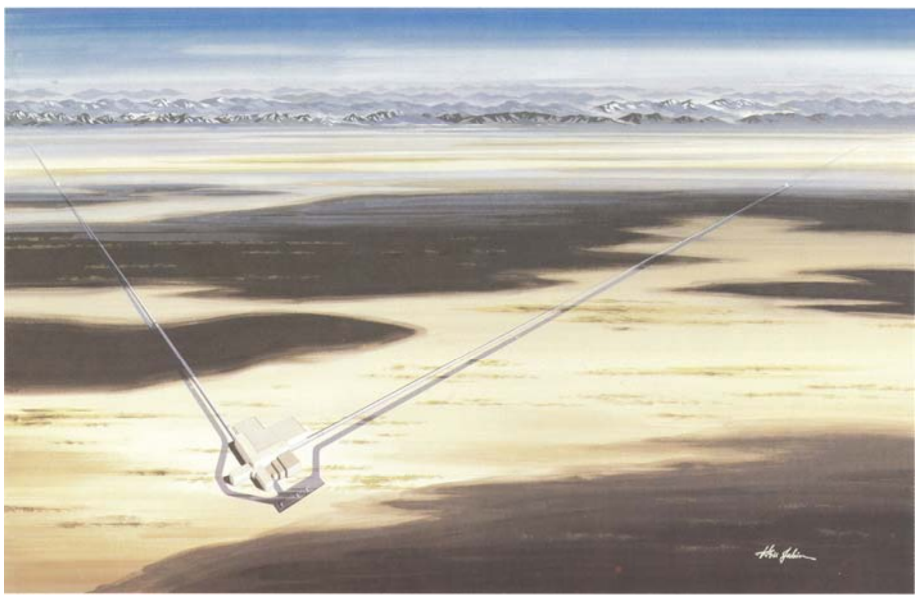
An Idiosyncratic History of Technical Developments Leading to LIGO

Idiosynchratic: "peculiar to the individual"



Stan Whitcomb

CaJGWAR Seminar

20 April 2010

LIGO-G1000475-v1

Outline of Talk

- Review some of the technical developments that enabled LIGO, with emphasis on pre-1995 era
  - » "Invention" of laser interferometers for GW detection
  - » Residual Gas Noise (Vacuum requirement)
  - » Thermal noise
  - » Mirror figure requirements
  - » Mirror angular control
  - » International collaboration

Goal of Talk

- Review some of the technical developments that enabled LIGO, with emphasis on pre-1995 era
  - » "Invention" of laser interferometers for GW detection
  - » Residual Gas Noise (Vacuum requirement)
  - » Thermal noise
  - » Mirror figure requirements
  - » Mirror angular control
  - » International collaboration
- Help us appreciate:
  - » How little we really knew when this started
  - » How far we have come in our understanding
  - » How far we still have to go (perhaps)
  - » (What did some of those old guys that you see at the meetings really do when they were young and productive?)
-

Disclaimer

- Review some of the technical developments that enabled LIGO, with emphasis on pre-1995 era
  - » “Invention” of laser interferometers for GW detection
  - » Residual Gas Noise (Vacuum requirement)
  - » Thermal noise
  - » Mirror figure requirements
  - » Mirror angular control
  - » International collaboration
- Help us appreciate:
  - » How little we really knew when this started
  - » How far we have come in our understanding
  - » How far we still have to go (perhaps)
  - » (What did some of those old guys that you see at the meetings really do when they were young and productive?)
- Disclaimer: Not comprehensive, not ordered by importance, not even necessarily correct, …

Reference Documents

Three documents 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

The RLE Paper

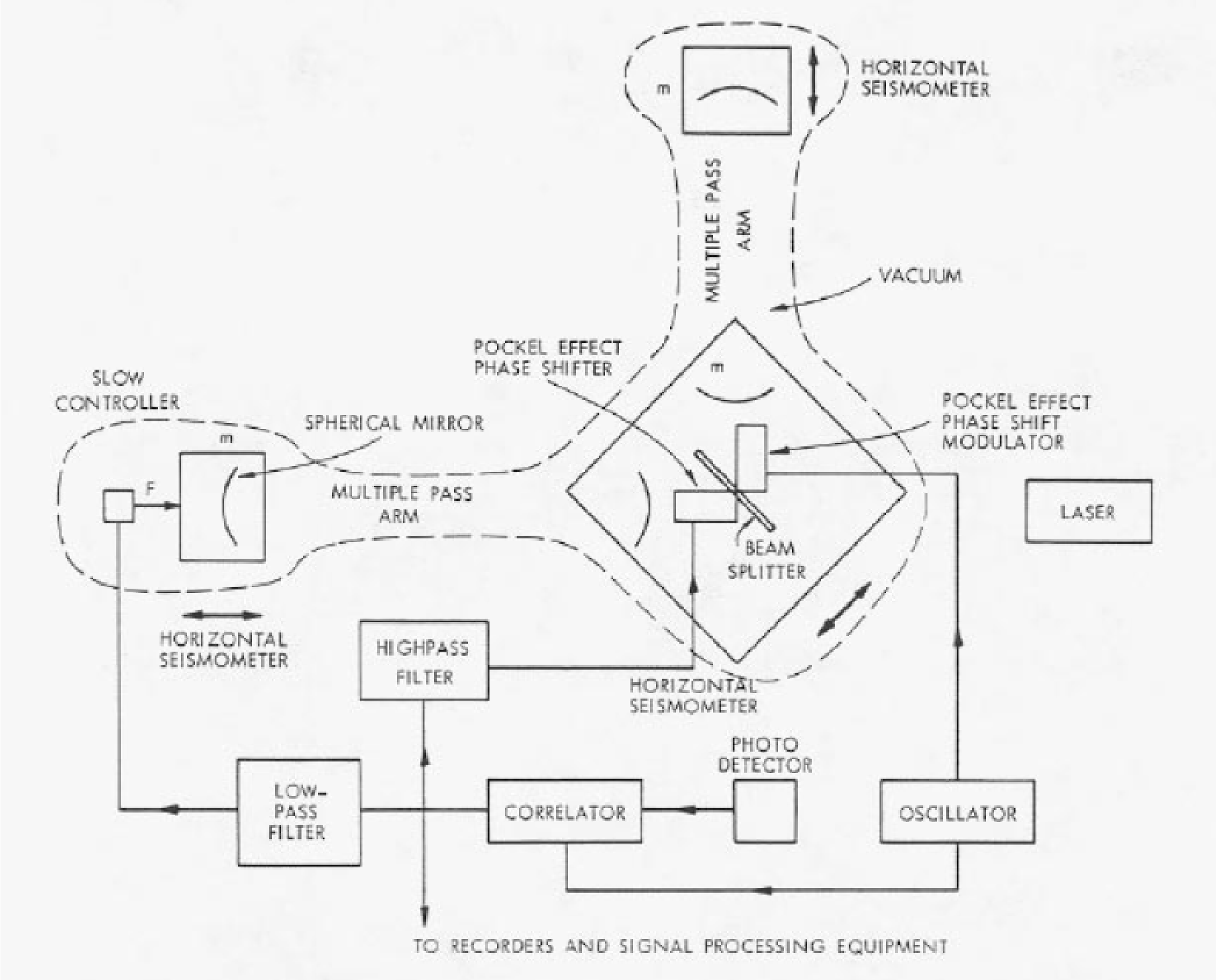


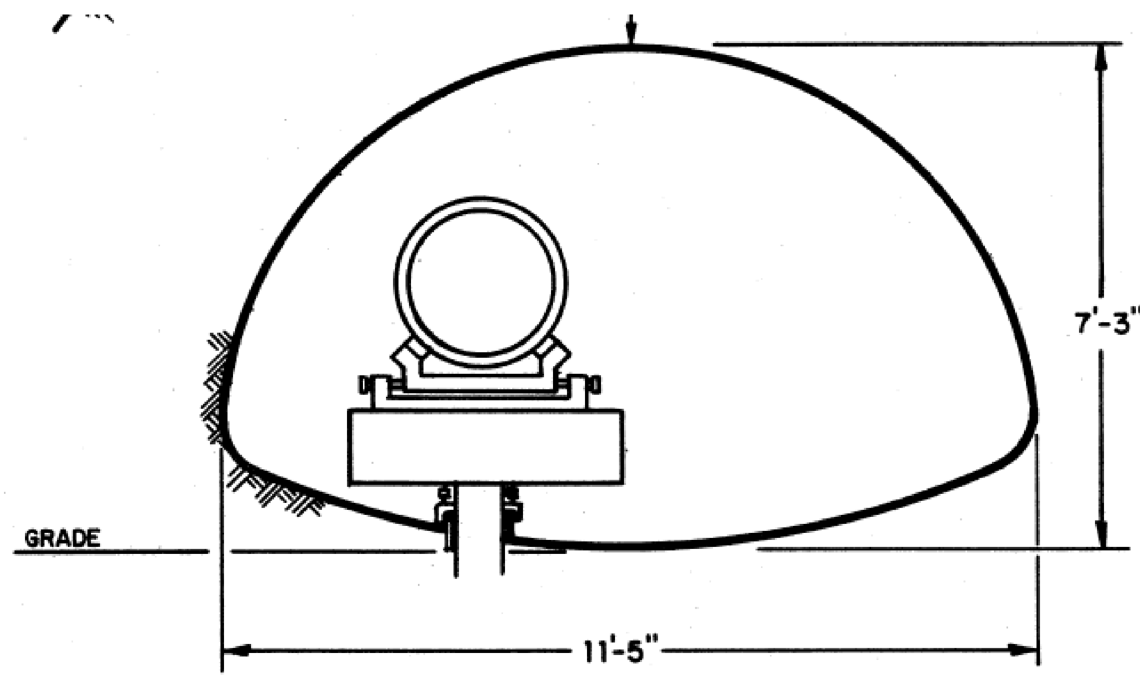
Fig. V-20. Proposed antenna.

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
» …

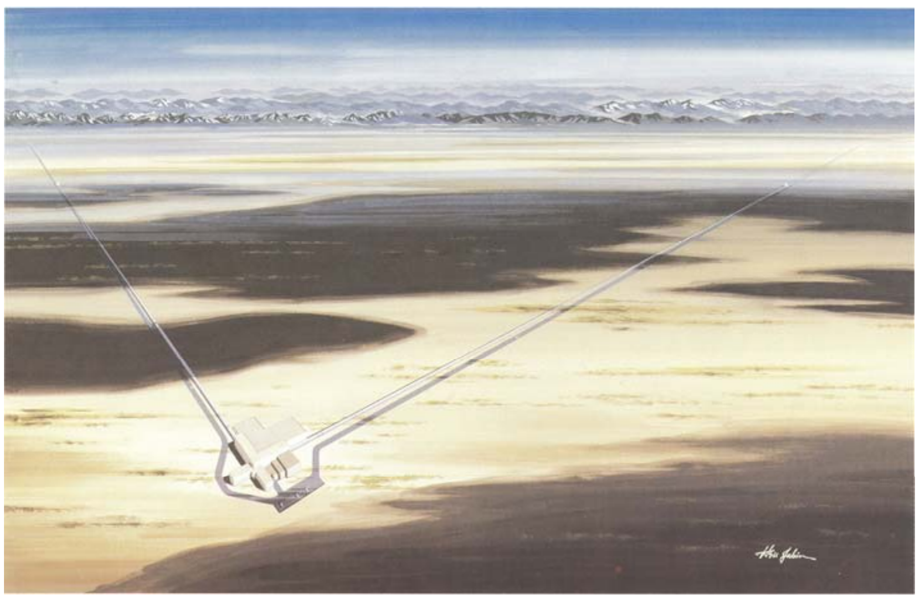
The Blue Book

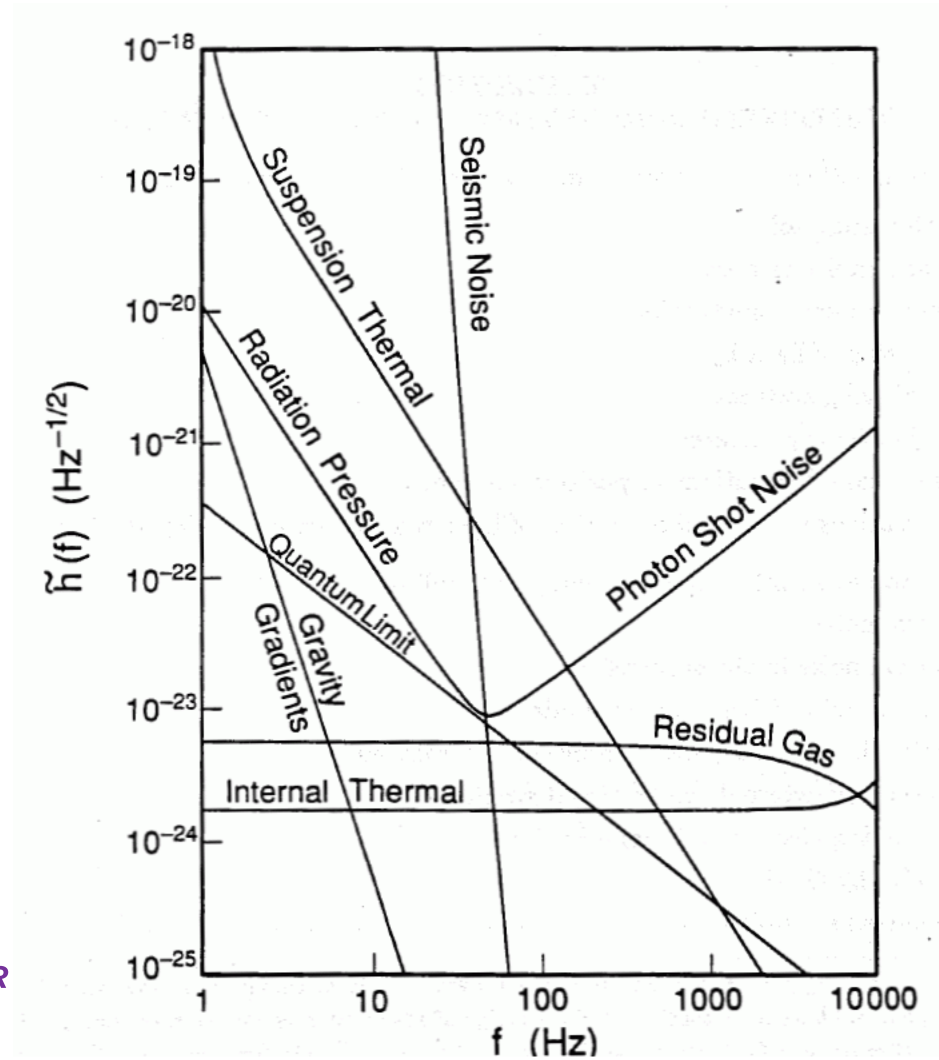
- Science and Engineering study of feasibility
- Comprehensive scope—Chapter titles
  - » Sources of Gravitational Radiation
  - » Physics and Detection
  - » Prototypes and Optical Concepts
  - » Noise sources
  - » Vacuum System
  - » Site survey
  - » Construction
  - » Proposed Design
- Important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





Who Invented the Laser Interferometer Gravitational Wave Detector?

Because everyone asks this…

Multiple Independent Inventions

- (At least one) early gedanken experiment using interferometry to detect GWs:
  - » F.A.E. Pirani, *Acta Phys. Polon*. **15**, 389 (1956)
  - » (predates invention of laser by 4 years)
  - » Cited in Rai's RLE paper (but don't ask me how he found it!)
- Often cited as first suggestion:
  - » M.E.Gertsenshtein and V.I. Pustovoit, Zh. Eksp. Teor. Fiz. **43**,605 (1962); Sov. Phys JETP,**16**, 433 (1063).
  - » Not cited in RLE paper, but was noted by Braginsky in "Gravitational radiation and the prospect of its experimental discovery," *Sov. Phys. Usp.* **8**, 513 (1966).
- Rai's RLE paper represented an independent invention ("several years" before 1972)
- RLE paper cites Philip Chapman (NASA) as having independently proposed technique

First Interferometer Prototype

- Started at Hughes Research Labs in 1966!
  - » Described in G.E. Moss, R.L. Miller and R.L. Forward, "Photon-noise-Limited Laser Tranducer for Gravitational Antenna" *Applied Optics* **10**, 2495 (1971).

> The idea of detecting gravitational radiation by using a laser to measure the differential motion of two isolated masses has been suggested often in the past.[5]
>
> 5. To our knowledge, the first suggestion was made by J. Weber in a telephone conversation with one of us (RLF) on 14 September 1964.

  - » Also acknowledges Weiss and Chapman
- First search result published in 1978
  - » "Wideband laser-interferometer gravitational-radiation experiment," R.L. Forward, *Phys Rev* D, 17, 379 (1978)

Forward Interferometer

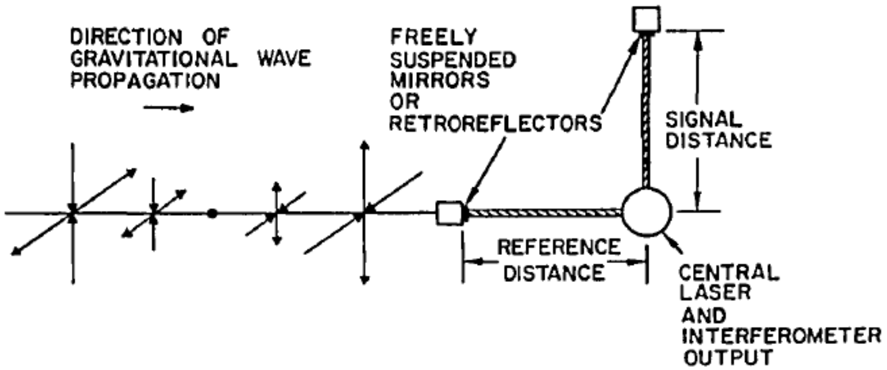


Fig. 1. Right angle interferometer antenna. The reference distance is not changed by gravitational radiation in the direction of propagation shown.

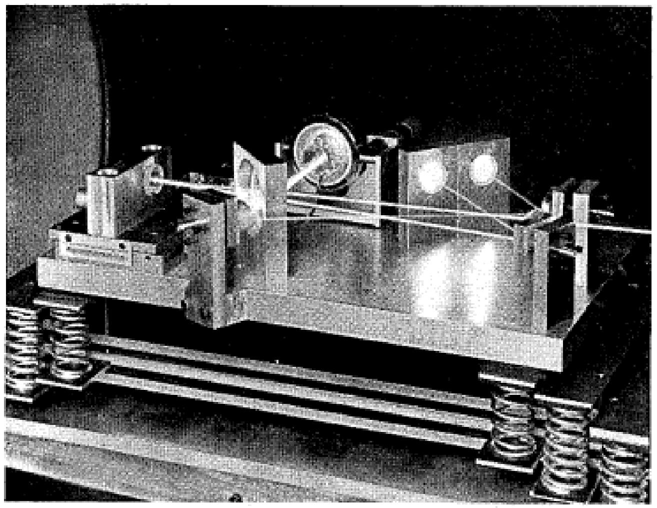


Fig. 4. Photograph of interferometer setup on 3-Hz isolation suspension.

Data Analysis section:
"Calibration of the Ear"

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 Calculations

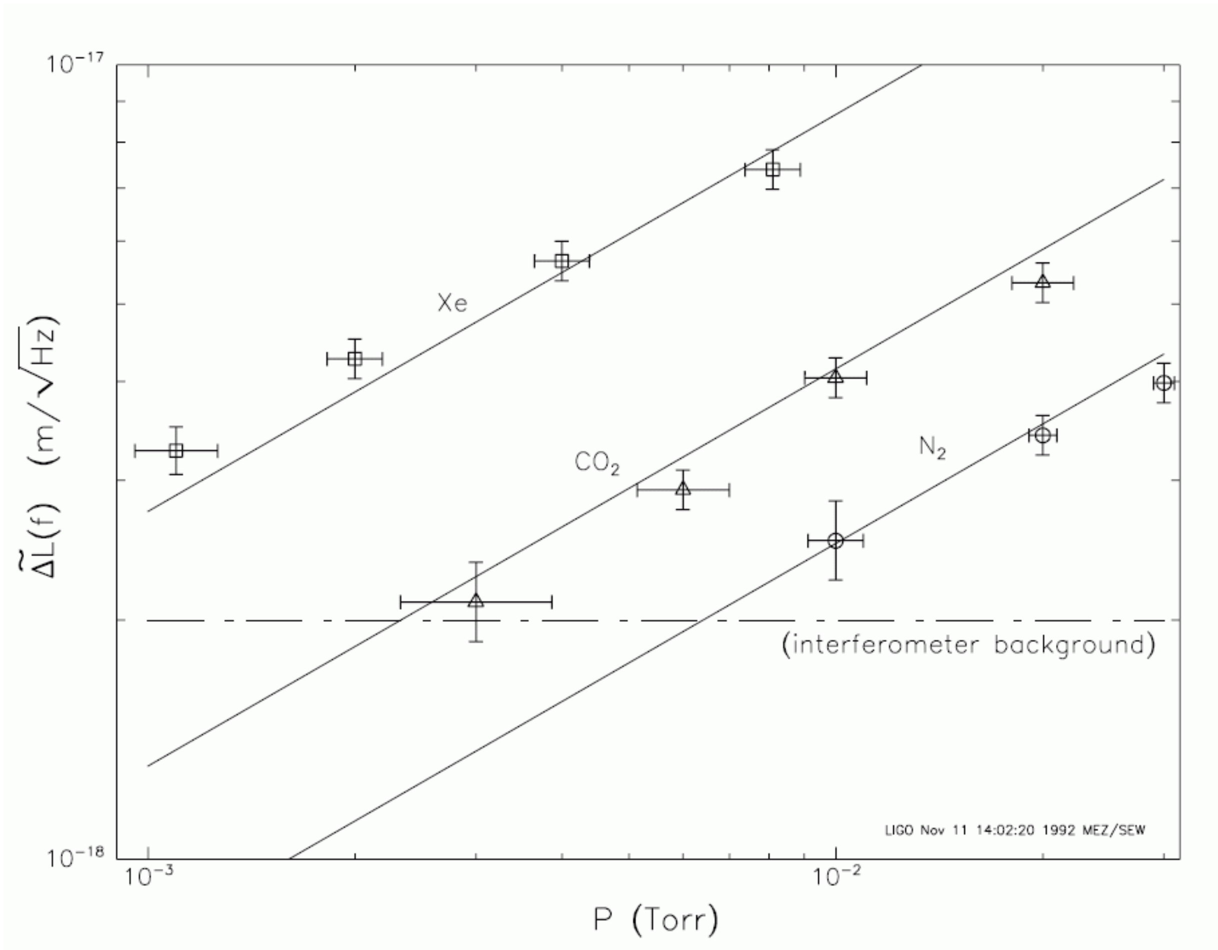
- Not mentioned in Rai's RLE paper
- The Blue Book (1983)
  - » Has an essentially correct treatment of the noise due to residual gas—statistical fluctuations in the number of gas molecules in the beam causing fluctuations in refractive index
  - » Correct initial LIGO requirement ~10^{-6} torr
- Correct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

Residual Gas Noise Calculations, cont.

- Not entirely a straight line progression
- 1987 LIGO R&D proposal
  - » Initial LIGO requirement quoted (at least one place) as 10^{-3} torr
- ’89 proposal
  - » A new formulation of the problem, in terms of the forward scattering matrix for individual gas molecules
  - » Simple algebraic error ended up with incorrect formula
  - » Gave ~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)



Thermal Noise

- One of the most important and complex fundamental noise sources

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

The RLE Paper

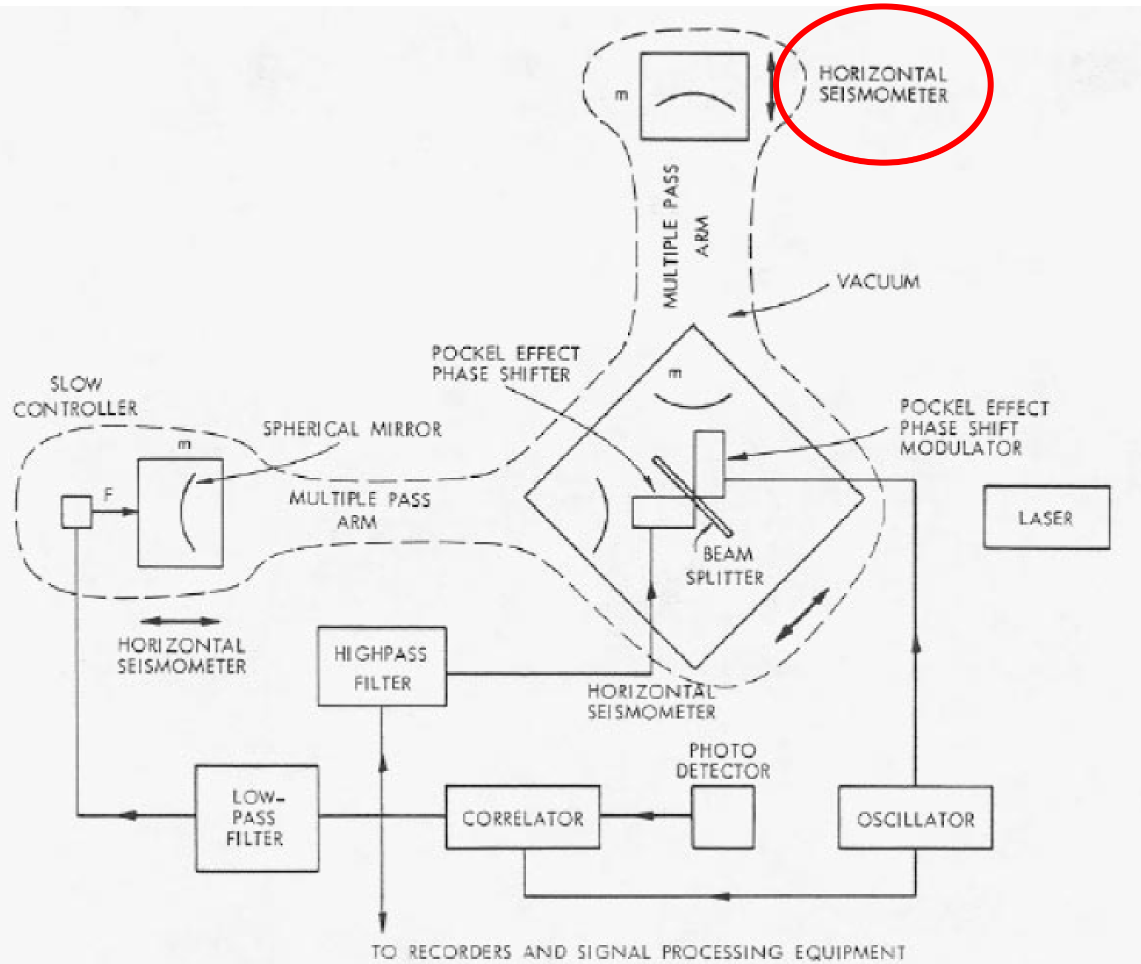


Fig. V-20. Proposed antenna.

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
- Multimode nature recognized
  - » "The general problem with suspension in the real world is that they have not one degree of freedom but many,…"

Thermal Noise

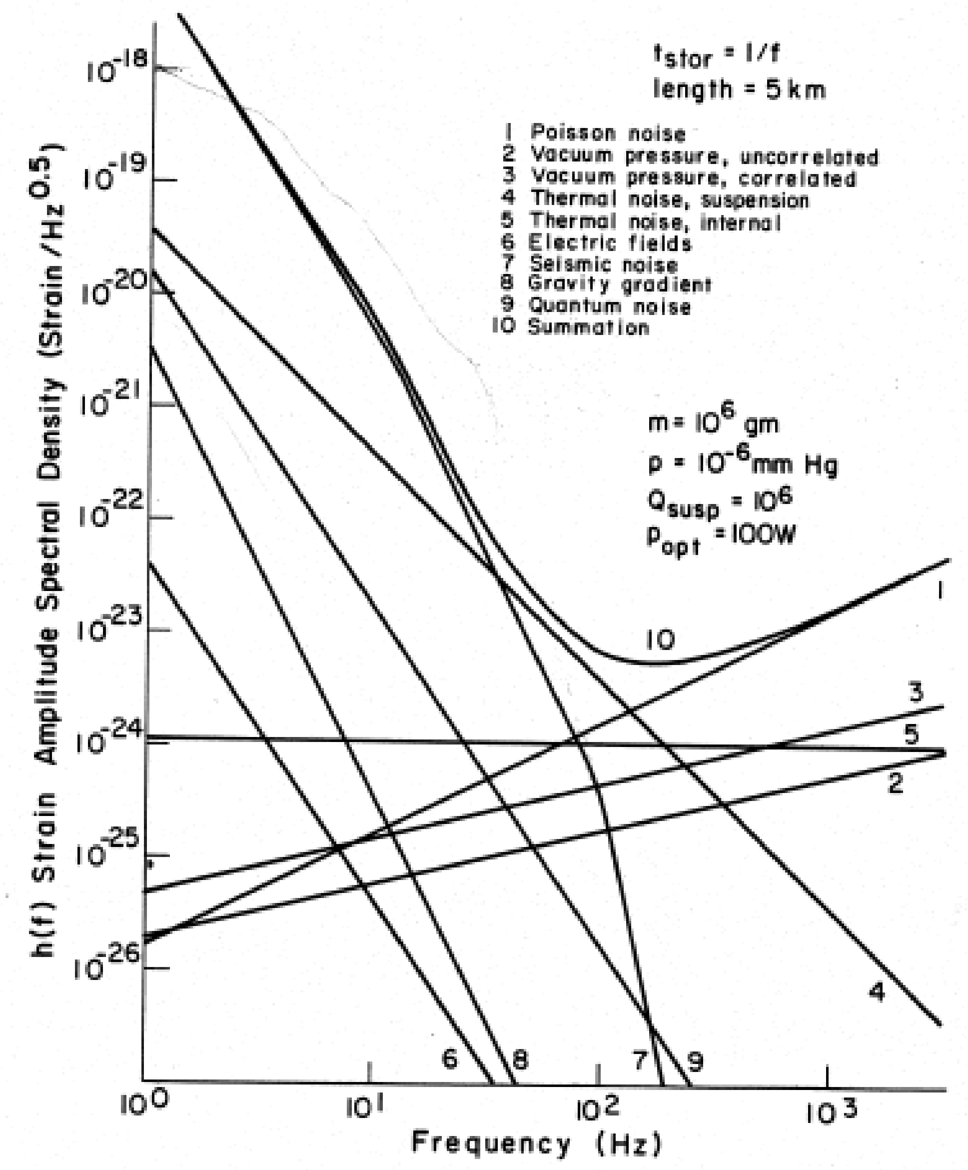
The “Blue Book”

- 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 conclusions
  - » Fused silica Q_{mat} given as $\sim 10^4$

Thermal Noise, cont

Blue Book

- Noise Budget
  - » The careful reader will note that the residual gas curves have the wrong slope. The formula in the blue book is correct—apparently the wrong curve was plotted.



Thermal Noise, cont.

The ’89 proposal

- First (?) mention of the Fluctuation-Dissipation Theorem
  - » Not really used, however
- Noise estimates still based on viscous damping
  - » “…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
- One of the first presentations 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
- Initial LIGO requirement: 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
  - » Requirement given as 20 nm (for laser wavelength ~500 nm)
  - » (Correcting for wavelength difference, ~60 times poorer than initial LIGO requirement

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

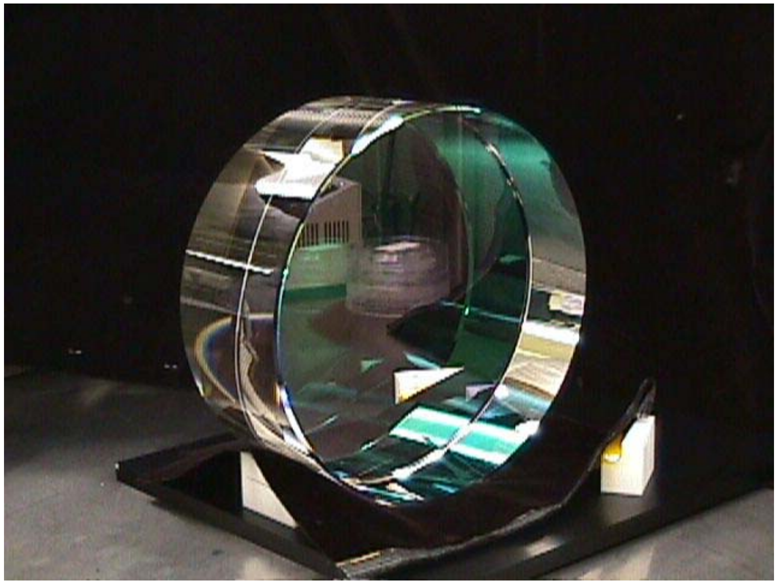
Parameter	Value	Notes[1]
Mirror Coatings		
Cavity storage time	2 msec	
Scattering + absorption	$\lesssim$ 50 ppm	
Surface microroughness	< 3 Å rms	for < 50 ppm scattering
Coating uniformity	$\lesssim$ 1.5%	rms variation of transmission coefficient over central 8 cm
Cavity length L	4.0 km	(2.0 km)
Mirror 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.

- Initial concern was for the specification of the substrate uniformity
  - » Mike Burka initiated a program of measurements and modeling to study the effects of ITM substrate inhomogenities on the dark port contrast (to assure adequate recycling gain)
- Slowly the requirement began to tighten
  - » Application of modal model for full interferometer
  - » First FFT models for interferometer
- By 1995
  - » Requirement had tightened to $\lambda/400$
  - » 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

- Evolution to final specification (another factor of ~2)
- 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



Mirror Orientation Noise

- Was a dominant source of noise in 40m circa 1990
- Significant because of one of the first bi-linear noise mechanisms studied

Mirror Orientation Noise

- Not mentioned in RLE paper
- Mentioned, but not discussed as a serious noise source in Blue Book
  - » "These effects are only second order in the [angles.]"

$$\Delta d = -(R+D)^2\,\phi^2\left(\frac{1}{r} + \frac{1}{2(R+D)}\right)$$

- Not discussed in detail in '89 Proposal, but requirements indicate that it is still dismissed as second order

TABLE IV–B–6
STABILITY OF CAVITY BEAMS AND TEST MASSES

Parameter	Value	Notes
Test-mass stability		
Angular stability	$< 4 \cdot 10^{-7}$ rad	Peak motion at low frequency
Position stability	$\lesssim 0.7$ mm	Peak motion at low frequency
Beam stability		
Angular fluctuations	$< 10^{-12}$ rad/$\sqrt{\text{Hz}}$	$f \approx 1$ kHz
Position stability	$\lesssim 0.7$ mm	Peak motion at low frequency

Mirror Orientation Noise, first clue

- 1990: 40 m interferometer noise was high, not understood
  - » LIGO construction proposal under review, and it was important for the prototypes to show steady progress on sensitivity
  - » Seiji Kawamura began investigations of orientation control systems
  - » Interest first piqued by the broad lines at multiples of 60 Hz, and the obvious sideband structure

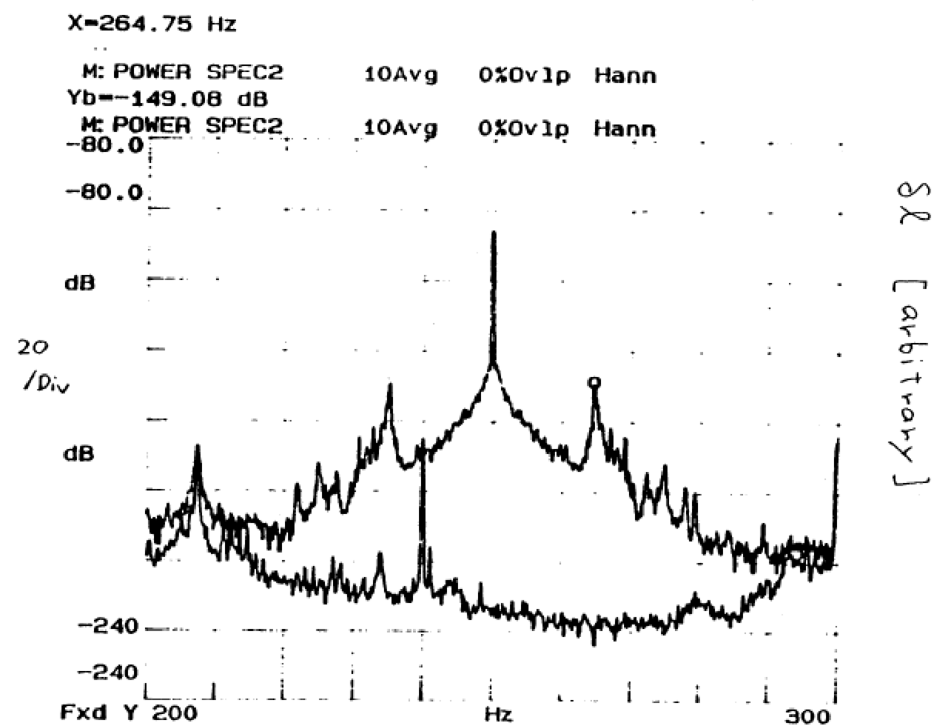


Fig. 3 Displacement spectrum.
Upper : with angle variations at 250 Hz
Lower : natural

Mirror Orientation Noise, continued

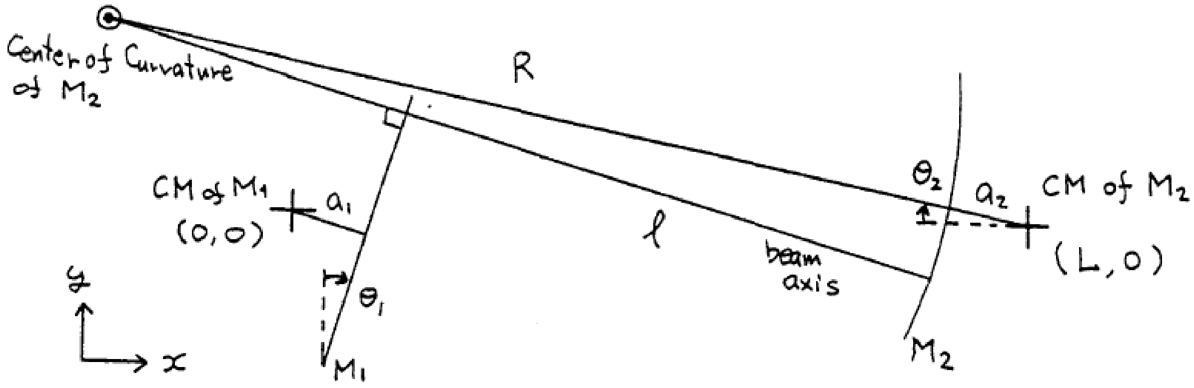


Fig. 1 Arm cavity of the 40m prototype

- Worked out the geometrical length of a misaligned cavity
- First interpretation was in terms of a static misalignment (displacement of the cavity spot from the center of rotation)

Evolution of Understanding

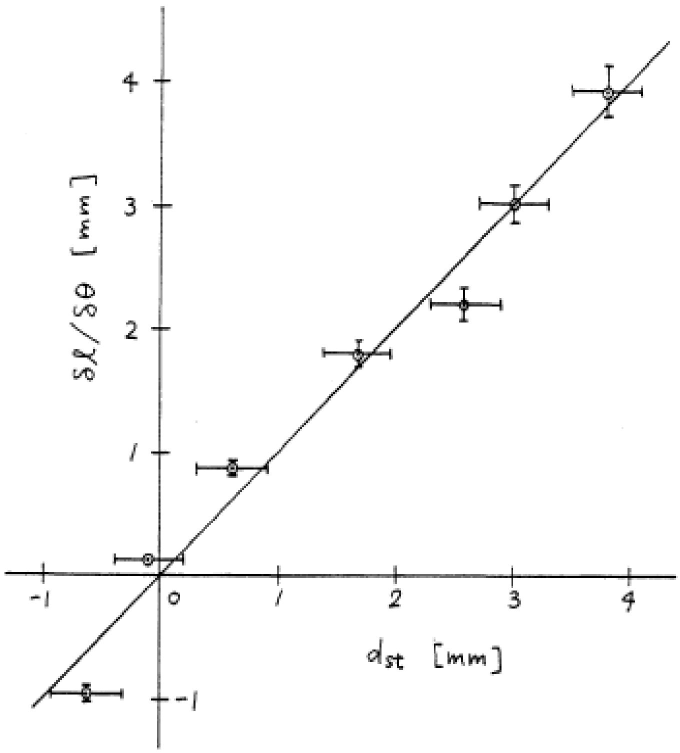
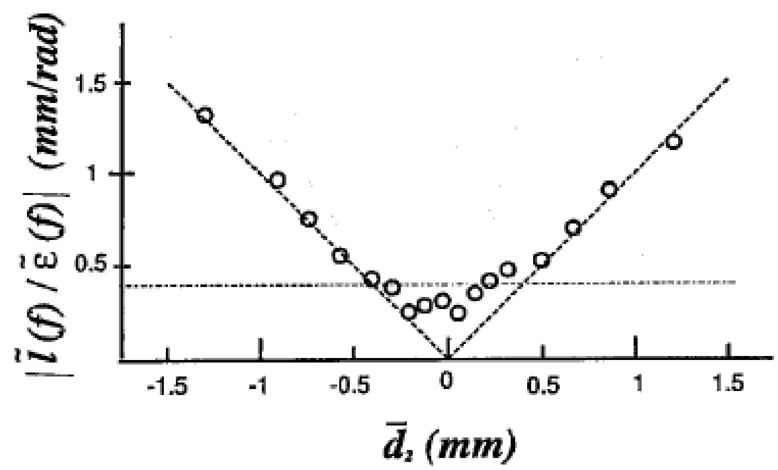


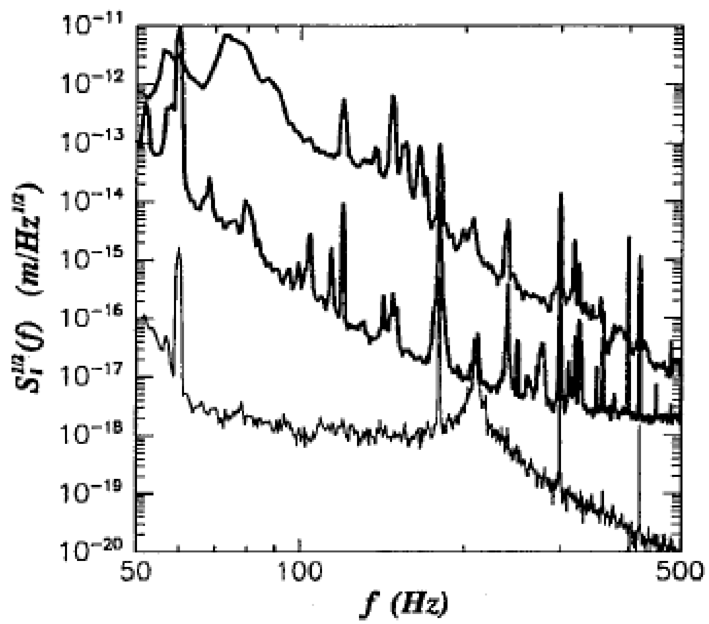
Fig. 2 Linear effect of mirror angle – displacement coupling as a function of static beam spot position. The solid line is $\delta\ell/\delta\theta = d_{st}$

Important recognition was that the large amplitude low frequency mixes with in-band angular noise to create displacement noise



Improved 40 m performance

- Improved noise in 40 m at a critical time
  - » Published as "Mirror-orientation noise in a Fabry-Perot interferometer gravitational wave detector," S. Kawamura and M Zucker, *Applied Optics*, **33**, 3912 (1994).
  - » Obvious once it is pointed out, but under-appreciated in my view
  - » Opened many people's eyes to the large class of bi-linear noise sources



International Collaboration

- An important development in the last 5 years

International Collaboration

- Sometimes dreaming big pays off

Caltech *GRP*-341

The LIGO/VIRGO Gravitational-Wave Detection System

Kip S. Thorne

Theoretical Astrophysics, California Institute of Technology Pasadena, CA 91125; and Institute for Theoretical Physics, University of California Santa Barbara, CA 93106

Submitted to *Proceedings of Fourth Rencontres on Particle Astrophysics*, Blois France, July 1992, ed. J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, France)

Research supported in part by National Science Foundation Grants PHY-9213508 and PHY-8904035.

Conclusion

- A lot of Stuff happened in the past, more Stuff will happen in the future
  - » Some things were right, and the insights people had were amazing
  - » Some were not, and the insights that they didn't have were equally amazing
- Let's not waste time with questions when there is wine in the next room