kip Thorne, Fred Raab, but with contributions from many others

Rai's RLE Paper

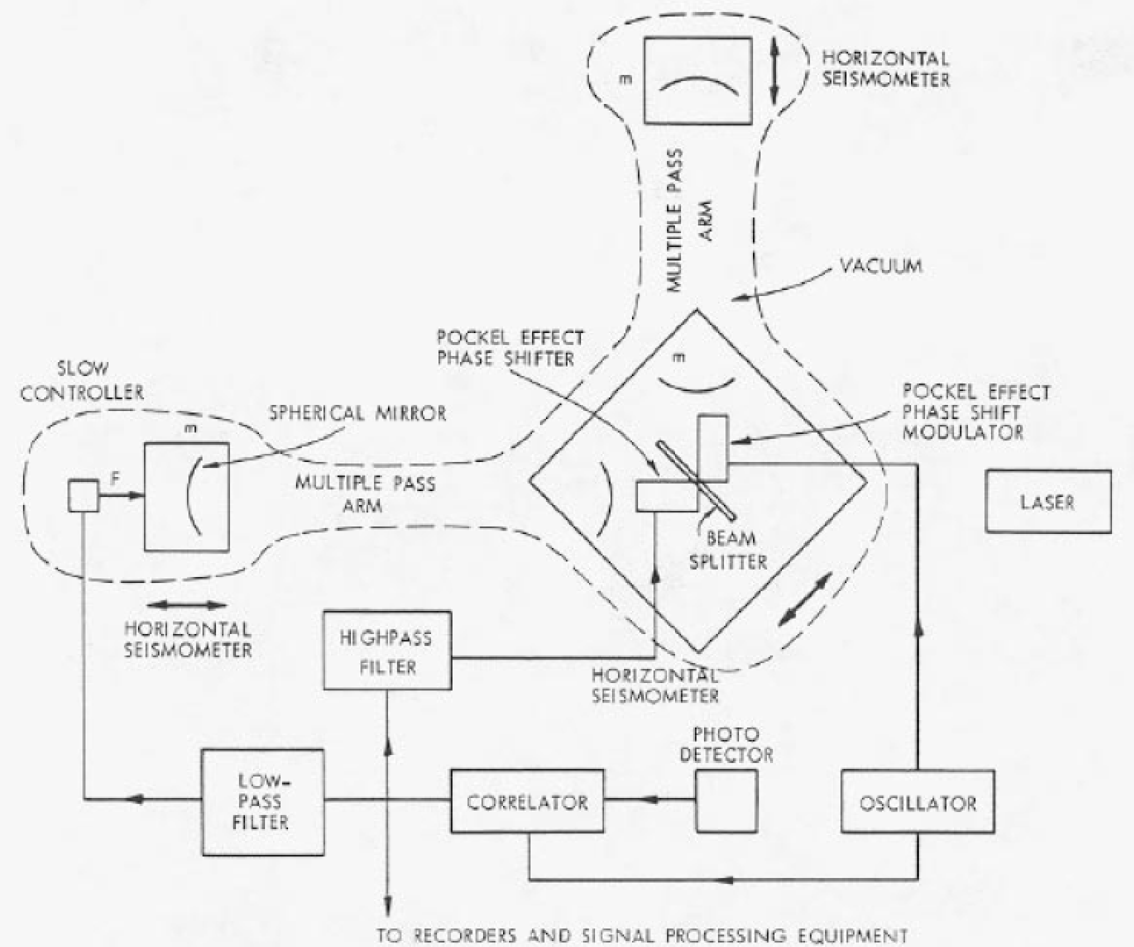


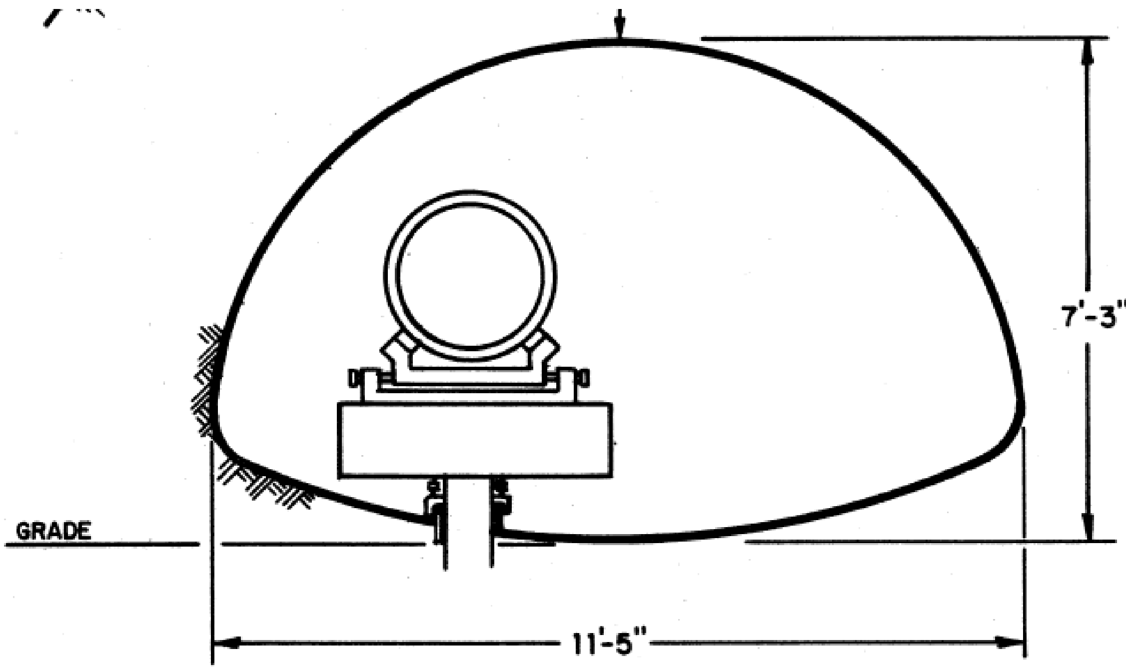
Fig. V-20. Proposed antenna.

Not first suggestion of a laser interferometer to measure GWs, but first detailed noise/ sensitivity analysis

» Shot noise/ radiation pressure
» Thermal noise
» Seismic noise
» Gravity gradient
» …

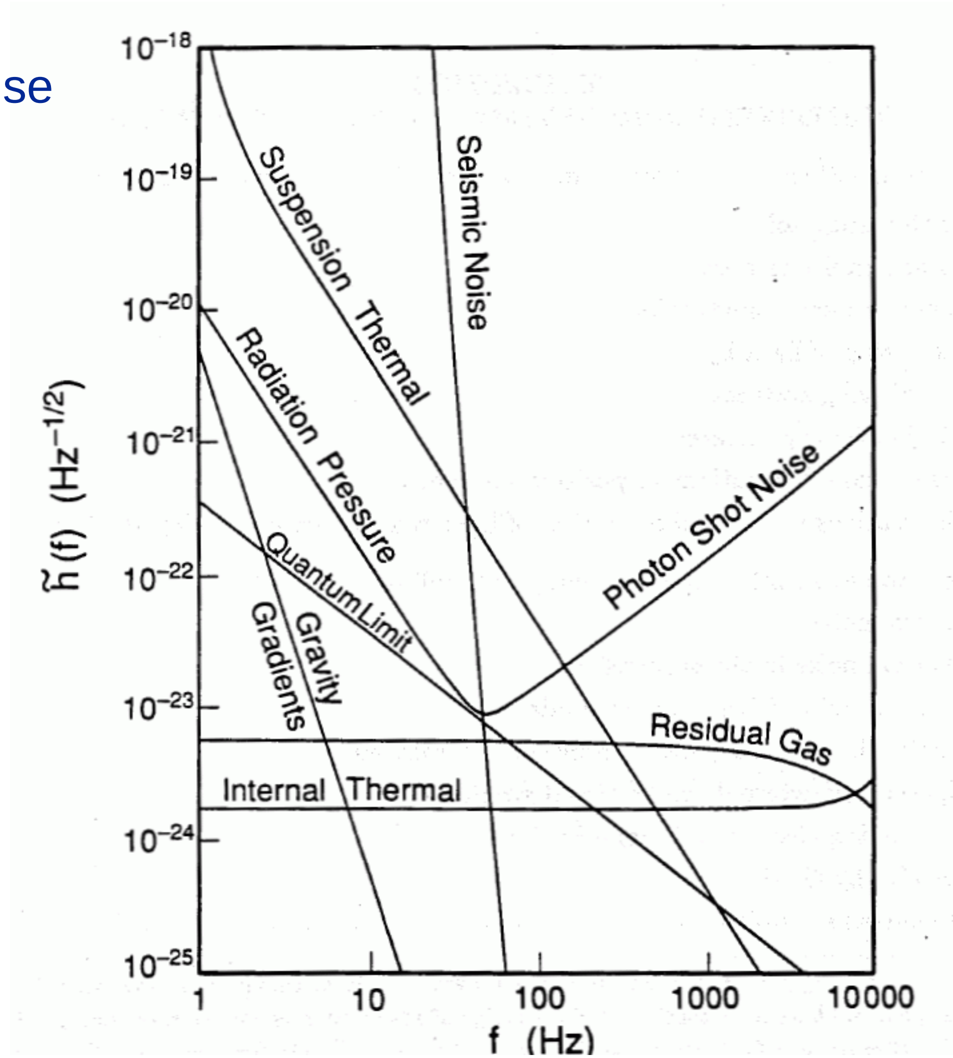
The Blue Book

- Science and Engineering study of feasibility
- Comprehensive scope—Chapter titles
  - » Sources of Gravitational Radiation
  - » Physics and Detection
  - » Prototypes and Optical Concepts
  - » Noise sources
  - » Vacuum System
  - » Site survey
  - » Construction
  - » Proposed Design
- Important because of first engagement of engineering firms



The '89 Proposal

- Two Volumes
  - » Science case, detector physics, noise analysis, prototype experience
  - » Engineering design and cost basis
- Defined sensitivity goals, phased approach, scope



Residual Gas Noise

- Not the most interesting noise source to typical physicist, but important because the vacuum system is one of the largest cost items in LIGO

Residual Gas Noise

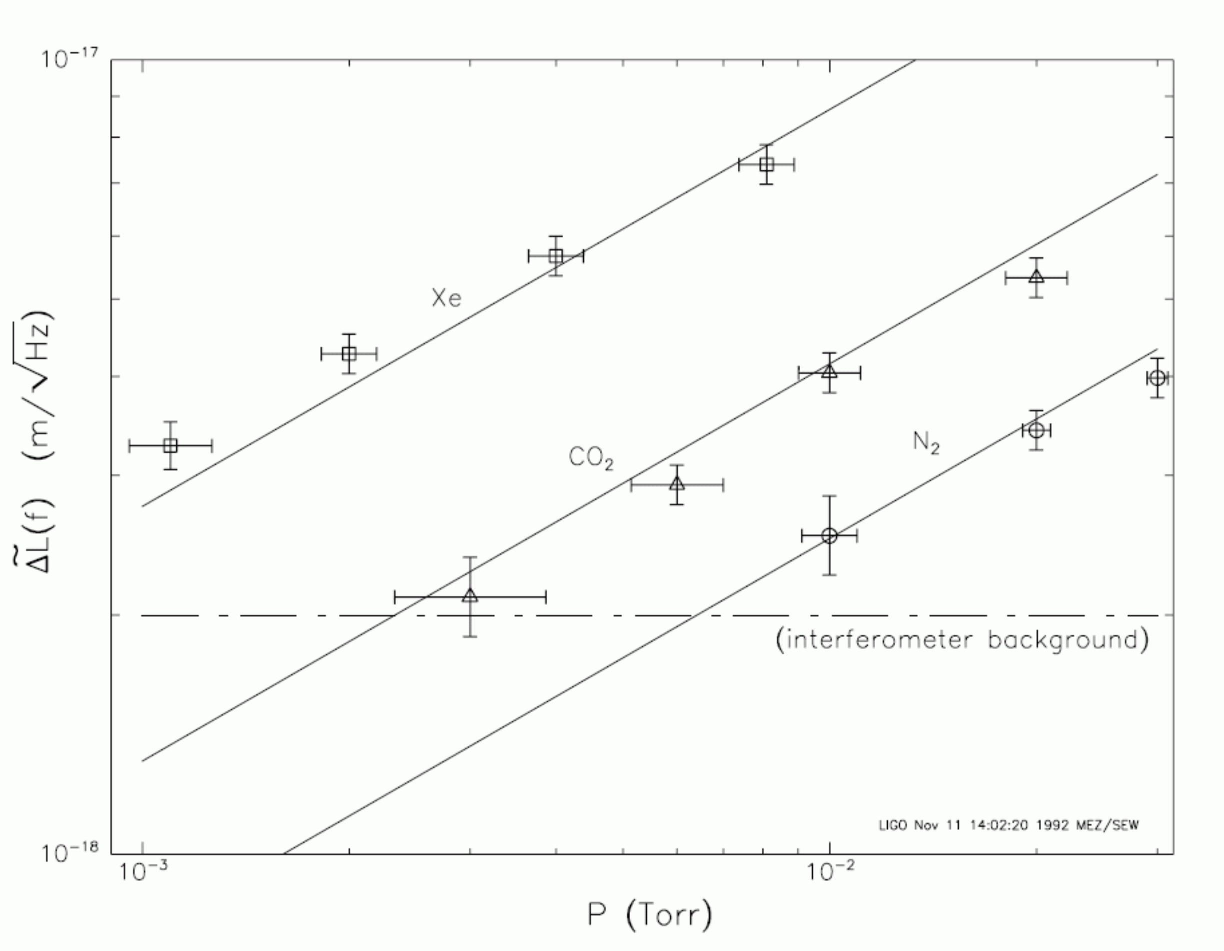
- Even though very small, the residual gas in the vacuum system contributes to index of refraction
- Not mentioned in Rai's RLE paper
- The Blue Book (1983)
  - » Has an essentially correct treatment of the noise due to residual gas—statistical fluctuations in the number of gas molecules in the beam causing fluctuations in refractive index
  - » Correct requirement for initial LIGO (~10^{-6} torr)
- Correct formulation independently published by the Munich/Garching group
  - » Referenced to Albrecht Rüdiger as unpublished derivation in paper on Munich 30 m prototype ("Noise behavior of the Garching 30-meter prototype gravitational wave detector," Shoemaker et al., *Phys Rev* **D 38**, 423 (1988))

Residual Gas Noise, cont.

- Not entirely a straight line progression
- 1987 LIGO R&D proposal
  - » Initial LIGO requirement quoted (at least one place) as 10^{-3} torr, three orders of magnitude too high
- LIGO '89 proposal
  - » A new formulation of the problem, in terms of the forward scattering matrix for individual gas molecules
  - » Simple mathematical error ended up with incorrect formula
  - » Gave approximately correct vacuum requirement (probably why the incorrect formula was not noticed)

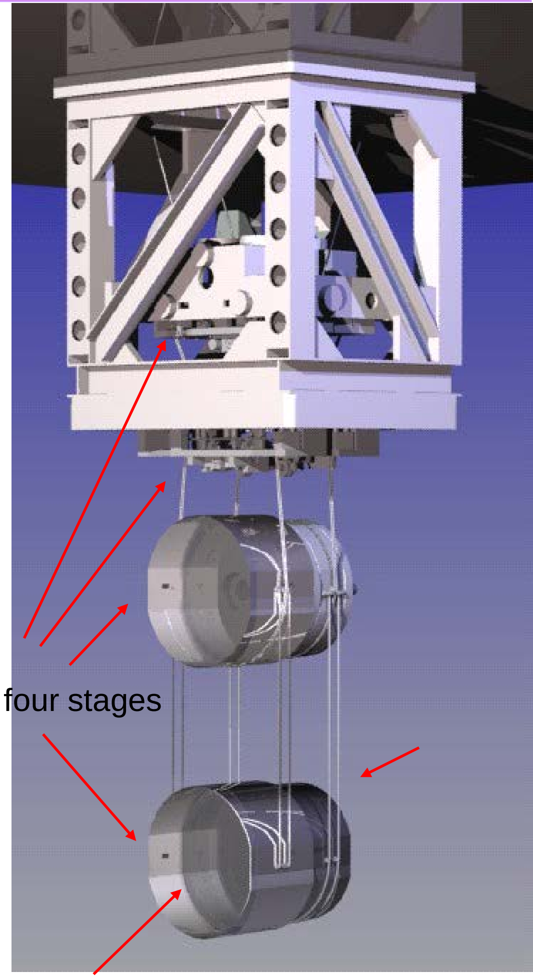
Residual Gas Noise Experiment

- Finally, definitively resolved (better than √2 level) and confirmed experimentally in 1994
  - » “Measurement of Optical Pathlength Fluctuations due to Residual Gas in the LIGO 40m Interferometer,” M. E. Zucker et al., in *Proc. Of the Seventh Marcel Grossmann Conference*, (1994)
- Just prior to beginning construction (whew!)



Thermal Noise

- One of the most important and complex fundamental noise sources



40 kg silica
test mass

Thermal Noise

Rai's RLE paper

- Importance clearly recognized (third noise source mentioned after shot noise and laser frequency noise)
- Single mode analysis for thermal noise, assuming viscous damping (suspension modes and internal modes)
- Suspension not defined as a pendulum
  - » Described as a "long-period seismometer suspension"

The RLE Paper

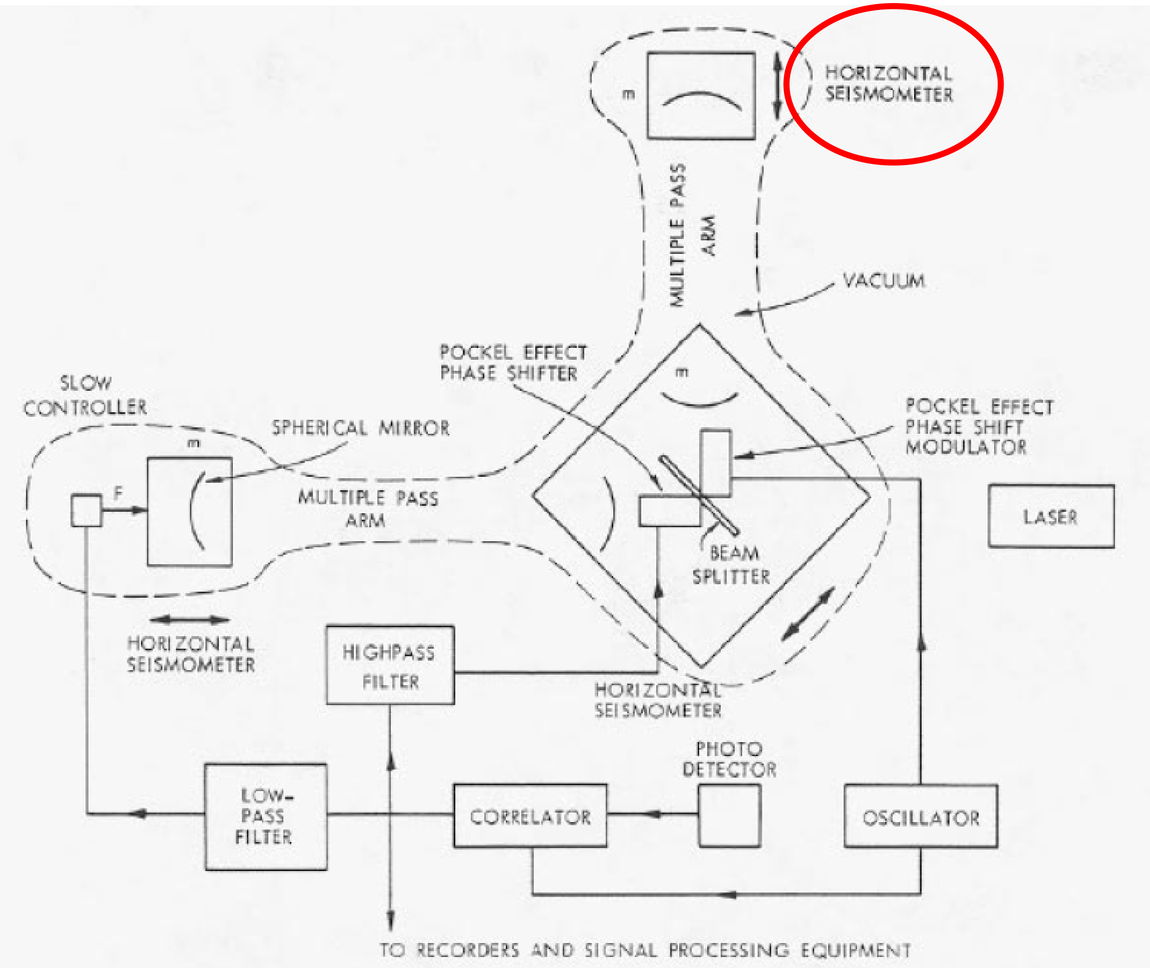


Fig. V-20. Proposed antenna.

Thermal Noise

Rai's RLE paper

- Importance clearly recognized (third noise source mentioned after shot noise and laser frequency noise)
- Single mode analysis for thermal noise, assuming viscous damping (suspension modes and internal modes)
- Suspension not defined as a pendulum
  - » Described as a "long-period seismometer suspension"
  - » "The suspensions are critical components in the antenna, and there is no obvious optimal design"
  - » Suspension mode Q ~10^4 (actual requirement for Advanced LIGO ~10^9)
- Multimode nature recognized
  - » "The general problem with suspensions in the real world is that they have not one degree of freedom but many,…"

Thermal Noise

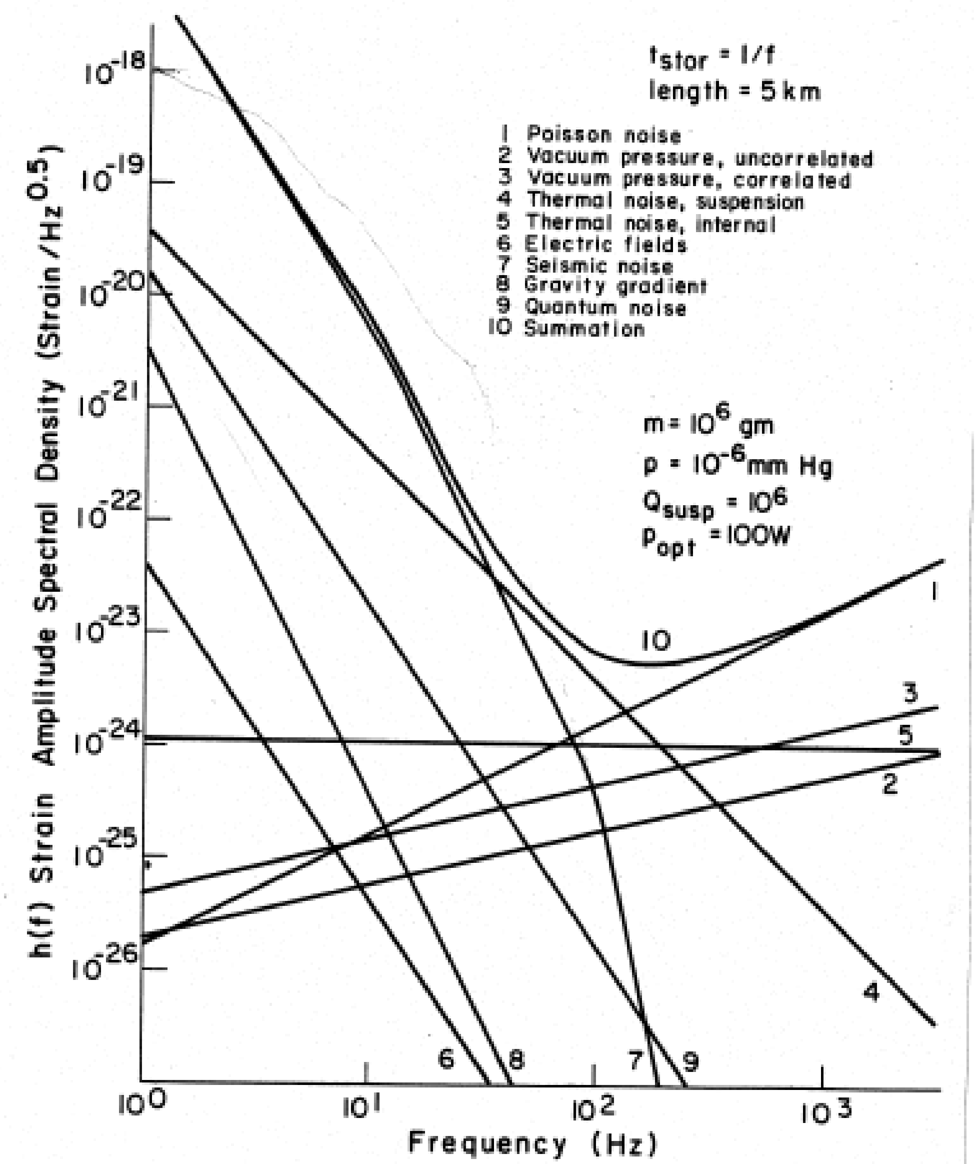
The "Blue Book"

- Still single mode analysis of thermal noise for estimating noise
- Beginning to recognize the complexity:
  - "…a frequency independent stochastic force is at this time still only a conjecture."
  - "There are situations where a blithe application of the model will give the wrong results." (coupled oscillators and servo damping)
- Largely unreferenced, so source of incorrect aspects hard to pin down
  - Fused silica Q_{mat} given as $\sim 10^{4}$. (actual $Q_{mat} \sim 10^{7}$)

Thermal Noise, cont

Blue Book

- Noise Budget
  - » Thermal noise from the suspensions (4) estimated to dominate in mid-frequency band



Thermal Noise, cont.

The '89 proposal

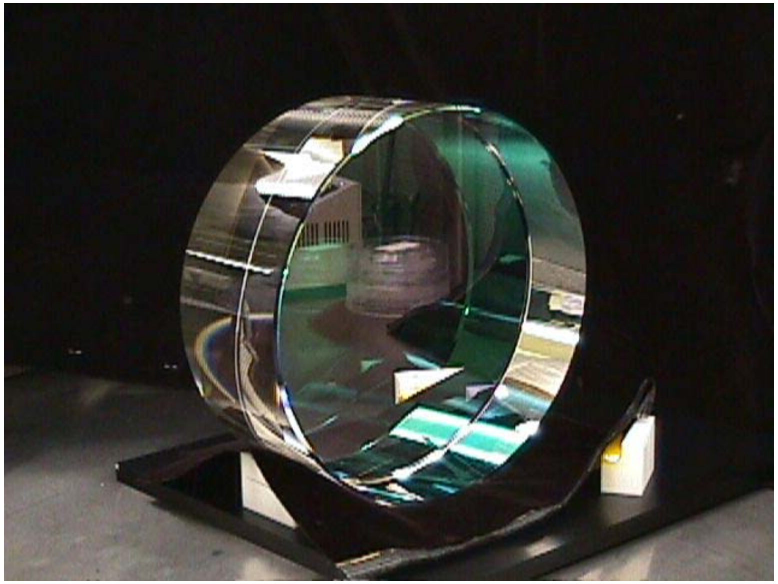
- First (?) mention of the Fluctuation-Dissipation Theorem (powerful theoretical tool)
  - » Not really used, however
- Noise estimates still based on viscous damping, but
  - » "…the damping can be frequency dependent so that a simple measurement of the Q of a resonance is not sufficient to predict the thermal noise off resonance."
- Recognized importance of overlap between internal mechanical modes and optical modes
  - » "Estimates of the equivalent gravitational wave strain … depend upon the overlap integral of the optical mode shape with the mechanical mode of the mass."

Thermal Noise

- Peter Saulson's paper
  - » "Thermal Noise in mechanical experiments," *Phys Rev* **D 42**, 2437 (1990)
  - » Complete set of references!
- Began while Peter was at MIT, during writing of '89 proposal, completed during a sabbatical at JILA
- First (?) presentation in the GW literature of:
  - » Structural damping on an equal basis with viscous damping
  - » Thermoelastic damping
  - » Clear discussion of Fluctuation-Dissipation Theorem
  - » Multi-mode systems, systems with localized losses, etc.
- Set the stage for progress in several areas: Yuri Levin's work, modern appreciation of coating thermal noise, etc.

Mirror Figure Requirement

- One of the biggest challenges in initial LIGO
- Requirement for Initial LIGO detectors: 0.6 nm rms



Mirror Figure Requirement

- Not mentioned in RLE paper
- Not mentioned in Blue Book
- 1987 LIGO R&D Proposal:
  - » "Mirror specifications (substrate material, surface polish, figure and slope errors) have been developed with industry."
  - » No clear discussion of where those requirements came from
  - » Requirement given as 20 nm (for laser wavelength ~500 nm) (Correcting for wavelength difference, ~60 times poorer than requirement for initial LIGO detectors)

Mirror Figure Requirement, cont.

- Same requirement repeated, without elaboration in ’89 proposal (still for wavelength ~500 nm)

TABLE IV–B–3
PARAMETERS FOR MAIN OPTICAL CAVITIES

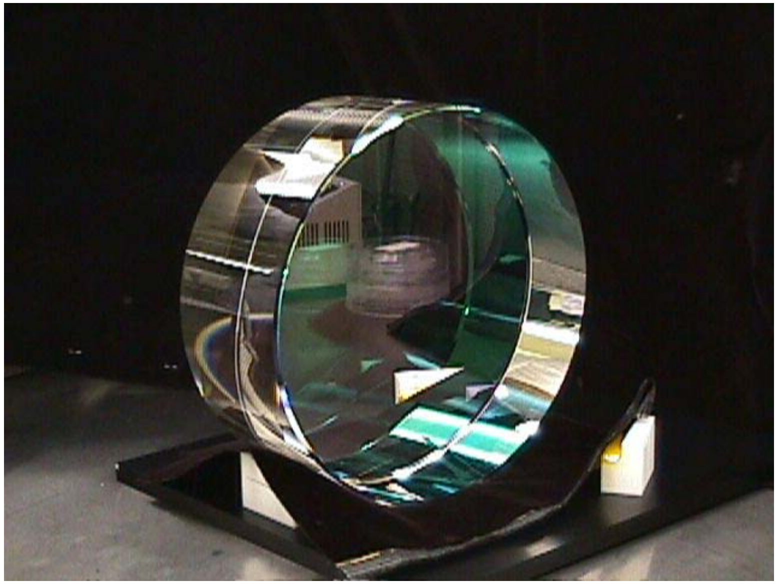
Parameter	Value	Notes[1]
Mirror Coatings		
Cavity storage time	2 msec	
Scattering + absorption	$\lesssim$ 50 ppm	
Surface microroughness	< 3 Å rms	for < 50 ppm scattering
Coating uniformity	$\lesssim$ 1.5%	rms variation of transmission coefficient over central 8 cm
Cavity length L	4.0 km	(2.0 km)
Mirror curvature R	3.0 km	(1.5 km)
Figure error	200 Å	rms over central 8 cm
Cavity stability parameter $g = 1 - \frac{L}{R}$	−0.33	(−0.33)

Mirror Figure Requirement, cont.

- Began to realize challenge as a result of effort to define specification of the substrate uniformity
  - » Mike Burka (MIT postdoc) undertook a program of measurements and modeling to study effects of mirror substrate inhomogenities on the dark port contrast (to assure adequate recycling gain)
- Slowly the requirement began to tighten
  - » Developed optical modal model for full interferometer
  - » First FFT models for interferometer a few years later
- By 1995, when construction of detectors began
  - » Requirement had tightened to λ/400
  - » Laser type changed from Ar+ laser to Nd:YAG (wavelength from 500 nm to 1064 nm)
  - » “Discovered” the AXAF Test Flat (LIGO sized optic polished by Perkin-Elmer for NASA x-ray satellite—approximately 1 nm rms)

Test Mass/Mirror Specification

- Detailed optical modelling led to final specification (another factor of ~4)
- Polishing
  - » Surface uniformity < 0.6 nm rms (λ / 1600)
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity $<10^{-3}$
- The final challenge was to convince industry that not only could they do it, they were already doing it



Take-Aways

- Some of the challenges facing LIGO were recognized early, and the path to overcoming them was steady, even if difficult (thermal noise)
- Some of the challenges were recognized early, and the path to overcoming them involved both positive and negative progress (residual gas noise)
- Some of the challenges were not recognized until rather late in the project, and had to be overcome under intense pressure (mirror figure reqt.)