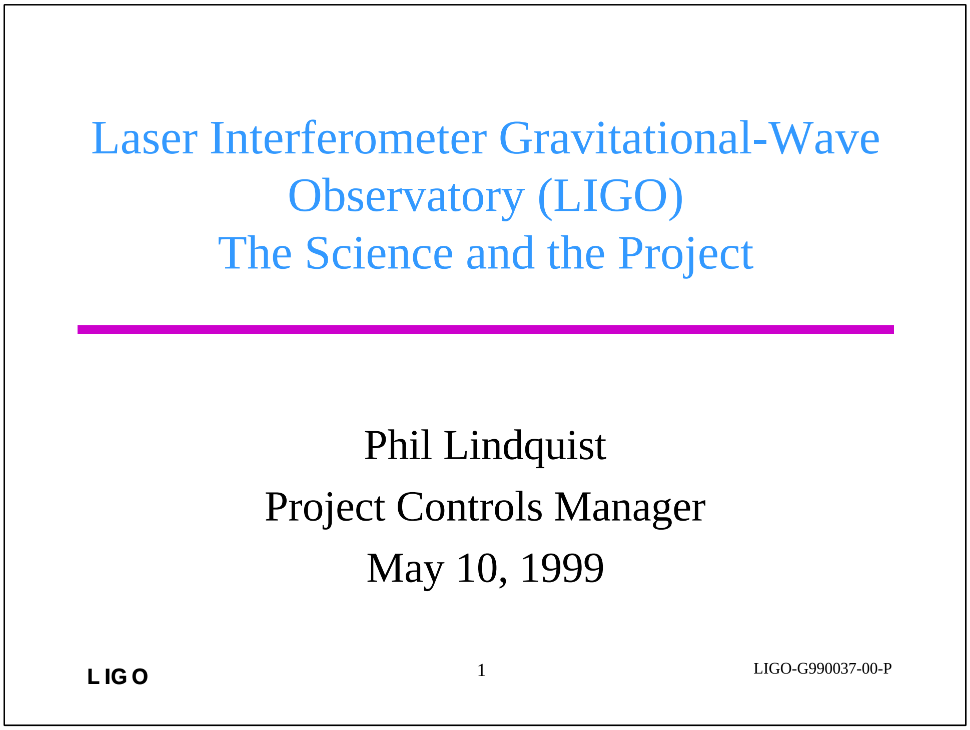


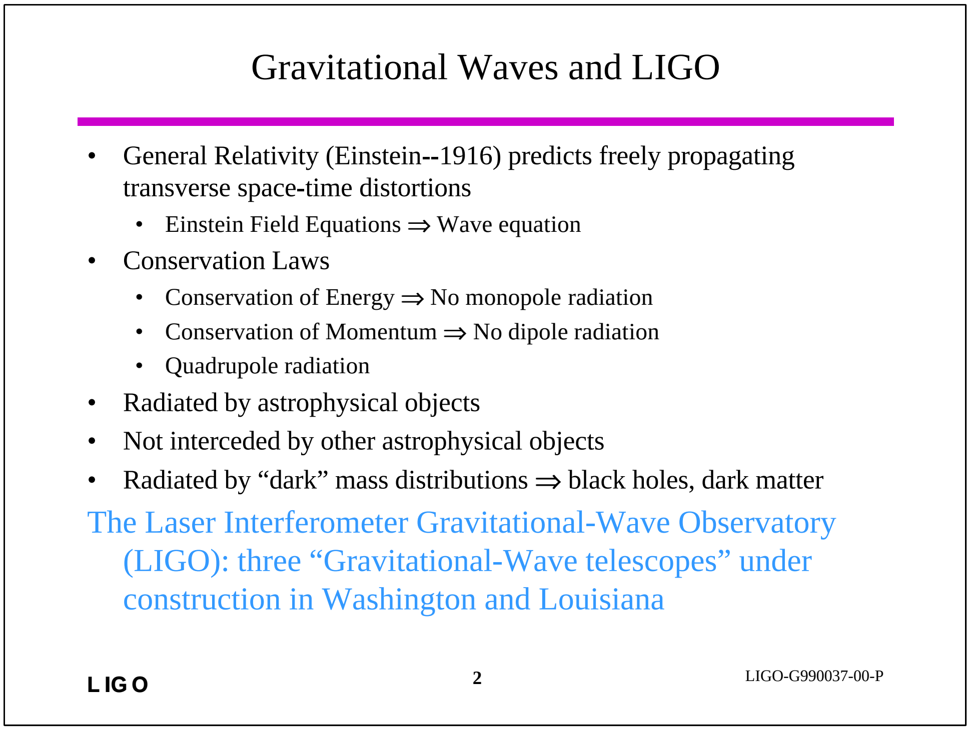
Laser Interferometer Gravitational-Wave Observatory (LIGO)
The Science and the Project

Phil Lindquist
Project Controls Manager
May 10, 1999

My talk is in two parts.

The first part talks about the physics and status of the LIGO Project

The second part is about the Project Management systems that have been use to manage the LIGO Project.



Gravitational Waves and LIGO

- General Relativity (Einstein--1916) predicts freely propagating transverse space-time distortions
  - Einstein Field Equations ⇒ Wave equation
- Conservation Laws
  - Conservation of Energy ⇒ No monopole radiation
  - Conservation of Momentum ⇒ No dipole radiation
  - Quadrupole radiation
- Radiated by astrophysical objects
- Not interceded by other astrophysical objects
- Radiated by “dark” mass distributions ⇒ black holes, dark matter

The Laser Interferometer Gravitational-Wave Observatory (LIGO): three “Gravitational-Wave telescopes” under construction in Washington and Louisiana

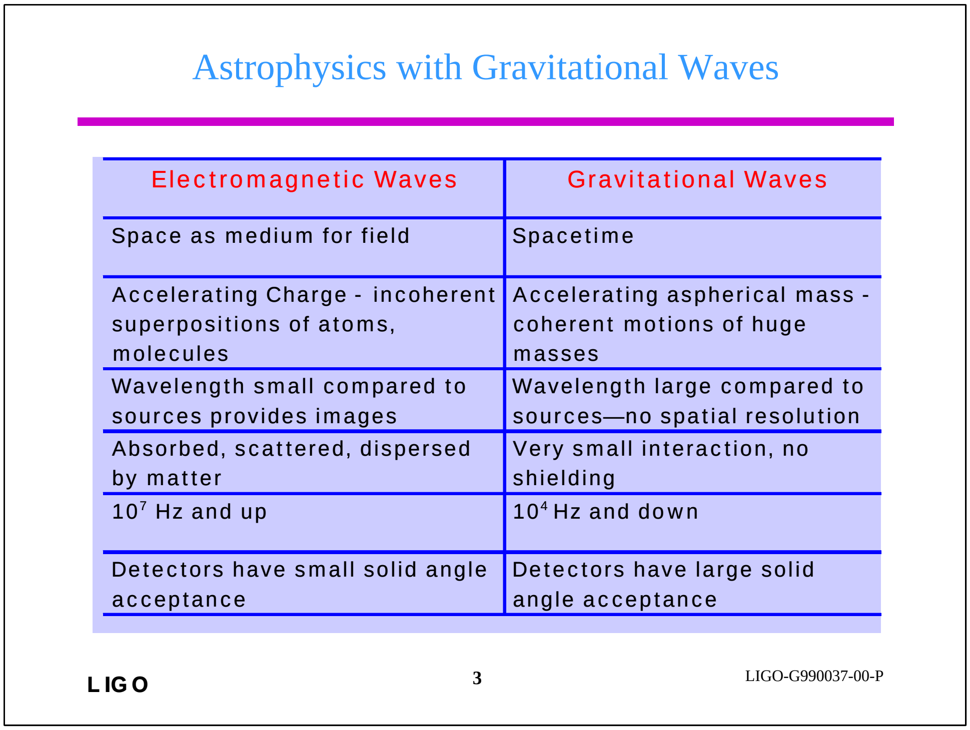
Einstein’s Theory of Relativity predicts freely propagating Gravitational Waves.

•Conservation Laws dictate that these waves will be quadrupole waves

•To generate Gravitational Waves requires very heavy objects accelerating very quickly

•Gravitational Waves are not absorbed by other astrophysical objects

•The LIGO Project is building three Gravitational-Wave Observatories in Washington state and Louisiana

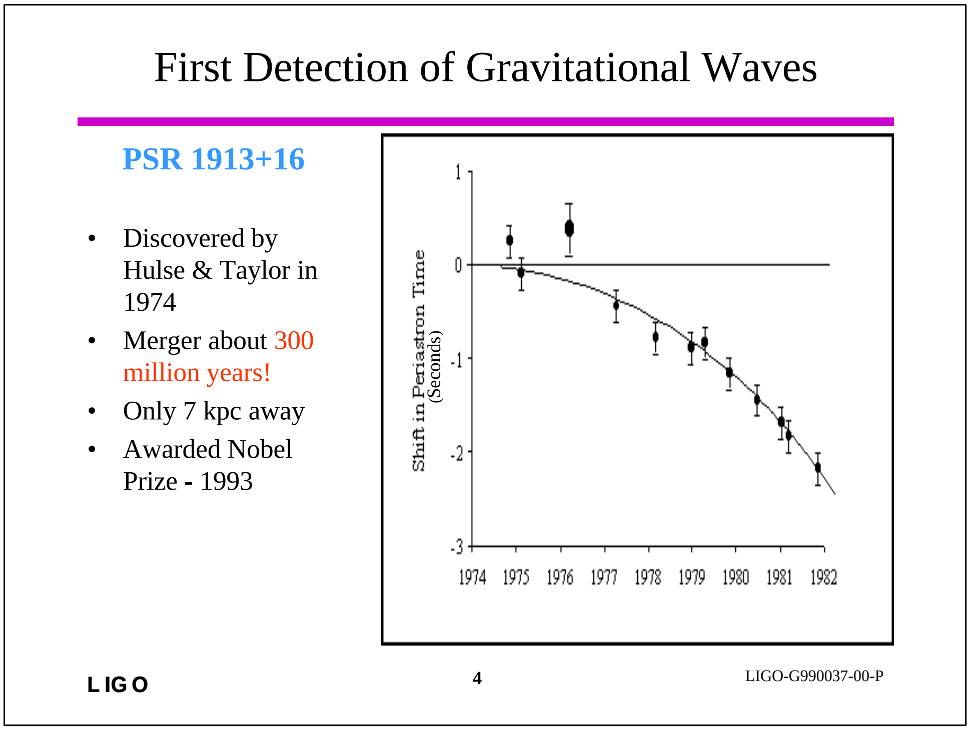


Astrophysics with Gravitational Waves

Electromagnetic Waves	Gravitational Waves
Space as medium for field	Spacetime
Accelerating Charge - incoherent superpositions of atoms, molecules	Accelerating aspherical mass - coherent motions of huge masses
Wavelength small compared to sources provides images	Wavelength large compared to sources—no spatial resolution
Absorbed, scattered, dispersed by matter	Very small interaction, no shielding
10^7 Hz and up	10^4 Hz and down
Detectors have small solid angle acceptance	Detectors have large solid angle acceptance

Electromagnetic Waves and Gravitational Waves are very different.

- Very different information, mostly mutually exclusive
- Difficult to predict GW sources based on Electromagnetic observations



First Detection of Gravitational Waves

PSR 1913+16

- Discovered by Hulse & Taylor in 1974
- Merger about 300 million years!
- Only 7 kpc away
- Awarded Nobel Prize - 1993

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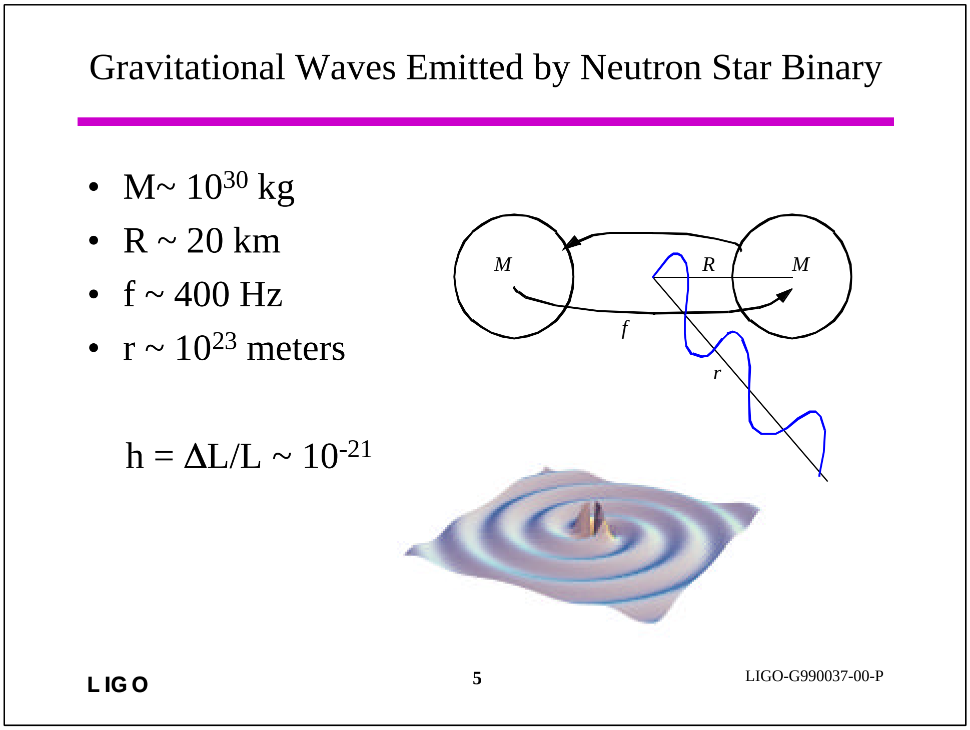
Gravitational-Waves have been measured indirectly
Hulse and Taylor in 1974 looked at a neutron star binary where one of the stars is a pulsar

- One lightyear = 3 x 10^{15} meters
- One parsec = 3.26 lightyears ~ 10^{16} meters



Gravitational Waves Emitted by Neutron Star Binary

- M~ 10^{30} kg
- R ~ 20 km
- f ~ 400 Hz
- r ~ 10^{23} meters

h = ΔL/L ~ 10^{-21}

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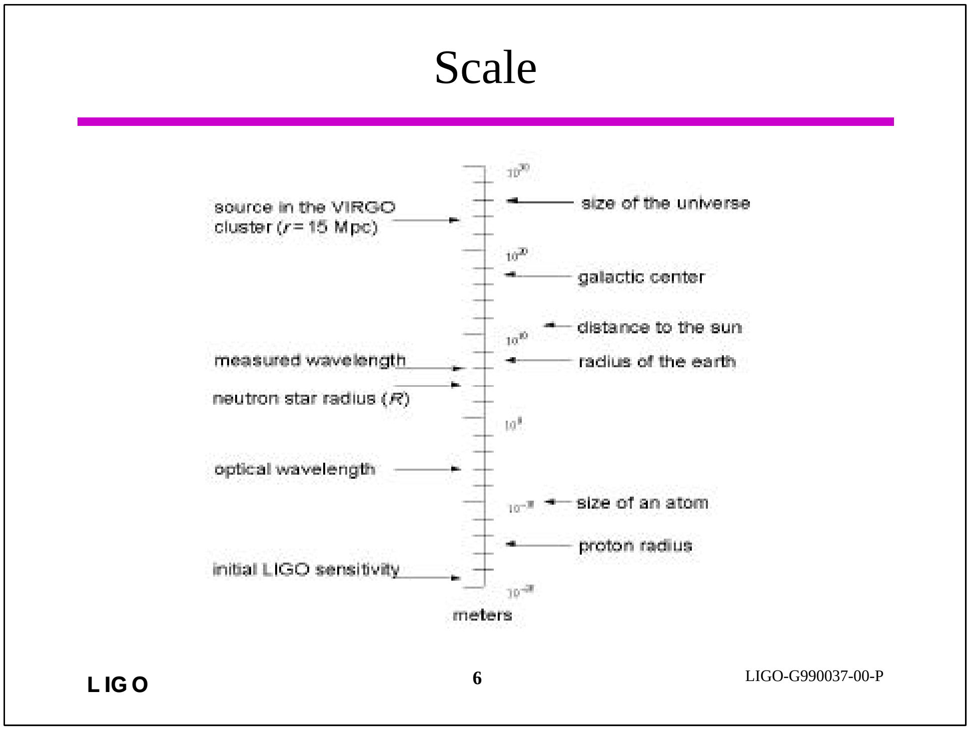
•Parsec = 10^{16} meters
•Speed of light = 10^{8} meters/sec
•One lightyear = 3.15 x 10^{15} meters
•One parsec = 3.26 lightyears
•r ~ 10 megaparsecs

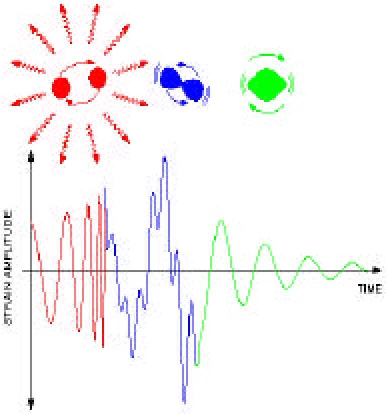


Scale

One parsec = 3.26 lightyears ~ 10^{16} meters

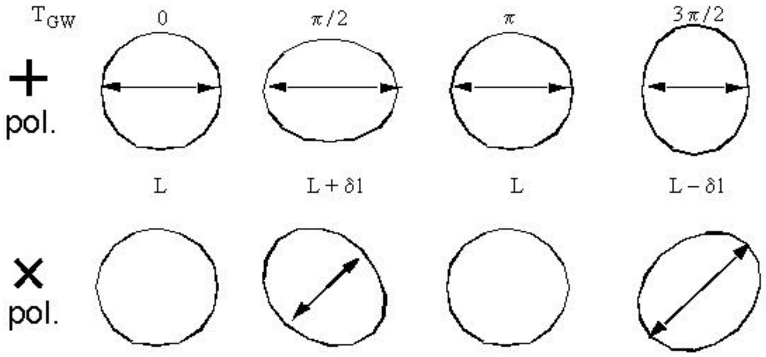
Astrophysical Sources of Gravitational Radiation

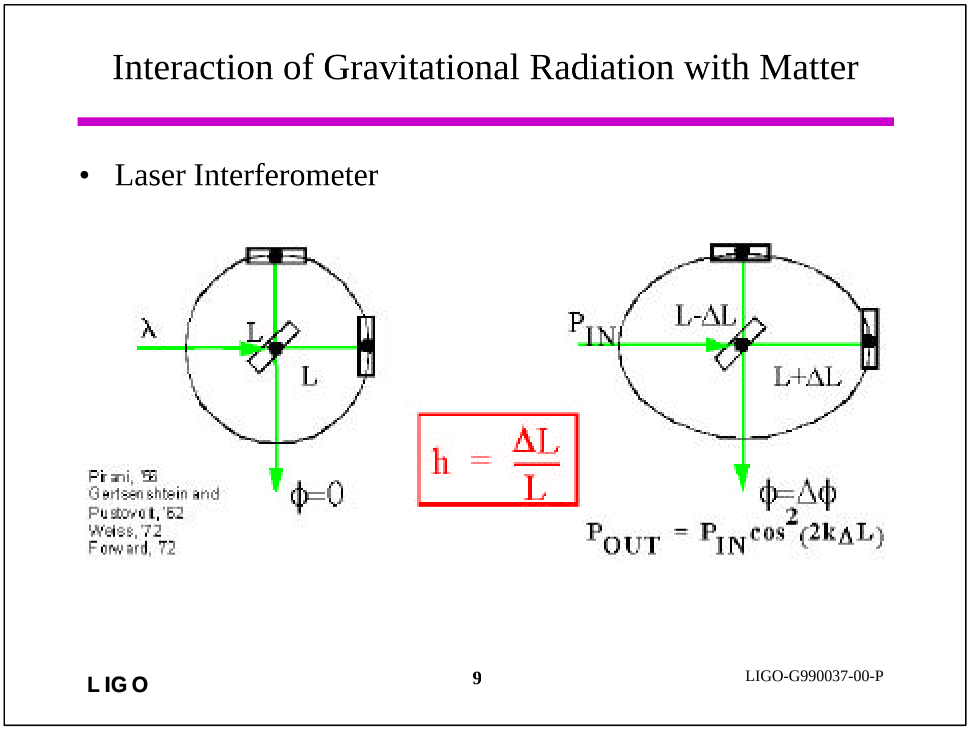
- Coalescing Compact Binaries
  - Neutron Star - Neutron Star
  - Neutron Star - Black Hole
  - Black Hole - Black Hole
- Other Periodic Sources
  - Spinning Neutron Stars
    (numerically difficult)
- Impulsive (Burst) Events
  - Supernovae
    (asymmetric collapse)
- Stochastic Background
  - Primordial Big-bang Background
  - Confusion Limit
- The Unexpected



Interaction of Gravitational Radiation with Matter

- Two Polarizations of Gravitational Waves





Interaction of Gravitational Radiation with Matter

- Laser Interferometer

$\phi = 0$

$h = \frac{\Delta L}{L}$

$\phi = \Delta\phi$

$P_{OUT} = P_{IN} \cos^2(2k\Delta L)$

Pirani, '56
Gertsenshtein and Pustovoit, '62
Weiss, 72
Forward, 72

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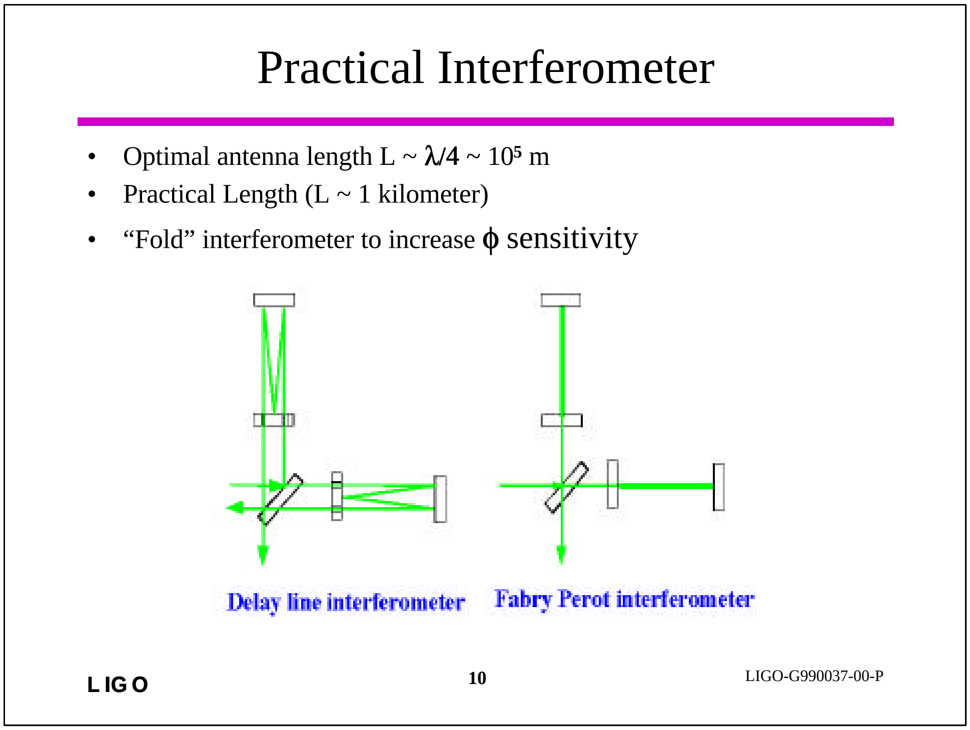
An interferometer provides a way to compare the relative lengths of the two interferometer arms.

If we suspend the mirrors an interferometer provides a good way to measure the distortion of space caused by Gravitational Waves.



Practical Interferometer

- Optimal antenna length L ~ $\lambda/4$ ~ 10^5 m
- Practical Length (L ~ 1 kilometer)
- "Fold" interferometer to increase ϕ sensitivity

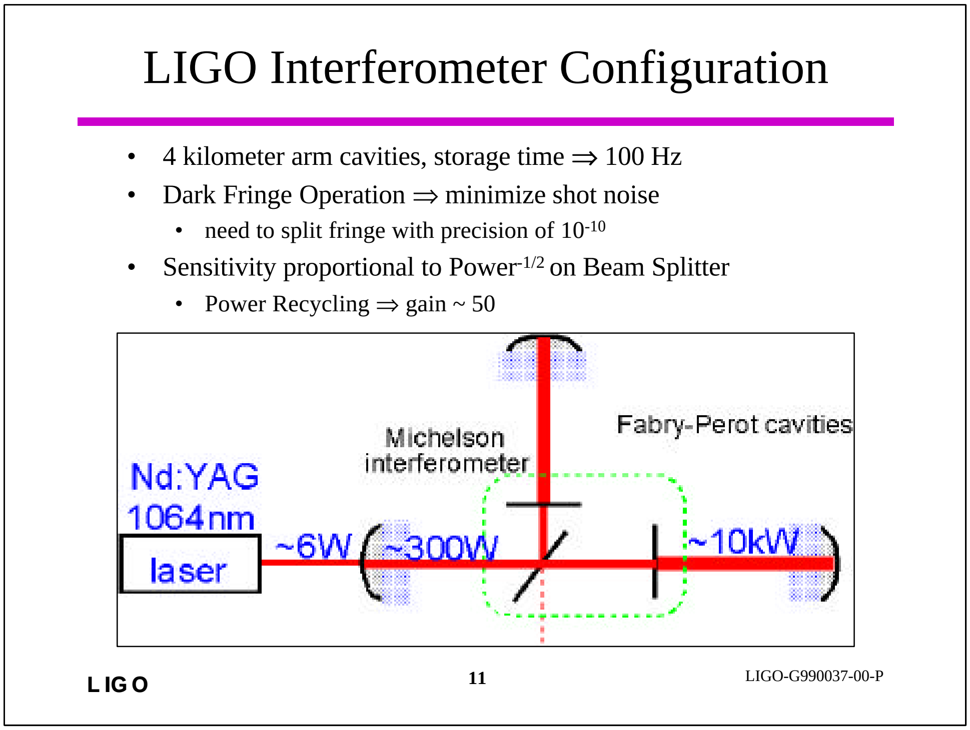
Delay line interferometer **Fabry Perot interferometer**

The best length of an antenna for measuring gravitational waves is on the order of 100 kilometers.

A practical length for an interferometer is a few kilometers.

Light storage provides a way to increase the effective length of the interferometer arms.

LIGO uses Fabry Perot cavities with an effective N ~ 100 where N is number of times photons hit the mirror.



LIGO Interferometer Configuration

- 4 kilometer arm cavities, storage time ⇒ 100 Hz
- Dark Fringe Operation ⇒ minimize shot noise
  - need to split fringe with precision of 10^{-10}
- Sensitivity proportional to Power$^{-1/2}$ on Beam Splitter
  - Power Recycling ⇒ gain ~ 50

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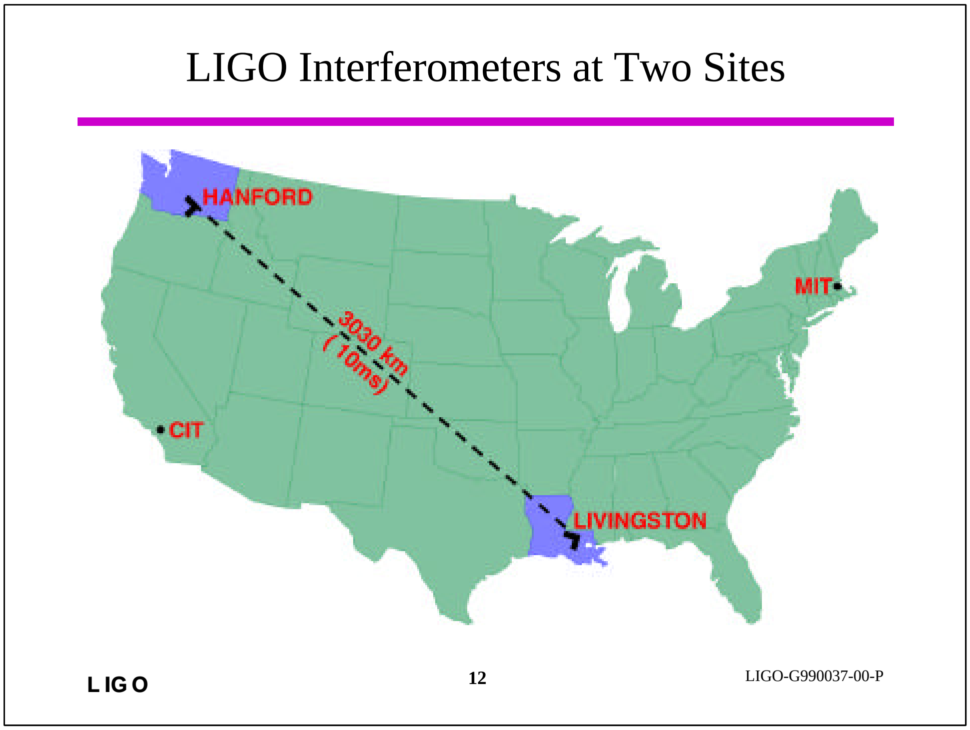
Design characteristics of the LIGO interferometers.

•Arm lengths are four kilometers.

•The light used is infrared with a wavelength of approximately one micron.

•To get the required sensitivity of 10^{-18} meters, it is necessary to measure a fringe with a precision of one part in 10^{10}.

•Most of the light in the interferometer is reflected back towards the source. Since we do not want to waste this light, LIGO uses a “Power Recycling” mirror the reflect the light back towards the Beam Splitter. This provides a power gain in the interferometer of approximately 50.



LIGO Interferometers at Two Sites

LIGO

LIGO-G990037-00-P

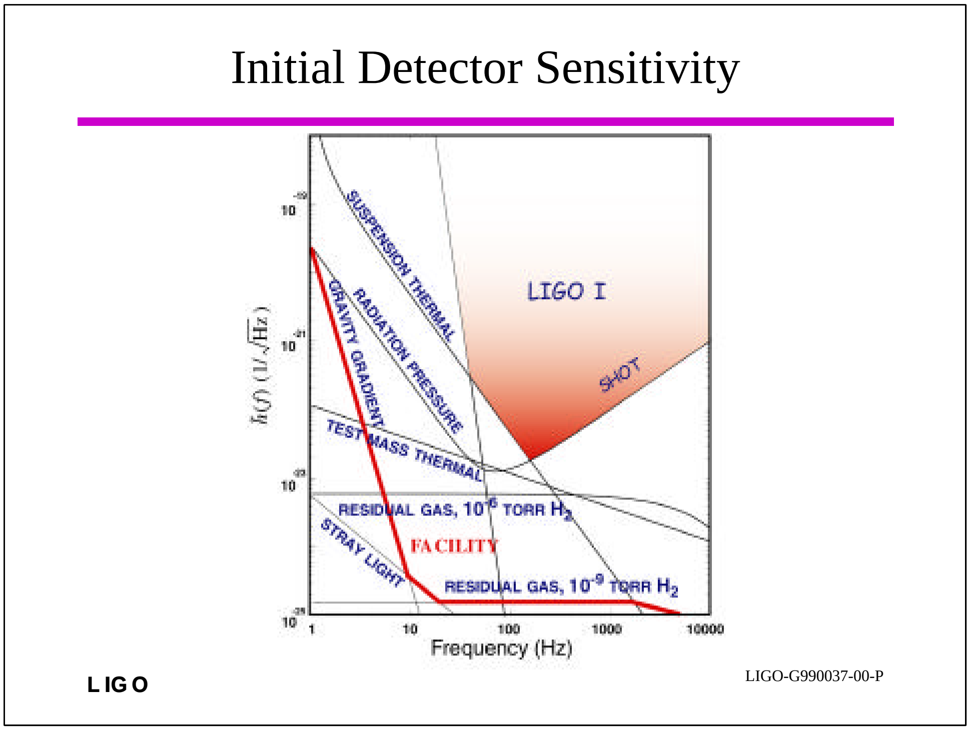
There are two LIGO sites, one is in Hanford, Washington, the other is in Livingston, Louisiana.

•There are two interferometers in Hanford, one is two kilometers in length, the other is four kilometers long.

•Multiple interferometers provide a way to compare signals and reject noise that may masquerade a gravitational wave.

•Multiple sites provide some capability for identifying the direction of the source.

•Additional interferometers in Italy, Germany, Japan, Australia will permit us to create a map of the sky similar to astronomy done with electromagnetic waves.



Initial Detector Sensitivity

LIGO

LIGO-G990037-00-P

This chart shows the sources of noise that limit LIGO sensitivity.

SEISMIC NOISE - Motion of Earth - LOW FREQUENCIES

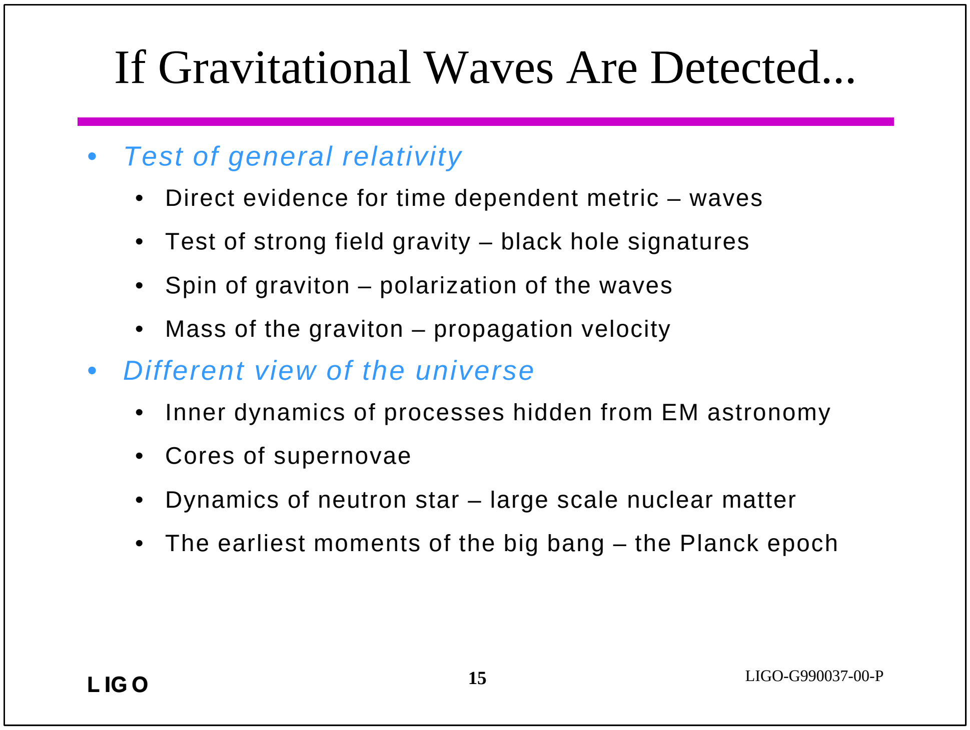
THERMAL NOISE - *Kbt* - INTERMEDIATE FREQUENCIES

SHOT NOISE - Photon Counting Statistics - HIGH FREQUENCIES

Limiting Noise Sources

- Photon Counting Statistics ⇒ Shot Noise
  - High Power, Low Loss Optics
- $k_B T$ Thermal Noise
  - Low Loss (high Q) Resonance for Pendulums and Test Masses
- Motion of Earth ⇒ Seismic Noise
  - 10 μm at μ-seismic peak (0.15 Hz)
  - Passive spring-mass systems in series (“stacks”)
  - Mirror on pendulum

Isolated Free Mass at $f >> f_o \sim 1$ hz



If Gravitational Waves Are Detected...

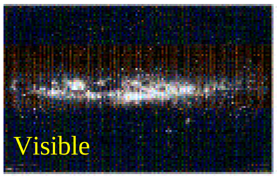
- *Test of general relativity*
  - Direct evidence for time dependent metric – waves
  - Test of strong field gravity – black hole signatures
  - Spin of graviton – polarization of the waves
  - Mass of the graviton – propagation velocity
- *Different view of the universe*
  - Inner dynamics of processes hidden from EM astronomy
  - Cores of supernovae
  - Dynamics of neutron star – large scale nuclear matter
  - The earliest moments of the big bang – the Planck epoch

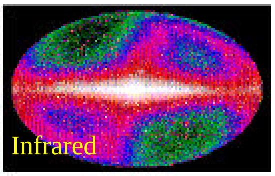
So what if we do detect Gravitational Waves?

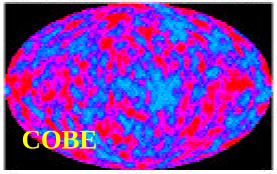
Gravitational Waves provide a direct test of General Relativity.

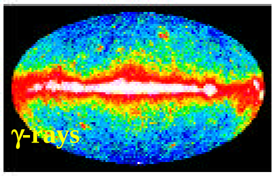
Gravitational Waves also will provide a new, different view of the universe

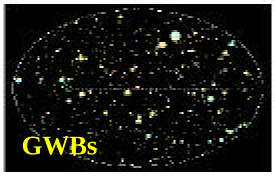
New Instrument, New Field, The Unexpected



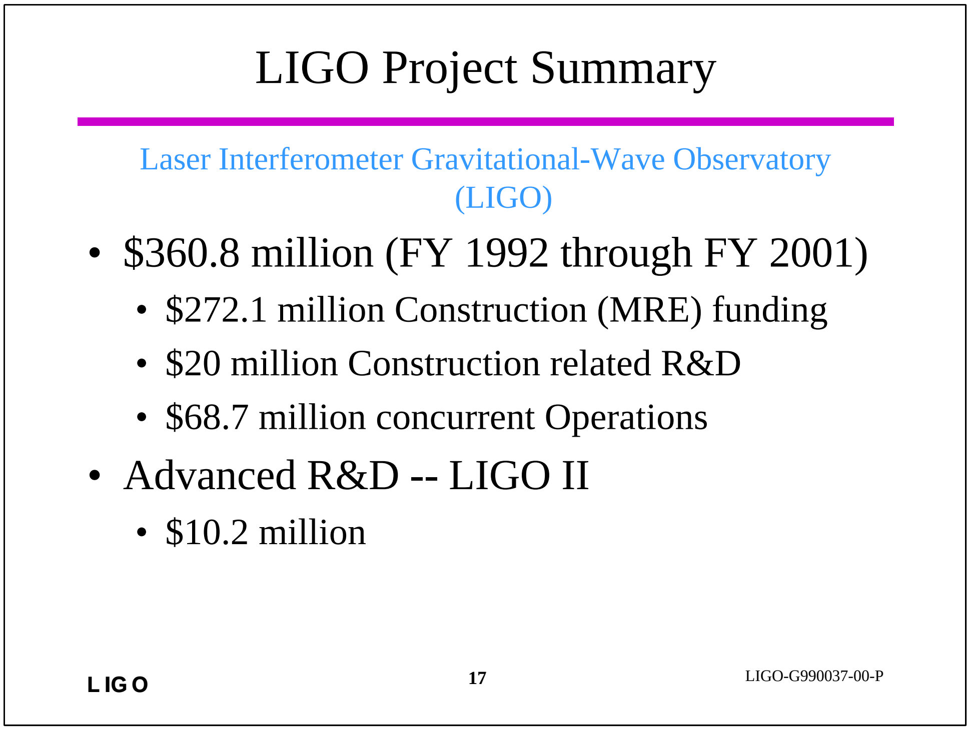








Gravitational
Waves ???



LIGO Project Summary

Laser Interferometer Gravitational-Wave Observatory
(LIGO)

- $360.8 million (FY 1992 through FY 2001)
  - $272.1 million Construction (MRE) funding
  - $20 million Construction related R&D
  - $68.7 million concurrent Operations
- Advanced R&D -- LIGO II
  - $10.2 million

MRE - Major Research Equipment

LIGO Project Funding

Fiscal Year	Construction	R&D	Operations	Advanced R&D	Total
Through 1994	35.9	11.2			47.1
1995	85.0	4.0			89.0
1996	70.0	2.4			72.4
1997	55.0	1.6	0.3	0.8	57.7
1998	26.0	0.9	7.3	0.5 + 1.3	36.0
1999	0.2		20.9	2.3	23.4
2000			21.1	2.6	23.7
2001			19.1 (10 months)	2.7	21.8
Total	272.1	20.0	68.7	10.2	371.0

All funding shown in "then year" $Millions

Project Schedule

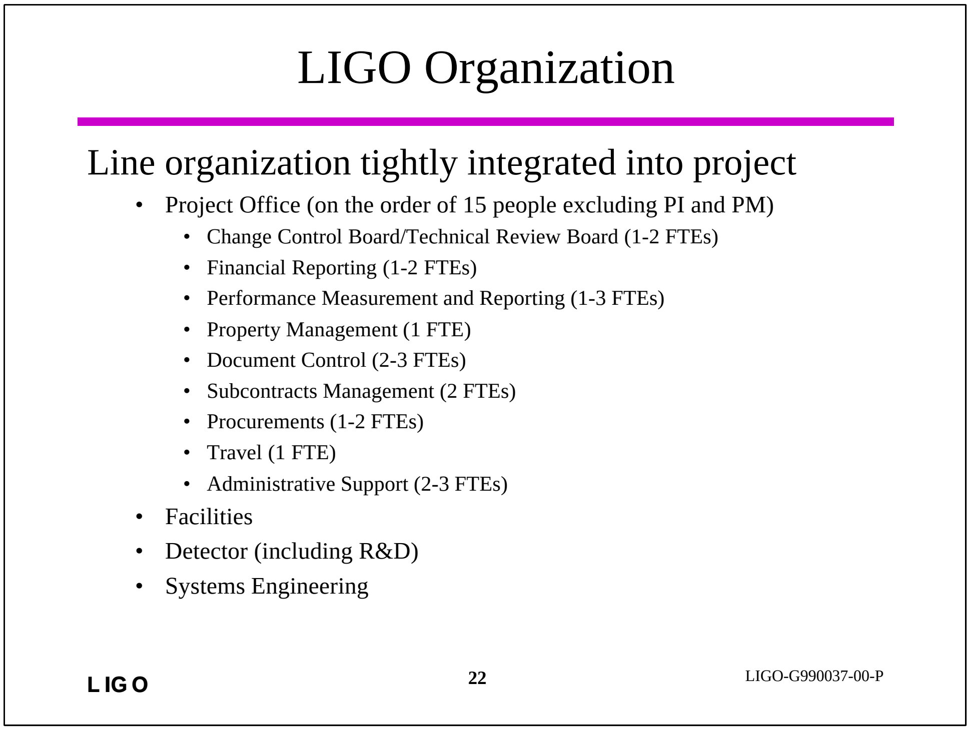
1996	Construction Underway mostly civil construction (buildings, slabs,…)
1997	Facility Construction beam pipe and concrete enclosure, vacuum chambers
1998	Construct Detectors completion of vacuum systems
1999	Install Detectors interferometer systems into vacuum system
2000	Commission Detectors First light in arms, subsystem testing
2001	Engineering Tests Sensitivity, engineering runs, characterization
2002	LIGO I Run Begins $h \sim 10^{-21}$

Pictures

- Satellite View
- LIGO Hanford
- LIGO Livingston
- Vacuum Equipment in Livingston
- Seismic Isolation BSC Chamber
- Prestabilized Laser
- Core Optics
- Core Optics Infrared Metrology
- First Suspended Large Optic
- First Installation of Large Mirror
- Adjusting Installed Recycling Mirror

Project Management and Control Systems

- Organization
- Planning and Budgeting
- Schedules
- Actual Costs
- Reporting
- Change Control



LIGO Organization

Line organization tightly integrated into project

- Project Office (on the order of 15 people excluding PI and PM)
  - Change Control Board/Technical Review Board (1-2 FTEs)
  - Financial Reporting (1-2 FTEs)
  - Performance Measurement and Reporting (1-3 FTEs)
  - Property Management (1 FTE)
  - Document Control (2-3 FTEs)
  - Subcontracts Management (2 FTEs)
  - Procurements (1-2 FTEs)
  - Travel (1 FTE)
  - Administrative Support (2-3 FTEs)
- Facilities
- Detector (including R&D)
- Systems Engineering

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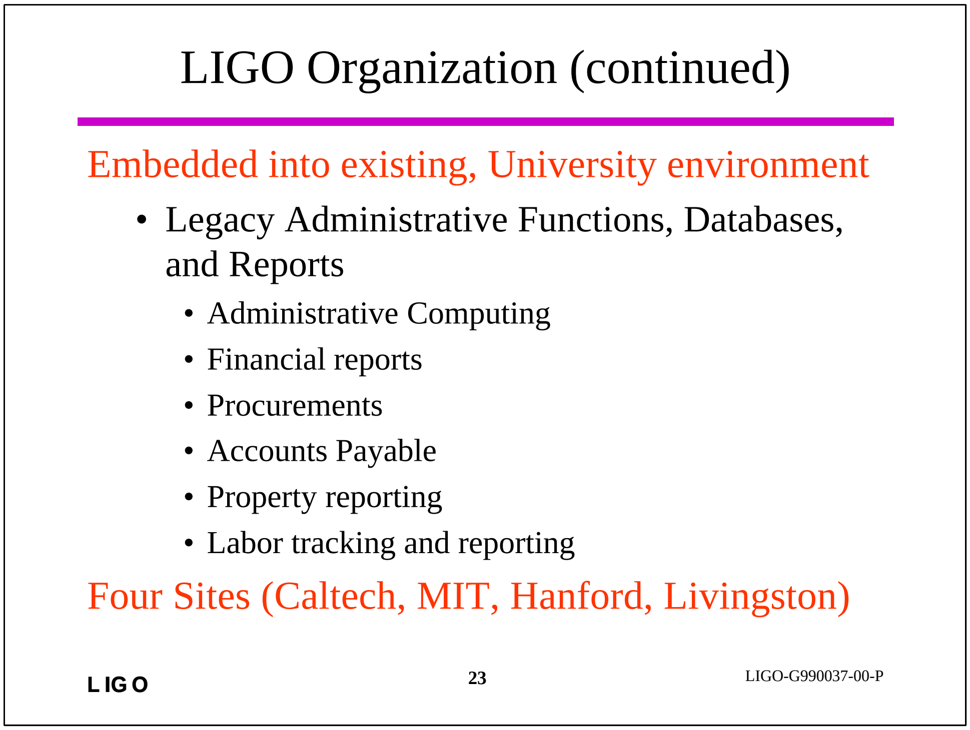
Show Organization Chart

Very Shallow Organization for a Project of this size



LIGO Organization (continued)

Embedded into existing, University environment

- Legacy Administrative Functions, Databases, and Reports
  - Administrative Computing
  - Financial reports
  - Procurements
  - Accounts Payable
  - Property reporting
  - Labor tracking and reporting

Four Sites (Caltech, MIT, Hanford, Livingston)

LIGO exists embedded into the Caltech Environment.

Caltech provides a number of Administrative Functions including…

We have completely swamped these systems

•Financial Reporting (financial systems originally unable to handle 7 digits on a check)

•Procurements

•Payments

•Property Accounting

•Labor tracking (there is only limited reporting)

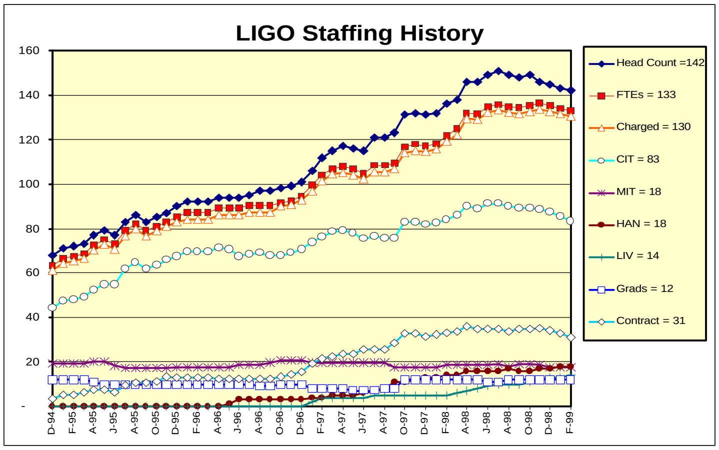
Caltech also not prepared for multiple sites

Another characteristic of the University Environment is the “R&D” mentality.

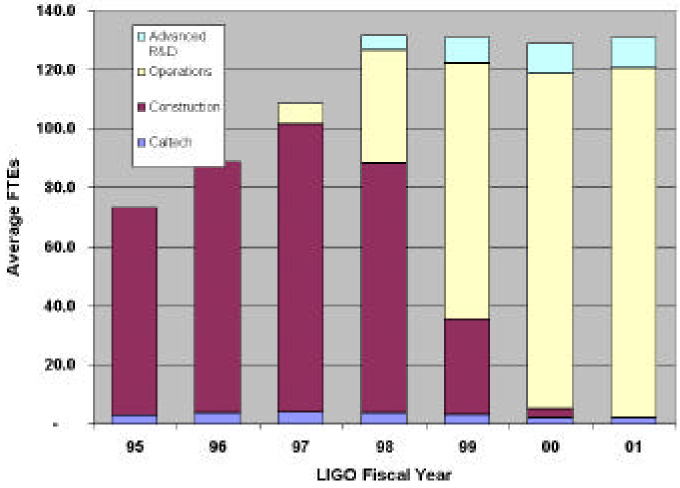
- the need to freeze designs and build something

- the need to commit large subcontracts

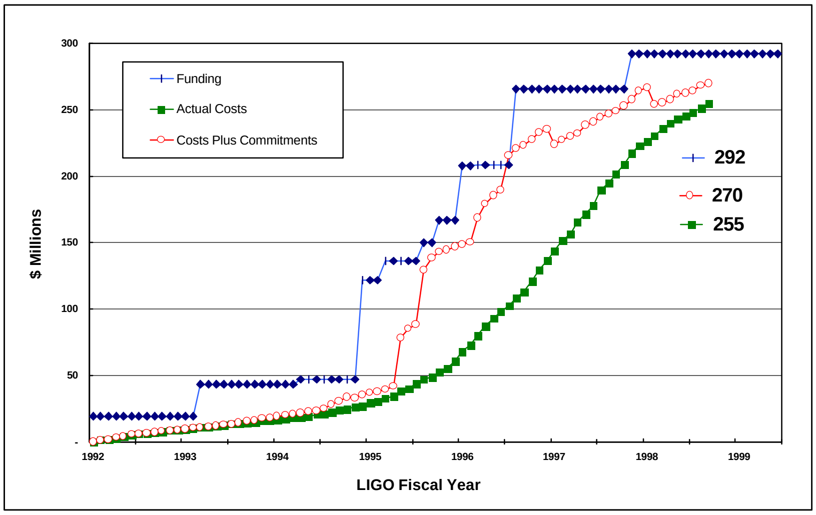
Staffing Chart

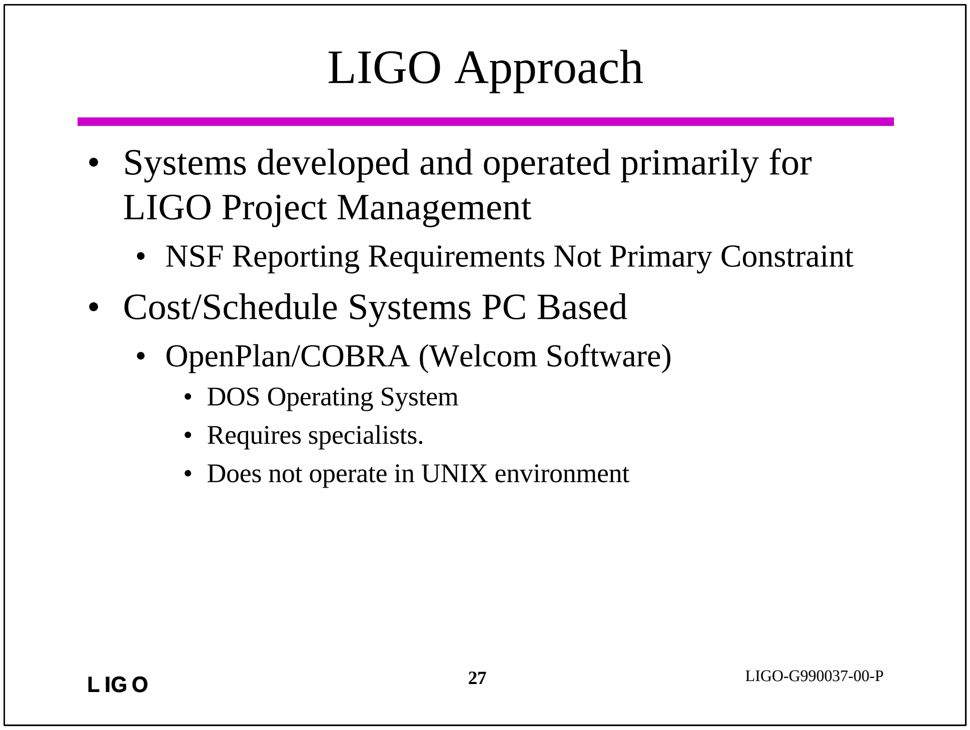


Staffing Chart by Source of Funds



Costs and Commitments vs. Funding





LIGO Approach

- Systems developed and operated primarily for LIGO Project Management
  - NSF Reporting Requirements Not Primary Constraint
- Cost/Schedule Systems PC Based
  - OpenPlan/COBRA (Welcom Software)
    - DOS Operating System
    - Requires specialists.
    - Does not operate in UNIX environment

NSF Reporting expectations were not a significant constraint.

OpenPlan and COBRA fairly tightly integrated.

Software **selected based on reporting capability and ability to work with PERT Charts** (actually never fully implemented).

The original intent was to have the scheduling package available to the task managers for planning purposes.

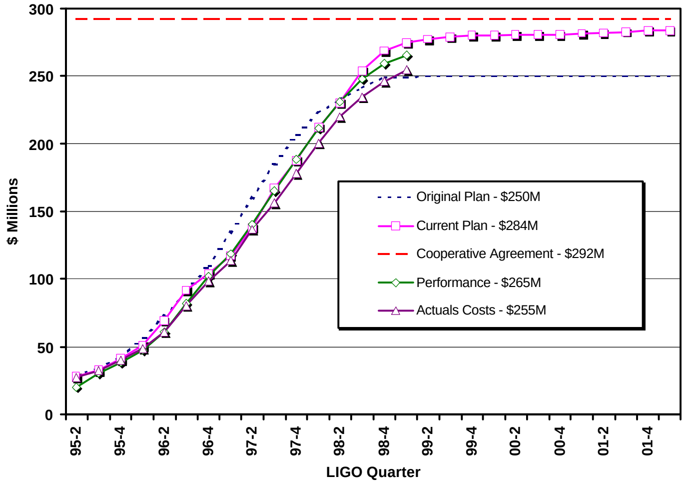
•Requires specialists.

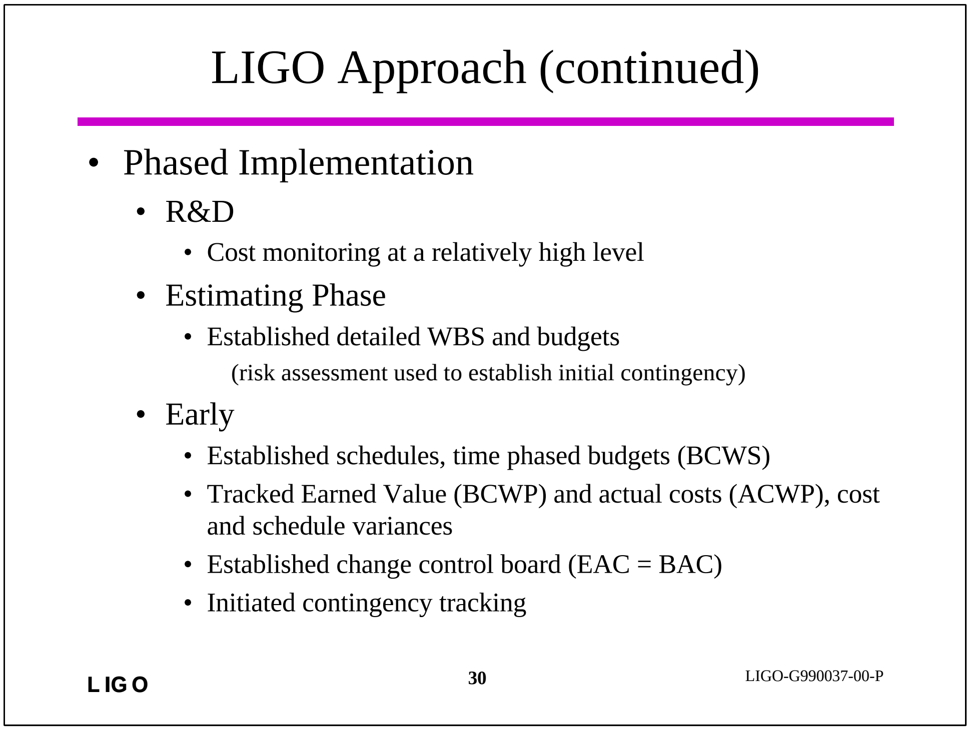
•Does not operate in UNIX environment

Cost Schedule Status Report (CSSR)

Reporting Level	Cumulative To Date					At Completion		
Work Breakdown Structure	Budgeted Cost of Work Scheduled (BCWS) (1)	Budgeted Cost of Work Performed (BCWP) (2)	Actual Cost of Work Performed (ACWP) (3)	Schedule Variance (2-1) (4)	Cost Variance (2-3) (5)	Budget-at-Completion (BAC) (6)	Estimate-at-Completion (EAC) (7)	Variance-at-Completion (6-7) (8)
1.1.1 Vacuum Equipment	43,564	43,564	43,760	-	(196)	43,564	43,900	(336)
1.1.2 Beam Tubes	47,203	47,203	47,021	-	182	47,203	46,967	236
1.1.3 Beam Tube Enclosure	19,991	19,986	19,415	(5)	571	19,991	19,487	504
1.1.4 Facility Design & Construction	52,293	52,430	51,639	137	791	52,500	52,588	(88)
1.1.5 Beam Tube Bake	3,470	3,178	3,584	(292)	(406)	4,879	5,600	(721)
1.2 Detector	54,848	45,968	39,420	(8,880)	6,548	57,819	56,743	1,076
1.3 Research & Development	23,490	23,490	21,552	-	1,938	23,490	23,470	20
1.4 Project Office	29,373	29,373	28,166	-	1,207	34,310	34,577	(267)
Subtotal	274,232	265,192	254,557	(9,040)	10,635	283,756	283,332	424
Contingency						-	8,768	(8,768)
Management Reserve						8,344	-	8,344
Total	274,232	265,192	254,557	(9,040)	10,635	292,100	292,100	-

Performance Curve





LIGO Approach (continued)

- Phased Implementation
  - R&D
    - Cost monitoring at a relatively high level
  - Estimating Phase
    - Established detailed WBS and budgets
      (risk assessment used to establish initial contingency)
  - Early
    - Established schedules, time phased budgets (BCWS)
    - Tracked Earned Value (BCWP) and actual costs (ACWP), cost and schedule variances
    - Established change control board (EAC = BAC)
    - Initiated contingency tracking

Even though risk assessment used to establish contingency at lowest level, it was not left there, rather is was lumped and held at the project level.

Phased Implementation (continued)

- Middle
  - Some Replanning
    - Major Contracts Awarded
    - Early Detector Schedules Planning Packages
  - Initiated Independent Estimate-to-Complete
  - Initiated Contingency Projection

Phased Implementation (continued)

- Late
  - Last few percent of Earned Value left to be claimed
  - Scrubbing commitments, financial systems
  - Tighter tracking of contingency and potential contingency needs
  - Shifting into Operations, Operations Organization, Operations Budgeting
  - Installation and Commissioning scheduling responsibilities assumed by Installation Engineer, detailed and flexible, Microsoft Project

Change Log

Change Board as needed

- Change of Scope

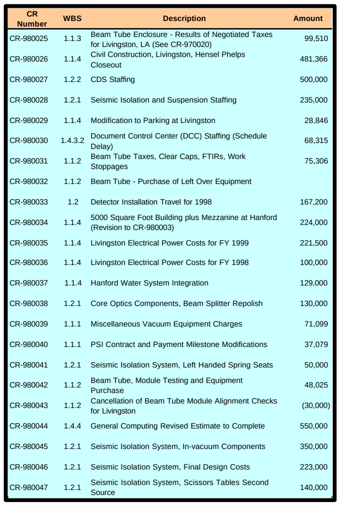
  ⇒ BAC ⇒ EAC

- Overrun

  ⇒ EAC ⇒ BAC

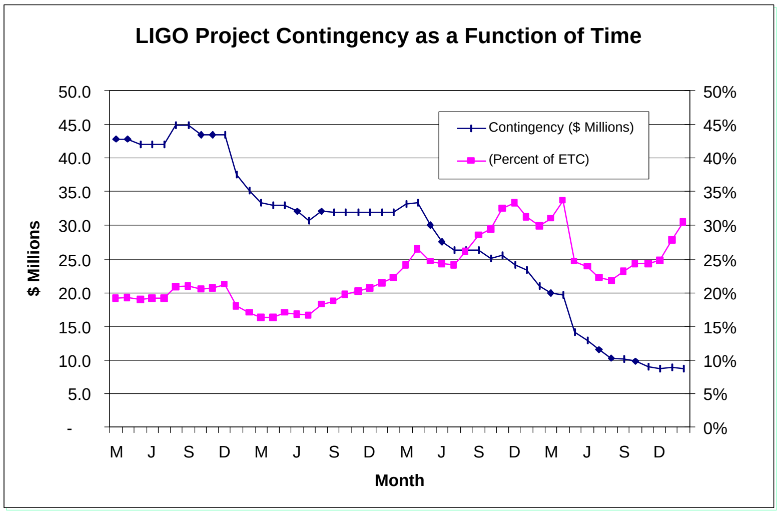
- Contingency = Target Lost less EAC

- Management Reserve = Target Cost less BAC

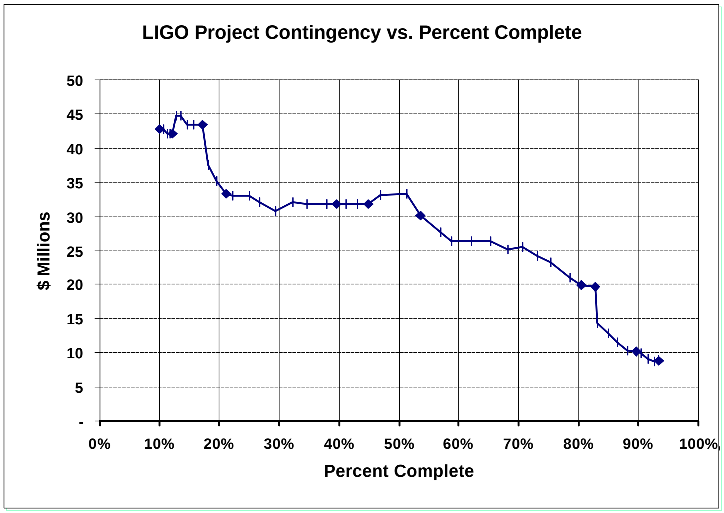


CR Number	WBS	Description	Amount
CR-980025	1.1.3	Beam Tube Enclosure - Results of Negotiated Taxes for Livingston, LA (See CR-970020)	99,510
CR-980026	1.1.4	Civil Construction, Livingston, Hensel Phelps Closeout	481,366
CR-980027	1.2.2	CDS Staffing	500,000
CR-980028	1.2.1	Seismic Isolation and Suspension Staffing	235,000
CR-980029	1.1.4	Modification to Parking at Livingston	28,846
CR-980030	1.4.3.2	Document Control Center (DCC) Staffing (Schedule Delay)	68,315
CR-980031	1.1.2	Beam Tube Taxes, Clear Caps, FTIRs, Work Stoppages	75,306
CR-980032	1.1.2	Beam Tube - Purchase of Left Over Equipment	
CR-980033	1.2	Detector Installation Travel for 1998	167,200
CR-980034	1.1.4	5000 Square Foot Building plus Mezzanine at Hanford (Revision to CR-980003)	224,000
CR-980035	1.1.4	Livingston Electrical Power Costs for FY 1999	221,500
CR-980036	1.1.4	Livingston Electrical Power Costs for FY 1998	100,000
CR-980037	1.1.4	Hanford Water System Integration	129,000
CR-980038	1.2.1	Core Optics Components, Beam Splitter Repolish	130,000
CR-980039	1.1.1	Miscellaneous Vacuum Equipment Charges	71,099
CR-980040	1.1.1	PSI Contract and Payment Milestone Modifications	37,079
CR-980041	1.2.1	Seismic Isolation System, Left Handed Spring Seats	50,000
CR-980042	1.1.2	Beam Tube, Module Testing and Equipment Purchase	48,025
CR-980043	1.1.2	Cancellation of Beam Tube Module Alignment Checks for Livingston	(30,000)
CR-980044	1.4.4	General Computing Revised Estimate to Complete	550,000
CR-980045	1.2.1	Seismic Isolation System, In-vacuum Components	350,000
CR-980046	1.2.1	Seismic Isolation System, Final Design Costs	223,000
CR-980047	1.2.1	Seismic Isolation System, Scissors Tables Second Source	140,000

Contingency History



Contingency vs. Percent Complete

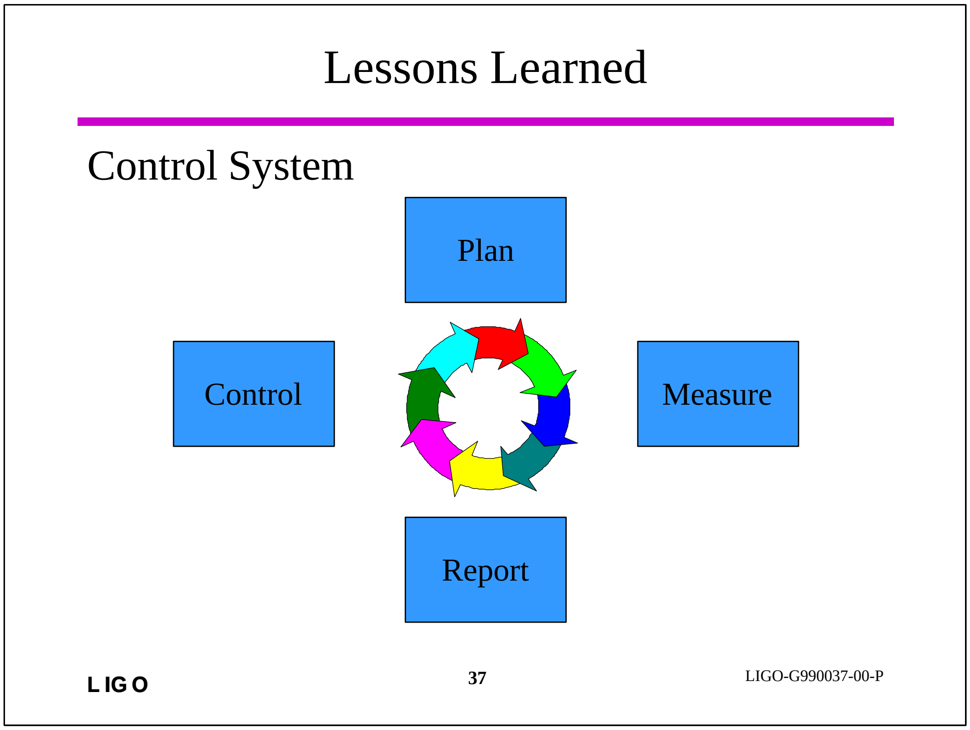


LIGO Approach (continued)

- Weekly Project Controls Meeting
  - Monthly Cost/Schedule Review with Variance Reporting

    (No written internal Variance Reports)
  - Weekly Contingency Review
- Overruns/Underruns addressed through CCB Actions
  - No At-Completion Variance end of Project

    (No Management Reserve)
  - Change Log documents Overruns/Underruns



Lessons Learned

Control System

Plan

Control

Measure

Report

LIGO

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At the end of any Project, they always ask you about “lessons learned!”

This is no exception, Beverly asked me to comment on lessons learned during the LIGO Project.

This is difficult to answer.

The Project Management and Control System is a simple Feedback Control System.

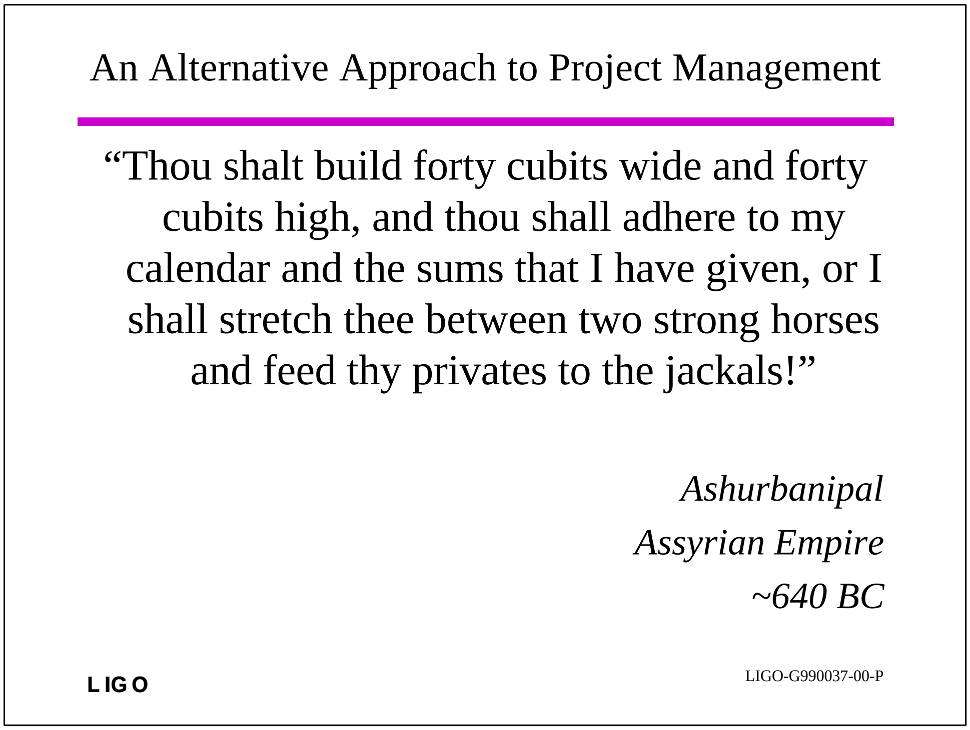
This is not “Brain Surgery!”

What makes it difficult, and the systems fail, are all of the external influences.

The Goal of the Project Manager

“See first that the design is wise and just: that ascertained, pursue it resolutely; do not for one repulse forego the purpose that you resolved to effect.”

William Shakespeare



An Alternative Approach to Project Management

“Thou shalt build forty cubits wide and forty cubits high, and thou shall adhere to my calendar and the sums that I have given, or I shall stretch thee between two strong horses and feed thy privates to the jackals!”

Ashurbanipal
Assyrian Empire
~640 BC

LIGO

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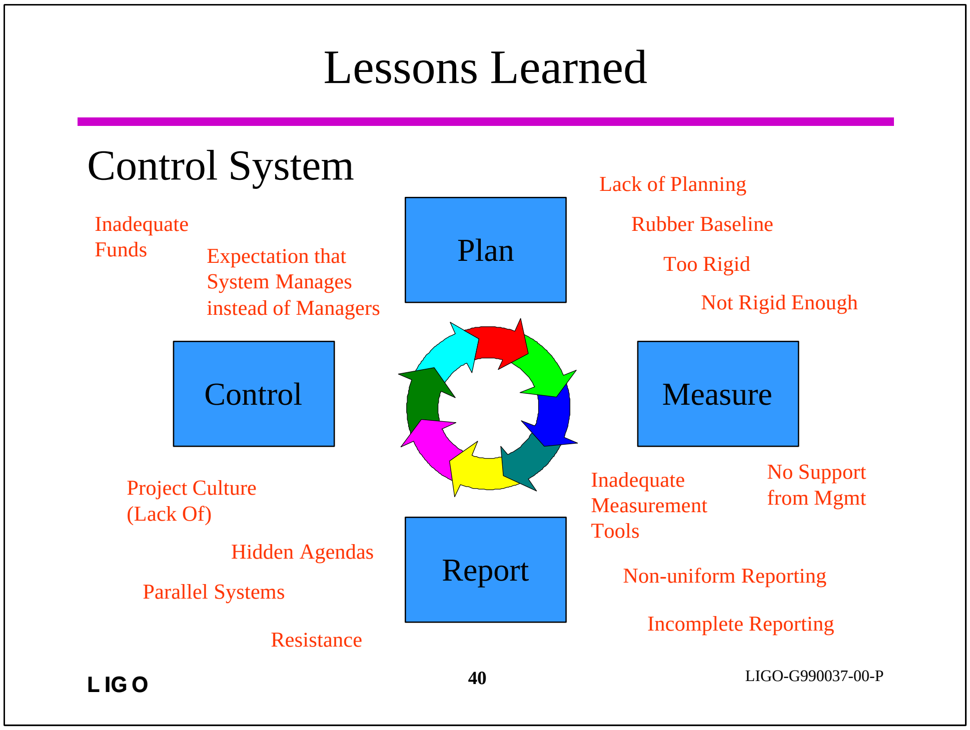
I believe that this was

DOE Project -(minus)640-0038



Lessons Learned

Control System

Plan

Measure

Report

Control

Lack of Planning

Rubber Baseline

Too Rigid

Not Rigid Enough

Inadequate Funds

Expectation that System Manages instead of Managers

Inadequate Measurement Tools

No Support from Mgmt

Non-uniform Reporting

Incomplete Reporting

Project Culture (Lack Of)

Hidden Agendas

Parallel Systems

Resistance

I’ve added a few of these to the Control System chart.

These include

•the Project Culture (or lack thereof)

•hidden agendas

•the expectation that the system provides the management rather than the managers.

I am sure that you can think of others.

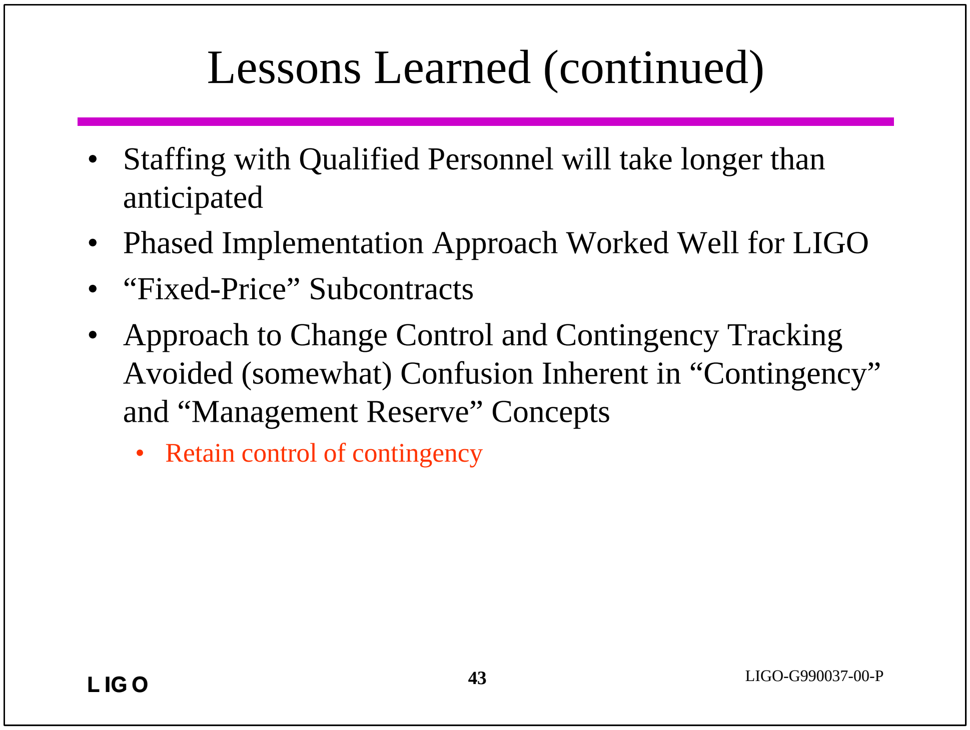
Lessons Learned (continued)

- Each Project/Environment Is Unique *(Commercial, DOD, DOE, NSF)*
- Make sure that the Project Funding is Adequate - *adjust scope as necessary*
  - Risk Assessment - *$157 million of LIGO Construction for Civil Facilities, well understood and defined*
  - Aggressive Funding Profile
    - No phased subcontracts
    - No commitments management
    - No rebaselining induced by funding slips

Each Project is unique. This means that I probably don’t have many “lessons” useful to another project like SNS.

Lessons Learned (continued)

- Project Management and Control System Must be Supported by Project and Line Management
  - Lead Engineers must understand system and expect to devote 20 percent of time to system
  - Project Systems Work Best if designed for Internal Use
  - Common Data and Reporting Procedures and Formats Must Be Demanded and Driven by Project Management



Lessons Learned (continued)

- Staffing with Qualified Personnel will take longer than anticipated
- Phased Implementation Approach Worked Well for LIGO
- “Fixed-Price” Subcontracts
- Approach to Change Control and Contingency Tracking Avoided (somewhat) Confusion Inherent in “Contingency” and “Management Reserve” Concepts
  - Retain control of contingency

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A rigid interpretation of the CSCSC dictates an independent EAC right from the beginning of the Project. This while the BAC is still being developed.

LIGO managed contingency, not the NSF

EMAIL ADDRESS

“Kip Thorne” <thorne_k@ligo.caltech.edu>