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The Status of Gravitational-Wave Detectors

Reported on behalf of LIGO colleagues by
Fred Raab,
LIGO Hanford Observatory

LIGO-G030249-02-W

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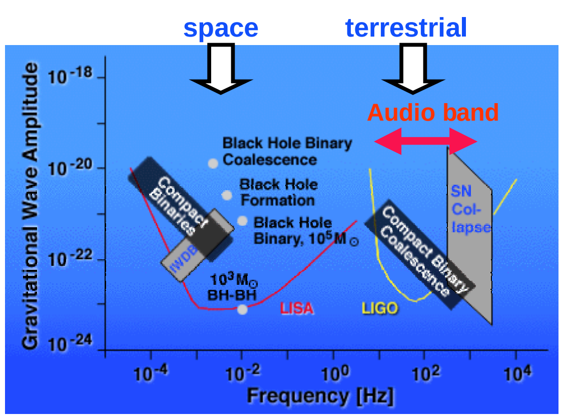
Different Frequency Bands of Detectors and Sources

- EM waves are studied over ~20 orders of magnitude
  - » (ULF radio –> HE γ rays)
- Gravitational Wave coverage over ~8 orders of magnitude
  - » (terrestrial + space)



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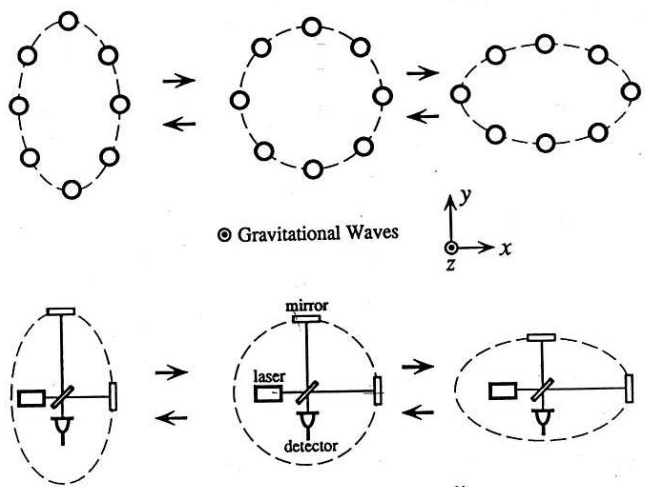
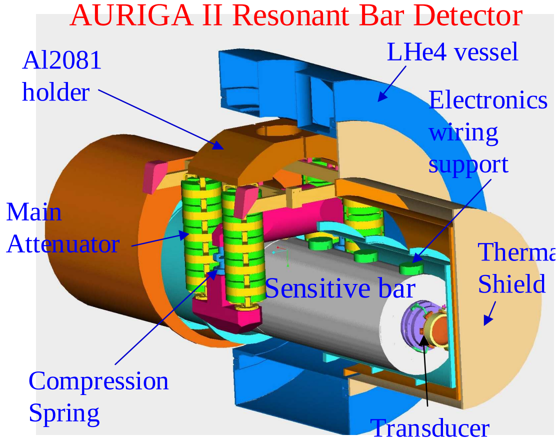
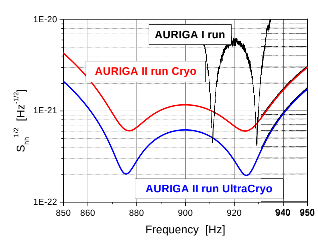
Basic Signature of Gravitational Waves for All Detectors



Original Terrestrial Detectors Continue to be Improved

AURIGA II Resonant Bar Detector

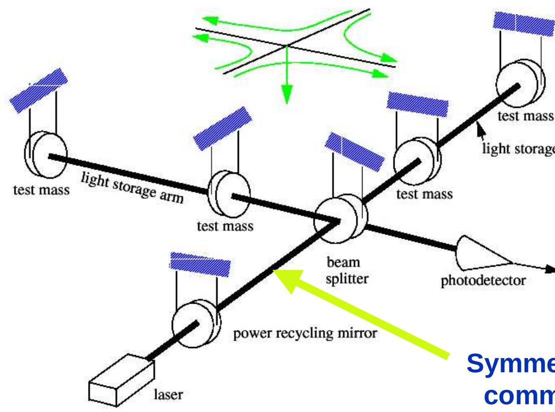




- Efforts to broaden frequency range and reduce noise
- Size limited by sound speed

Courtesy M. Cerdonnio

LIGO — New Generation of “Free-Mass” Detectors Now Online



suspended mirrors mark inertial frames

antisymmetric port carries GW signal

Symmetric port carries common-mode info

Intrinsically broad band and size-limited by speed of light.

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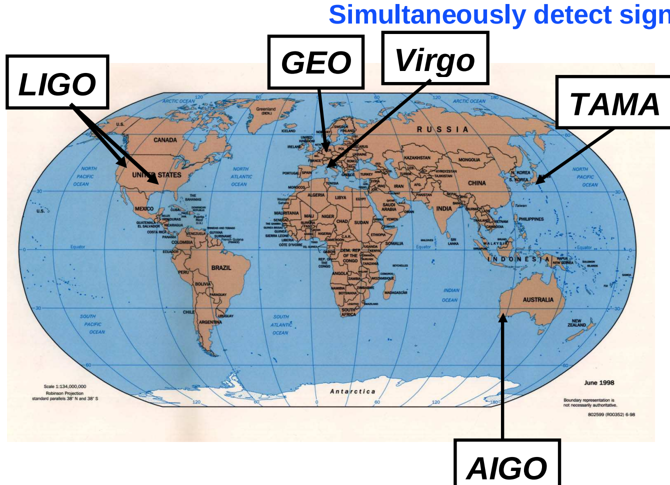
LIGO — The International Interferometer Network

Simultaneously detect signal (within msec)



detection confidence

locate the sources

decompose the polarization of gravitational waves

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The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)
(4-km and 2km)

LIGO (Louisiana)
(4-km)

Funded by the National Science Foundation; operated by Caltech and MIT; the research focus for more than 400 LIGO Scientific Collaboration members worldwide.

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Interferometers in Europe

GEO 600 (Germany)
(600-m)

Virgo (Italy)
3-km

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Interferometers in Asia, Australia

TAMA 300 (Japan)
(300-m)

AIGO (Australia)
(80-m, but 3-km site

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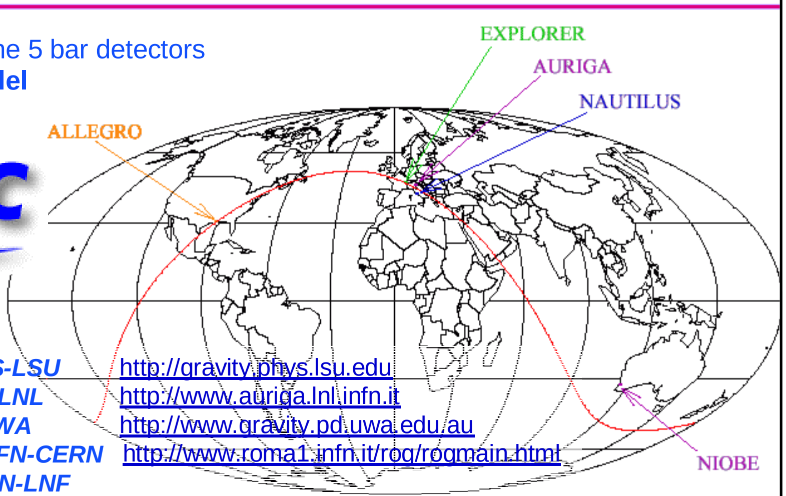
Bar Network: Int'l Gravitational Event Collaboration

Network of the 5 bar detectors almost **parallel**

IGEC



ALLEGRO NFS-LSU http://gravity.phys.lsu.edu
AURIGA INFN-LNL http://www.auriga.lnl.infn.it
NIOBE ARC-UWA http://www.gravity.pd.uwa.edu.au
EXPLORER INFN-CERN http://www.roma1.infn.it/rog/rogmain.html
NAUTILUS INFN-LNF

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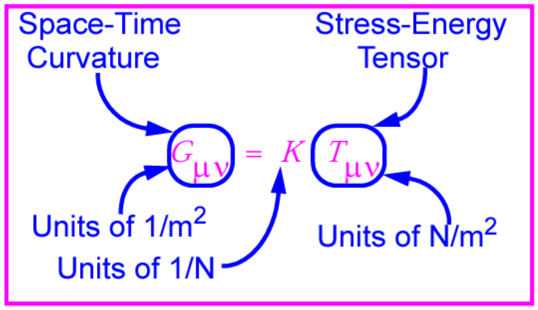
Spacetime is Stiff!



- K~[G/c^4] is lowest order combination of G, c with units of 1/N

=> Wave can carry huge energy with miniscule amplitude!

$$h \sim (G/c^4)\ (E_{NS}/r)$$

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Some of the Technical Challenges

- Typical Strains < 10^{-21} at Earth ~ 1 hair's width at 4 light years
- Understand displacement fluctuations of 4-km arms at the millifermi level (1/1000th of a proton diameter)
- Control arm lengths to 10^{-13} meters RMS
- Detect optical phase changes of ~ 10^{-10} radians
- Hold mirror alignments to 10^{-8} radians
- Engineer structures to mitigate recoil from atomic vibrations in suspended mirrors

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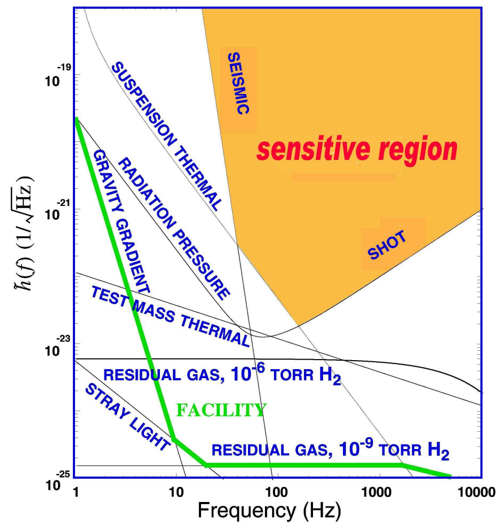
What Limits Sensitivity of Interferometers?

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels



LIGO-G030249-02-W LIGO De

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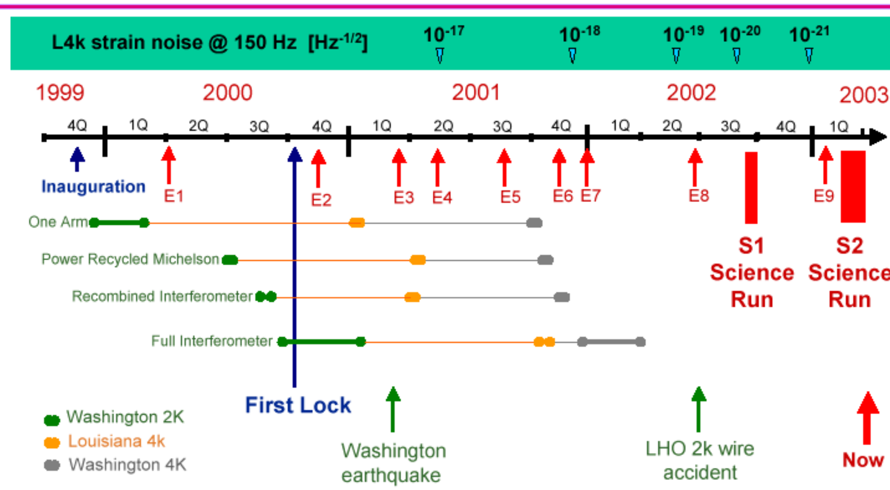
LIGO Commissioning Time Line



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Vibration Isolation Systems

» Reduce in-band seismic motion by 4 - 6 orders of magnitude
» Little or no attenuation below 10Hz
» Large range actuation for initial alignment and drift compensation
» Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation


HAM Chamber


BSC Chamber

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Seismic Isolation – Springs and Masses


damped spring
cross section

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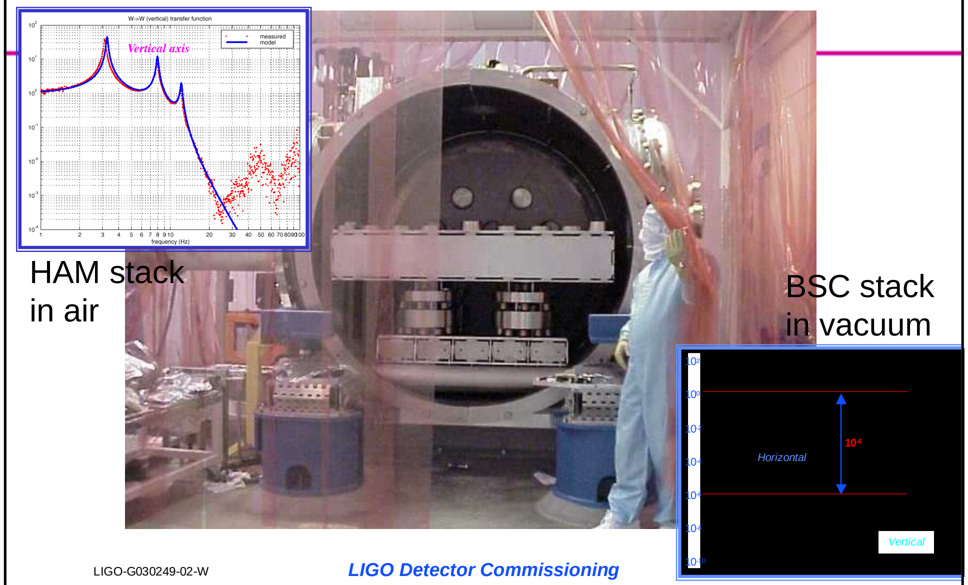
Seismic System Performance



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LIGO Detector Commissioning

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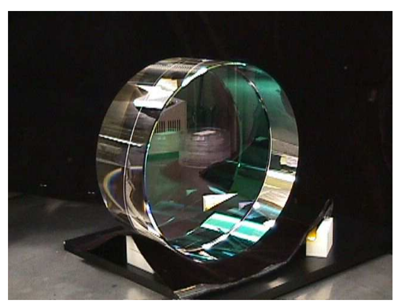
Core Optics

- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5 x 10^{-7}
  - » Internal mode Q's > 2 x 10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity <10^{-3}
- Production involved 6 companies, NIST, and LIGO



LIGO-G030249-02-W

LIGO Detector Commissioning

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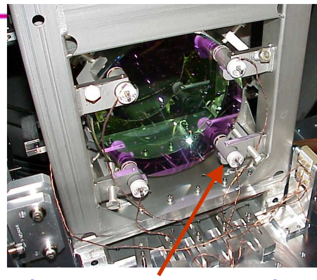
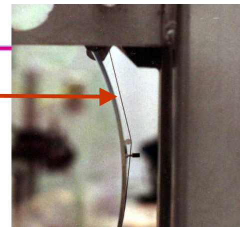
Core Optics Suspension and Control





Optics suspended as simple pendulums

Shadow sensors & voice-coil actuators provide damping and control forces

Mirror is balanced on 30 micron diameter wire to 1/100th degree of arc

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Feedback & Control for Mirrors and Light

- Damp suspended mirrors to vibration-isolated tables
  - » 14 mirrors × (pos, pit, yaw, side) = 56 loops
- Damp mirror angles to lab floor using optical levers
  - » 7 mirrors × (pit, yaw) = 14 loops
- Pre-stabilized laser
  - » (frequency, intensity, pre-mode-cleaner) = 3 loops
- Cavity length control
  - » (mode-cleaner, common-mode frequency, common-arm, differential arm, michelson, power-recycling) = 6 loops
- Wave-front sensing/control
  - » 7 mirrors × (pit, yaw) = 14 loops
- Beam-centering control
  - » 2 arms × (pit, yaw) = 4 loops

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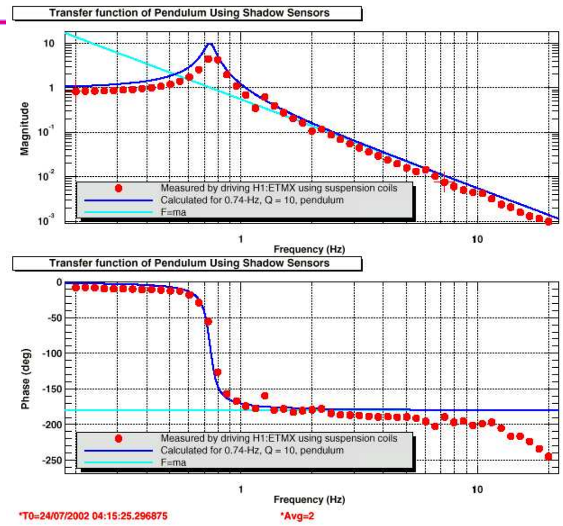
LIGO Suspended Mirror Approximates a Free Mass Above Resonance



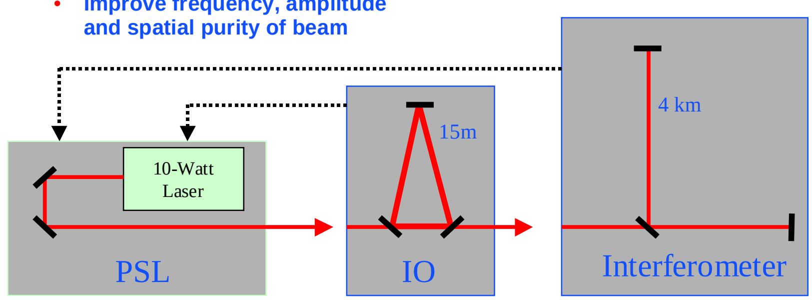
Blue: suspended mirror XF

Cyan: free mass XF

Data taken using shadow sensors & voice coil actuators

LIGO Frequency Stabilization of the Light Employs Three Stages

- Pre-stabilized laser delivers light to the long mode cleaner
  - **Start with high-quality, custom-built Nd:YAG laser**
  - **Improve frequency, amplitude and spatial purity of beam**
- Actuator inputs provide for further laser stabilization
  - **Wideband**
  - **Tidal**



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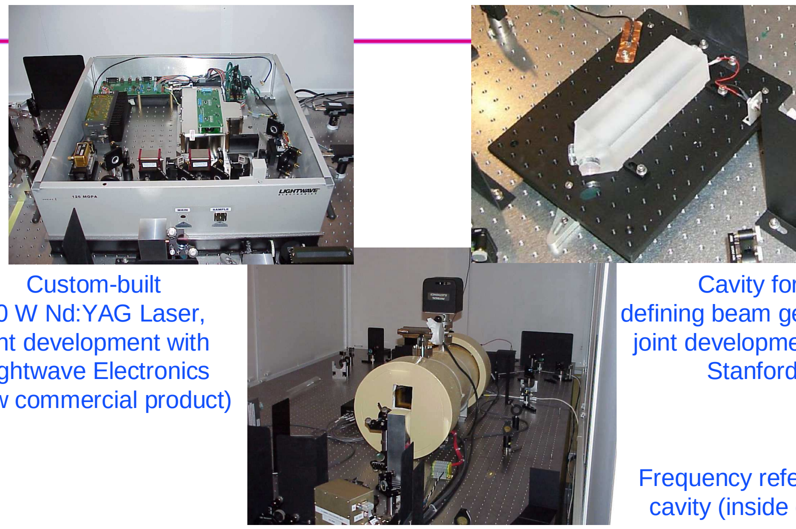
Pre-stabilized Laser (PSL)



Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics
(now commercial product)

Cavity for
defining beam geometry,
joint development with
Stanford

Frequency reference
cavity (inside oven)

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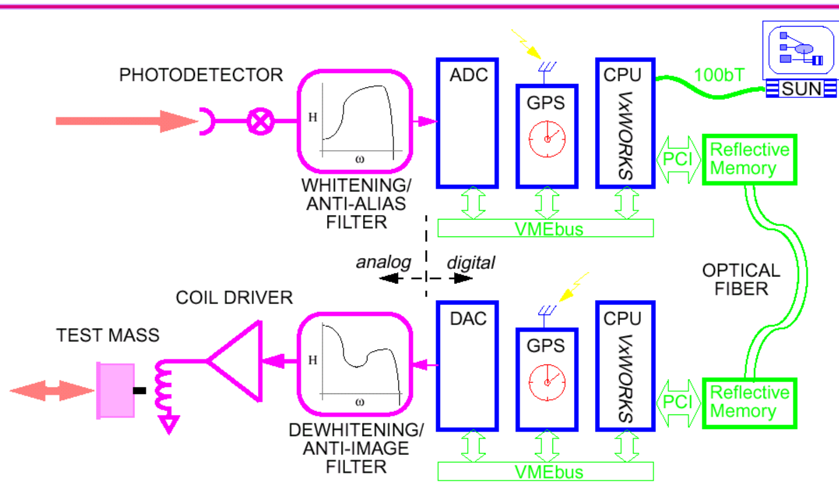
Digital Interferometer Sensing & Control System



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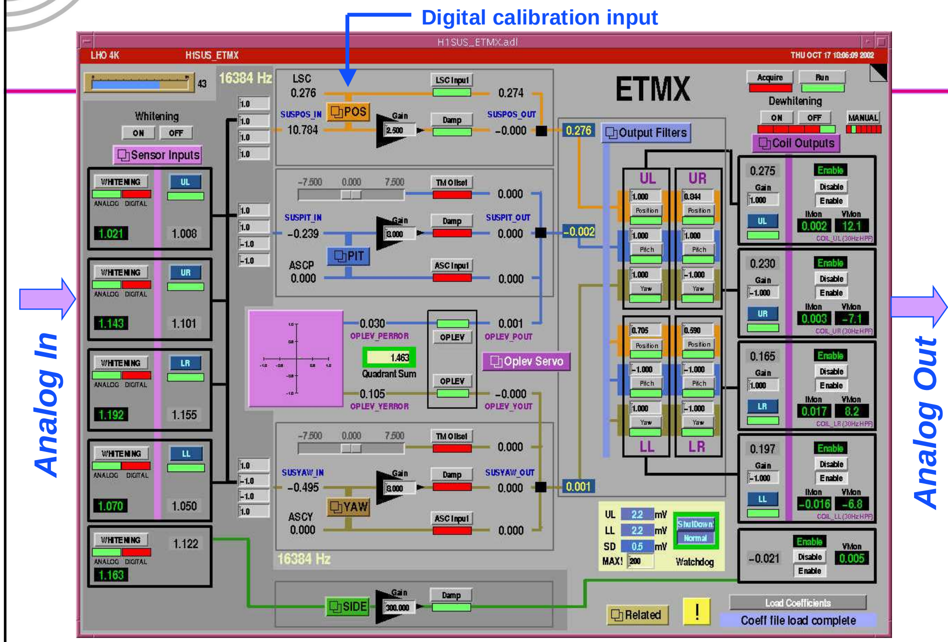
Digital Controls screen example



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Why is Locking Difficult?

One meter

÷10,000	*Earthtides, about 100 microns*
÷100	*Microseismic motion, about 1 micron*
÷10,000	*Precision required to lock, about 10^{-10} meter*
÷100,000	*Nuclear diameter, 10^{-15} meter*
÷1,000	*LIGO sensitivity, 10^{-18} meter*

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Tidal Compensation Data

Tidal evaluation on 21-hour locked section of S1 data

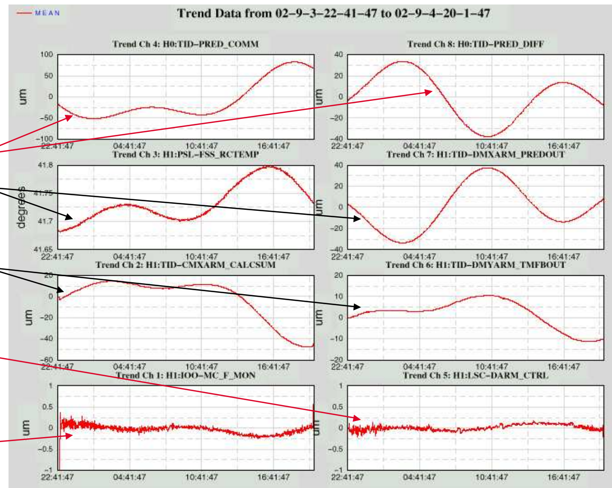
Predicted tides

Feedforward

Feedback

Residual signal on voice coils

Residual signal on laser



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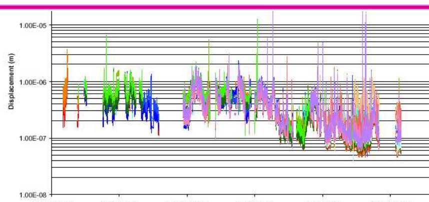
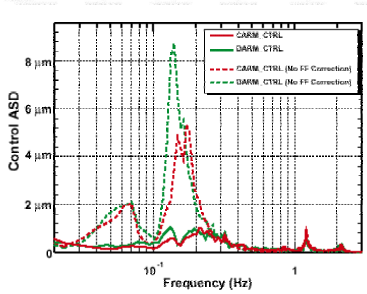
Microseism

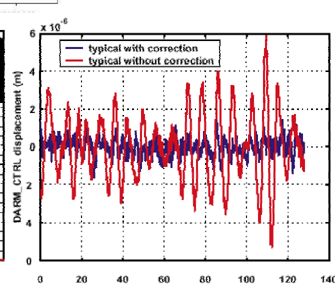
Microseism at 0.12 Hz dominates ground velocity



Trended data (courtesy of Gladstone High School) shows large variability of microseism, on several-day- and annual- cycles

Reduction by feed-forward derived from seismometers





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LIGO Science Run S1

- 17 days in Aug-Sep 2002
- 3 LIGO interferometers in coincidence with GEO600 and ~2 days with TAMA300
- Joint analyses with GEO reported at Spring APS meeting, papers in progress
- Remember: All performance data for all detectors are snapshots that reflect work in progress, not ultimate detector capability.

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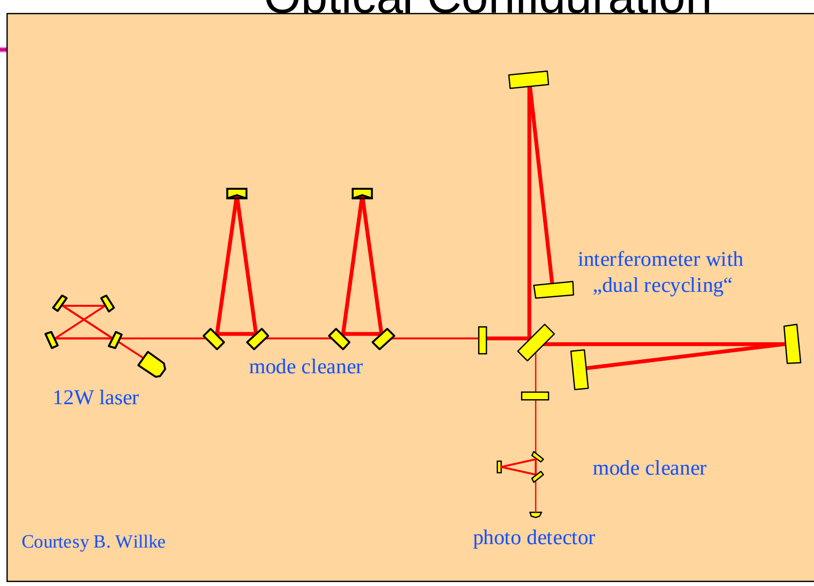
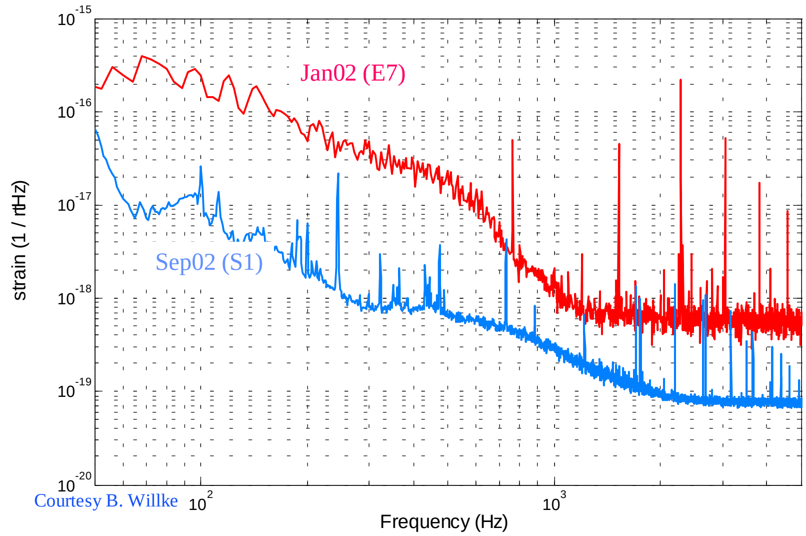
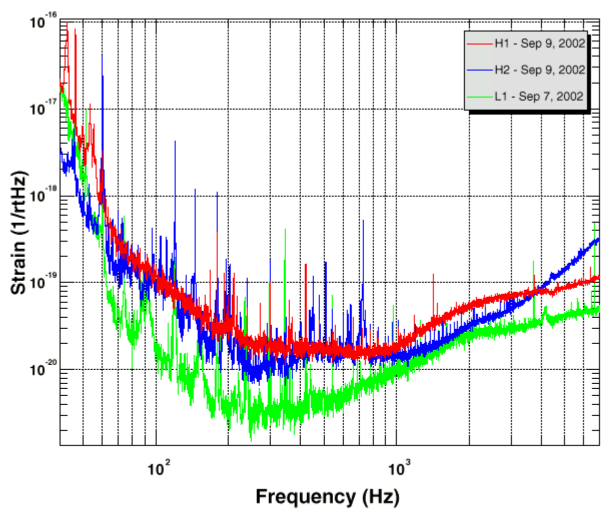
GEO600 Optical Configuration



LIGO Sensitivity of GEO600 During Joint E7 / S1Runs With LIGO



LIGO Noise Equivalent Strain Spectra of LIGO Interferometers for S1



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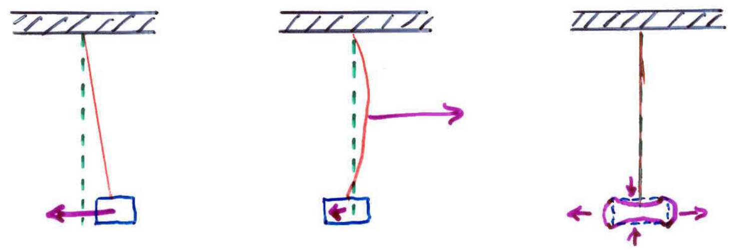
LIGO Background Forces in GW Band = Thermal Noise ~ $k_B T$/mode



pendulum mode	violin mode	test mass vibrational mode
$x_{rms} \approx 10^{-11}$ m	$x_{rms} \approx 2\times10^{-17}$ m	$x_{rms} \approx 5\times10^{-16}$ m
f < 1 Hz	f ~ 350 Hz	f ≥ 10 kHz

Strategy: Compress energy into narrow resonance outside band of interest ⇒ require high mechanical Q, low friction

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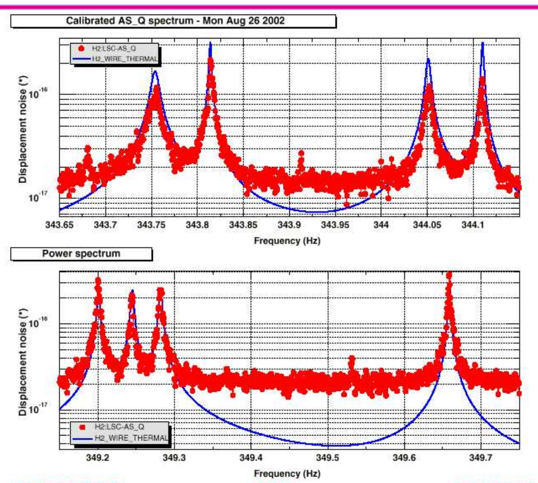
LIGO Thermal Noise Observed in 1st Violins on H2, L1 During S1



~ 20 millifermi RMS for each free wire segment

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Binary Neutron Stars: S1 Range

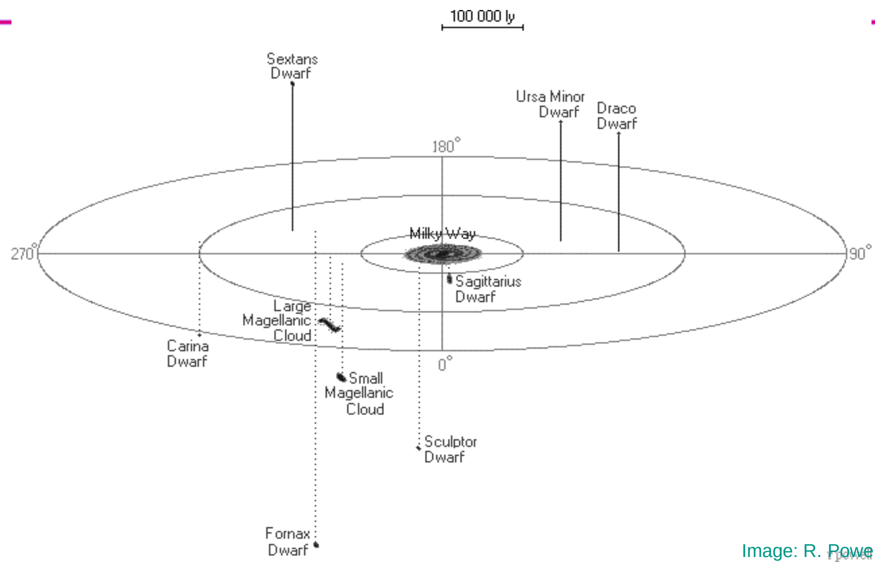

Image: R. Powell

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LIGO Science Run S2

- Feb 14 – Apr 14, 2003
- 3 LIGO interferometers in coincidence with TAMA300; GEO600 not available for science running

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GEO Progress in 2002 / 2003

- test run E7 (28.12.01-14.01.02)
  75% duty cycle
  longest „lock“: 3h:38min
- data run S1 (23.8 – 9.9.2002)
  98.5 % duty cycle
  longest „lock“: 121h:26min
- installation of end mirrors on monolithic suspensions
- installation of signal recycling mirror and suspension: „dual-recycling“
  - development and test of control topology
  - worldwide first long baseline dual recycling lock (360s)
- installation of ring heater device to compensate for the radius of curvature mismatch of the end mirrors

Courtesy B. Willke

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Data Runs with TAMA300 (World’s Longest Running Interferometer)

Data Taking		Objective	Observation time	Typical strain noise level	Total data (Longest lock)
DT1	August, 1999	Calibration test	1 night	3×10^{-19} /Hz $^{1/2}$	10 hours (7.7 hours)
DT2	September, 1999	First Observation run	3 nights	3×10^{-20} /Hz $^{1/2}$	31 hours
DT3	April, 2000	Observation with improved sensitivity	3 nights	1×10^{-20} /Hz $^{1/2}$	13 hours
DT4	Aug.-Sept., 2000	100 hours' observation data	2 weeks (night-time operation)	1×10^{-20} /Hz $^{1/2}$ (typical)	167 hours (12.8 hours)
DT5	March, 2001	100 hours' observation with high duty cycle	1 week (whole-day operation)	1.7×10^{-20} /Hz $^{1/2}$ (LF improvement)	111 hours
DT6	Aug.-Sept., 2001	1000 hours' observation	50 days	5×10^{-21} /Hz $^{1/2}$	1038 hours (22.0 hours)
DT7	Aug.-Sept., 2002	Full operation with Power recycling	2 days		25 hours
DT8	Feb.-April., 2003	1000 hours Coincidence	2 months	3×10^{-21} /Hz ½	1157 hours (20.5 hours)

Courtesy M. Ando

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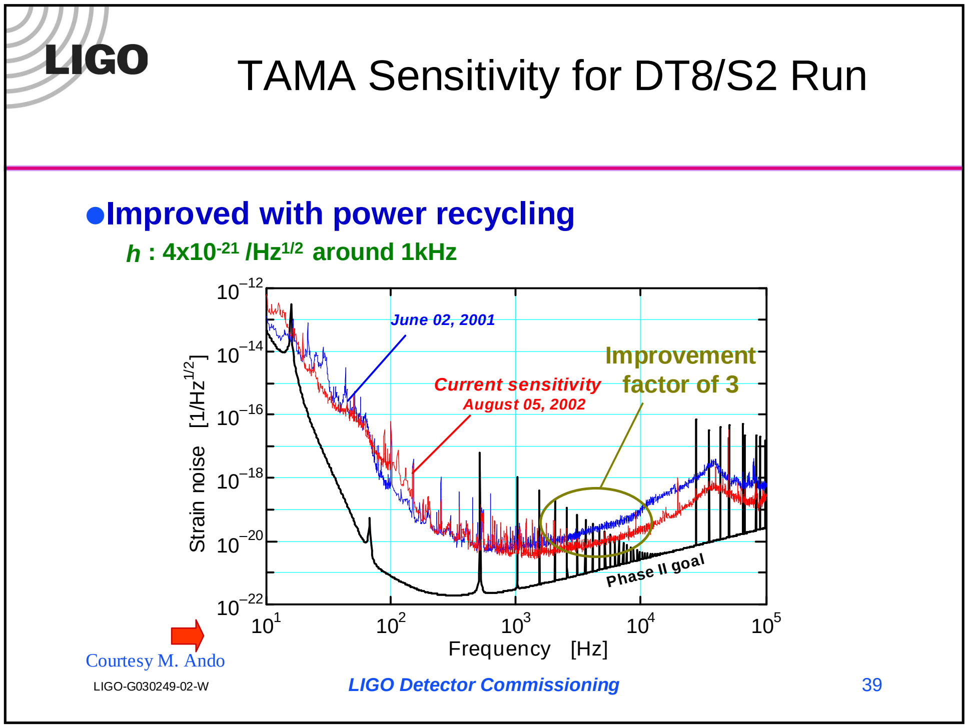
LIGO
TAMA Sensitivity for DT8/S2 Run
Improved with power recycling
h : 4x10-21 /Hz1/2 around 1kHz
June 02, 2001
Current sensitivity
August 05, 2002
Improvement
factor of 3
Phase II goal
Strain noise [1/Hz1/2]
Frequency [Hz]
Courtesy M. Ando
LIGO-G030249-02-W
LIGO Detector Commissioning
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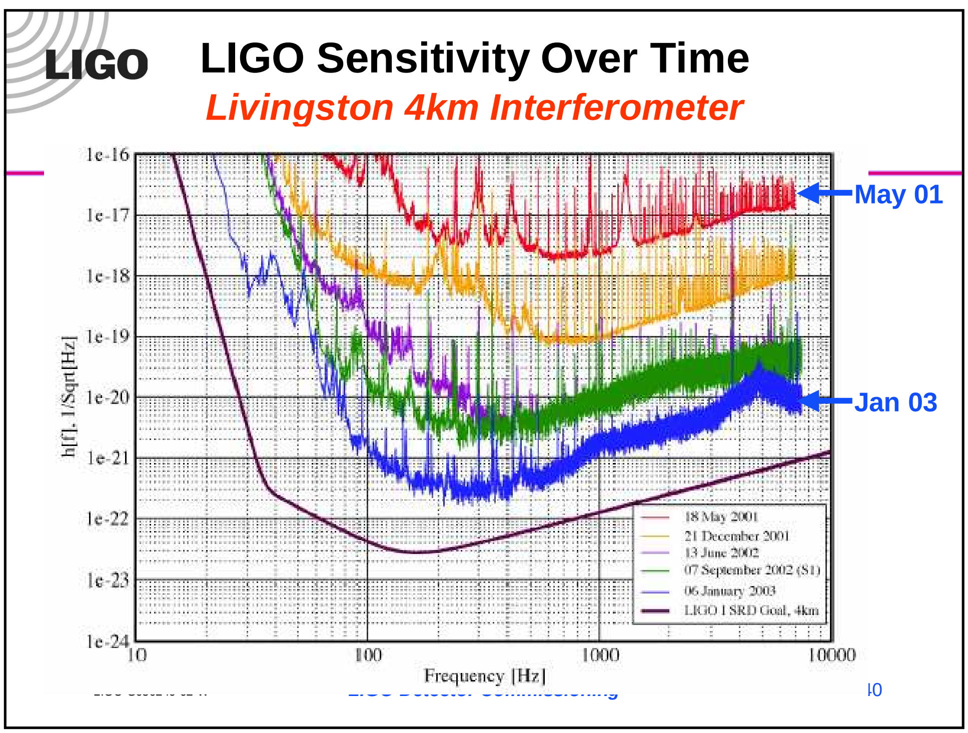
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LIGO Sensitivity Over Time
Livingston 4km Interferometer
May 01
Jan 03
h[f], 1/Sqrt[Hz]
Frequency [Hz]
18 May 2001
21 December 2001
13 June 2002
07 September 2002 (S1)
06 January 2003
LIGO I SRD Goal, 4km

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Binary Neutron Stars: S2 Range

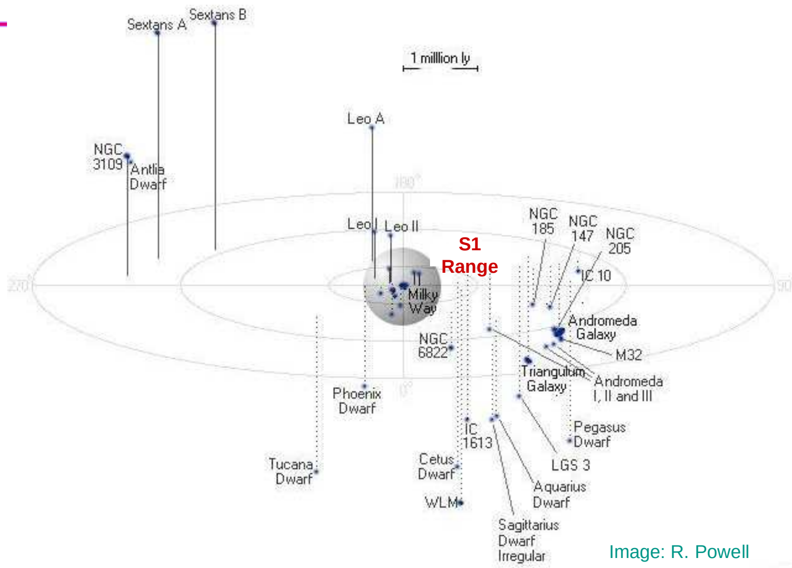

Image: R. Powell

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Future Plans for Terrestrial Detectors

- Improve reach of initial LIGO to run 1 yr at design sensitivity
- Virgo has made steady progress commissioning components in vertex, due to come on line in ~ 1 year
- GEO600, TAMA300, striving for design sensitivity
- IGEC expects to network with interferometers for future runs
- Advanced LIGO technology under development with intent to install by 2008

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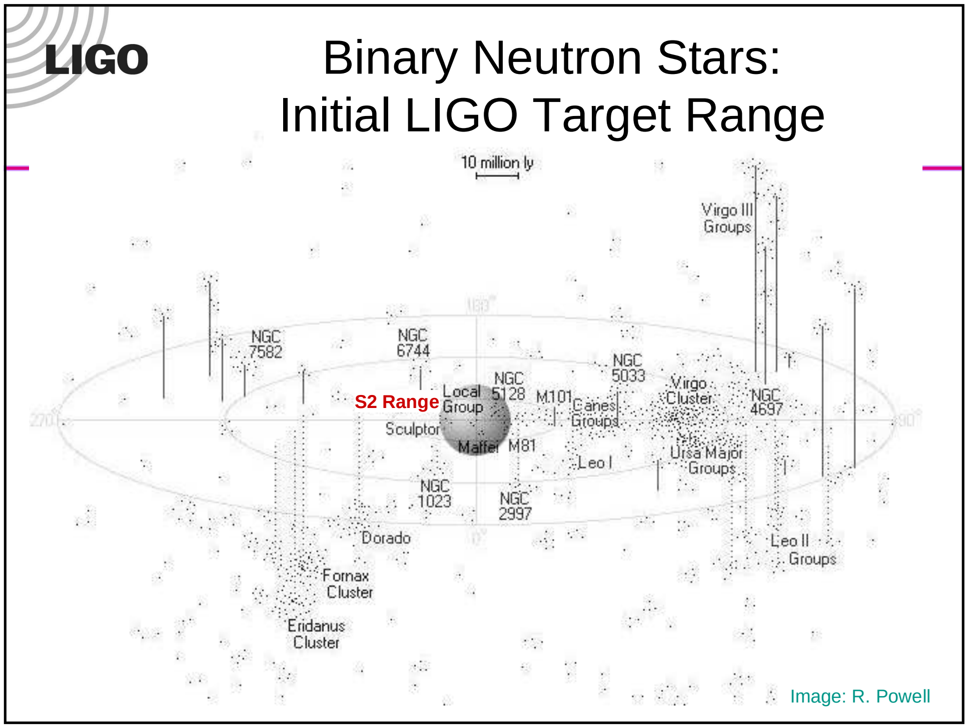
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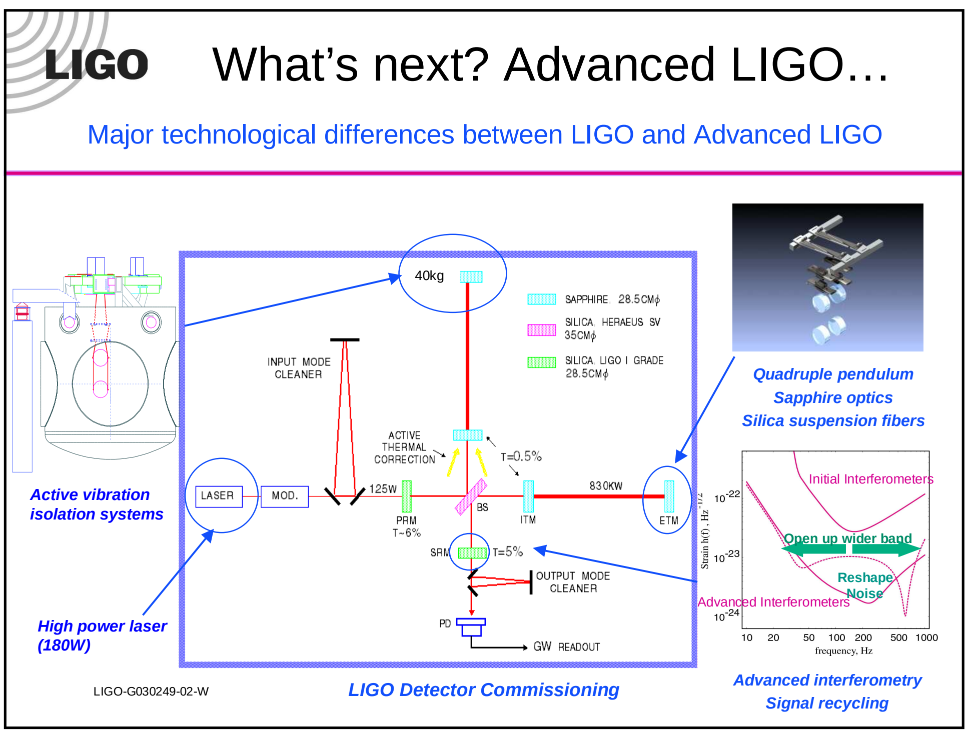
Binary Neutron Stars:
Initial LIGO Target Range
10 million ly
Virgo III Groups
NGC 7582
NGC 6744
NGC 5033
S2 Range
Local Group
NGC 5128
M101
Canes Groups
Virgo Cluster
NGC 4697
Sculptor
Maffei
M81
Leo I
Ursa Major Groups
NGC 1023
NGC 2997
Dorado
Leo II Groups
Fornax Cluster
Eridanus Cluster
Image: R. Powell


LIGO
What's next? Advanced LIGO…
Major technological differences between LIGO and Advanced LIGO
40kg
SAPPHIRE 28.5CMϕ
SILICA HERAEUS SV 35CMϕ
SILICA LIGO I GRADE 28.5CMϕ
INPUT MODE CLEANER
ACTIVE THERMAL CORRECTION
T=0.5%
LASER
MOD.
125W
PRM T~6%
BS
ITM
830KW
ETM
SRM
T=5%
OUTPUT MODE CLEANER
PD
GW READOUT
Quadruple pendulum
Sapphire optics
Silica suspension fibers
Initial Interferometers
Open up wider band
Reshape Noise
Advanced Interferometers
frequency, Hz
Active vibration isolation systems
High power laser (180W)
LIGO-G030249-02-W
LIGO Detector Commissioning
Advanced interferometry
Signal recycling

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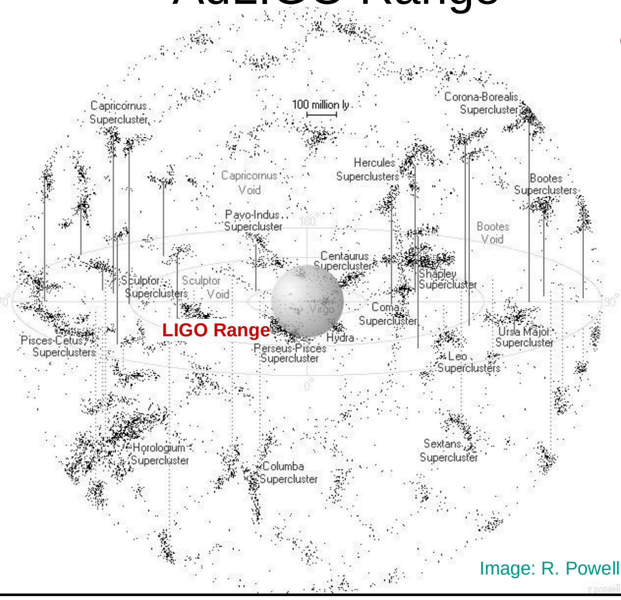
Binary Neutron Stars: AdLIGO Range



LIGO-G030249-02-W

Image: R. Powell

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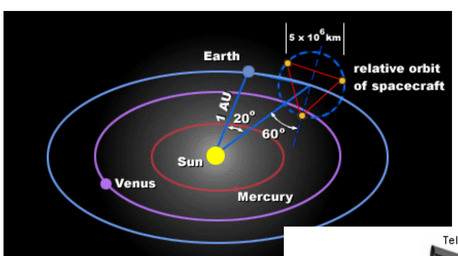
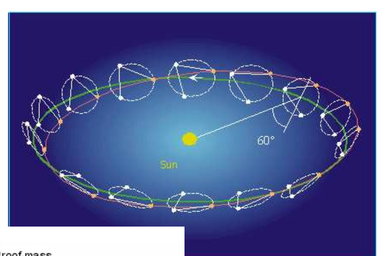
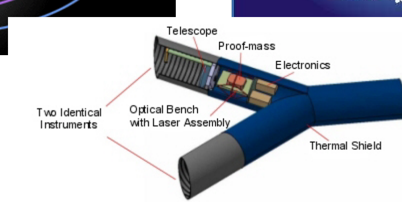
…and opening a new channel with a detector in space.







Planning underway for space-based detector, LISA, to open up a lower frequency band ~ 2011-ish

LIGO-G030249-02-W

LIGO Detector Commissioning

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LIGO

Summary

- We are currently experiencing a rapid advance in the sensitivity of searches for gravitational waves
- Elements of world-wide networks of interferometers and bars have been exercised
- The near future will see the confrontation of theory with many fine observational results

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