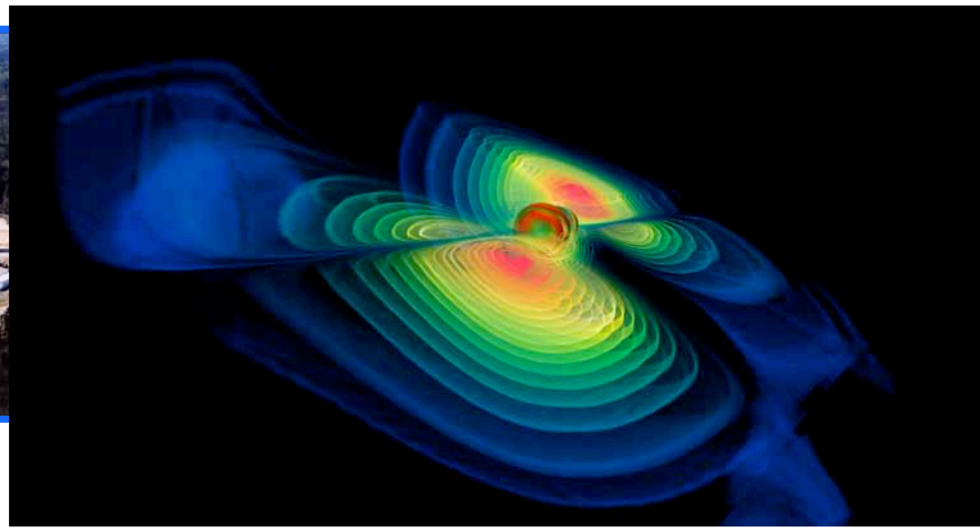
LIGO: The Laser Interferometer Gravitational Wave Observatory



Credit: Werner Benger/ZIB/AEI/CCT-LSU

Michael Landry

LIGO Hanford Observatory/Caltech
for the LIGO Scientific Collaboration (LSC)
http://www.ligo.org

Beamlines 2.0
2010 APS/EMC Users Meeting
5 May 2010
Argonne National Laboratory

LIGO-G1000391-v1

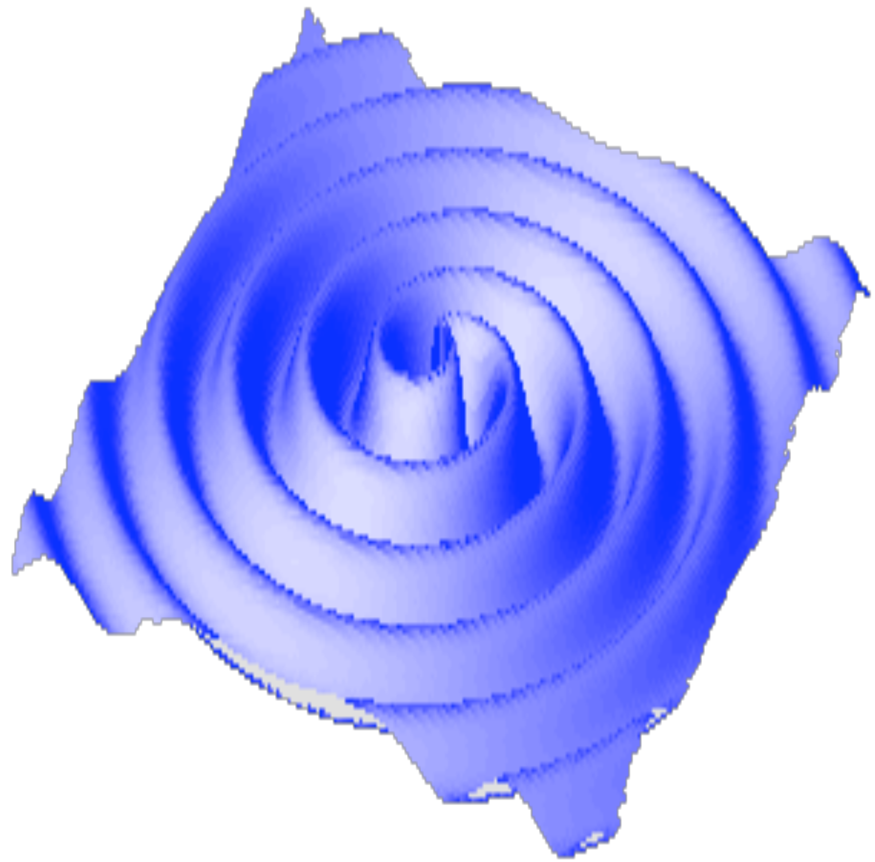
Talk overview

- The search for gravitational waves
- Facilities: beamtubes and vacuum
- Detector components
- Servos
  - Control km-scale arm lengths to 10^{-13} meters RMS
  - Hold mirror alignments to 10^{-8} radians
- Noise, mostly environmental
  - Plenty of technical noise sources not covered here
- Advanced LIGO

Gravitational waves

- GWs are "ripples in spacetime": rapidly moving masses generate fluctuations in spacetime curvature:
  - They are expected to propagate at the speed of light
  - They stretch and squeeze space

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$



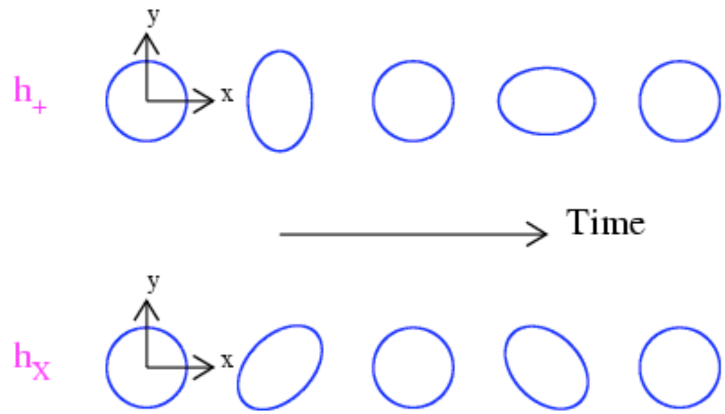
What is the observable effect?

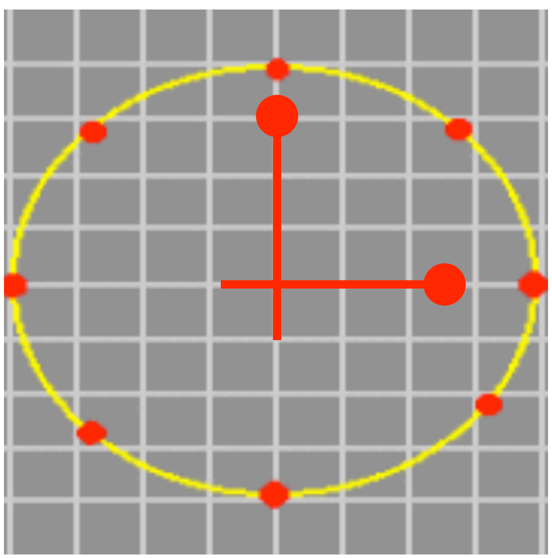
Example:

Ring of test masses

responding to wave

propagating along z

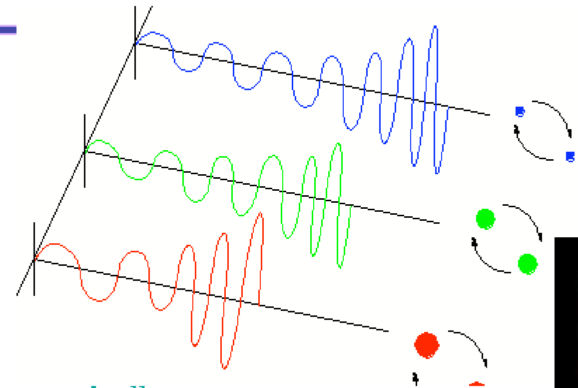




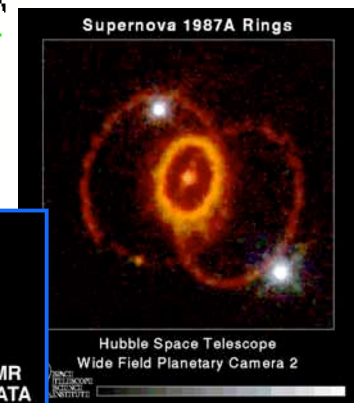
Amplitude parameterized by (tiny) dimensionless strain h:

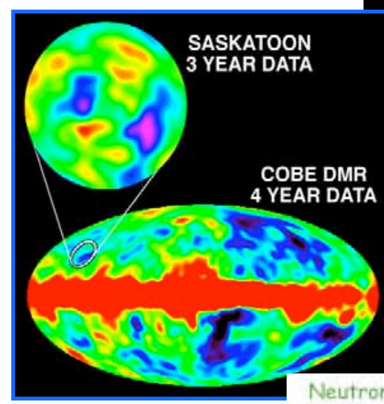
$$h(t) = \frac{\delta L(t)}{L}$$

What might make Gravitational Waves?

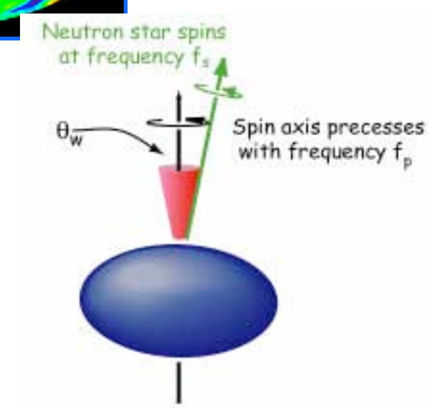


- Compact binary inspiral: *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms
- Supernovae / GRBs: *"bursts"*
  - » burst signals in coincidence with signals in electromagnetic radiation / neutrinos
  - » all-sky untriggered searches too



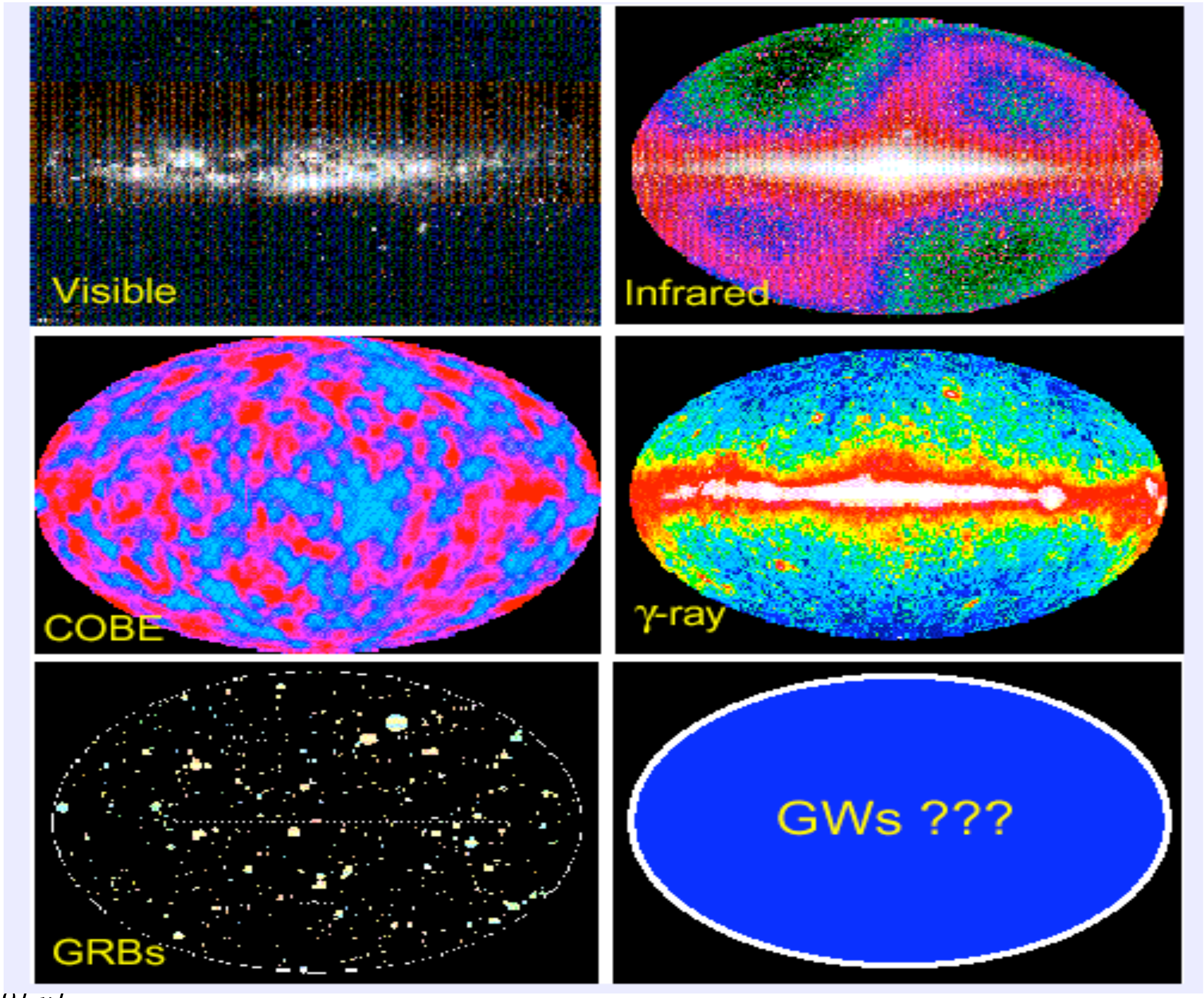


- Cosmological Signal: *"stochastic background"*
- Pulsars in our galaxy: *"periodic"*
  - » search for observed neutron stars
  - » all-sky search (computing challenge)



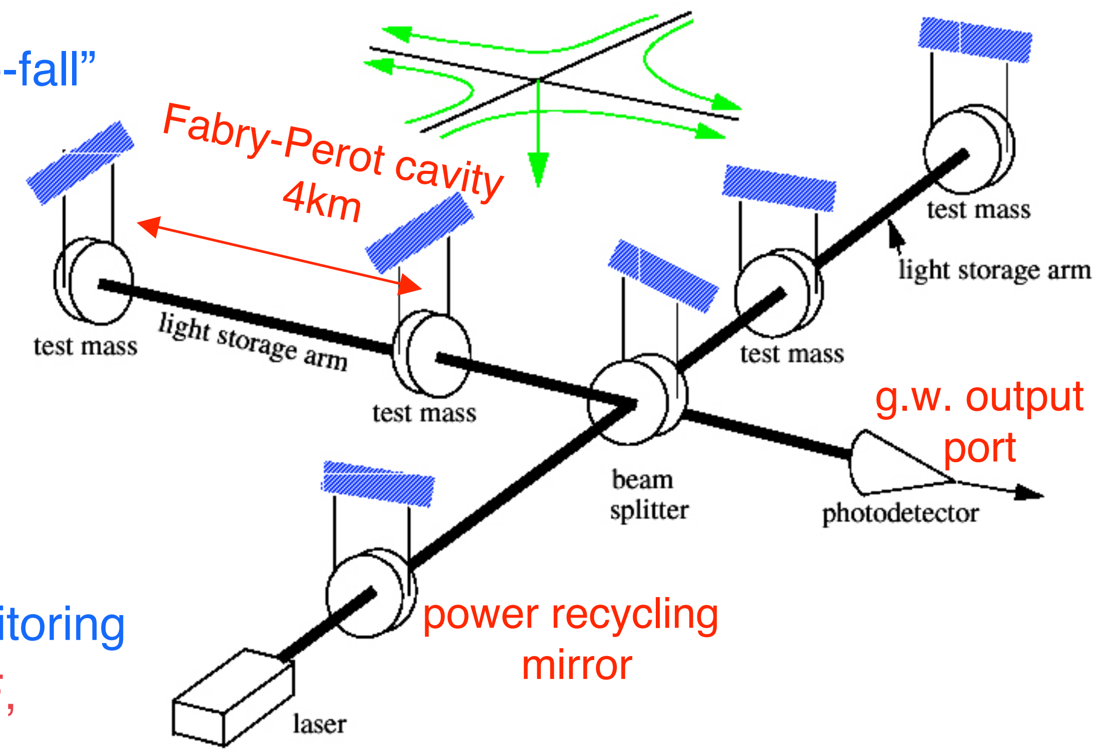
Also: the unknown!

Gravitational wave astronomy



Gravitational Wave Detection

- Suspended Interferometers
  - » Suspended mirrors in "free-fall"
  - » Michelson IFO is "natural" GW detector
  - » Broad-band response (~50 Hz to few kHz)
  - » Physical environment monitoring (e.g., seismic, weather, RF, acoustic, etc)



LIGO design length sensitivity: 10^{-18}m

LSC Sites

LIGO Hanford Observatory

(4km, 2km detectors)

LIGO Livingston Observatory

(single 4km detector)

Beamtubes

Beamtube facts, per site:

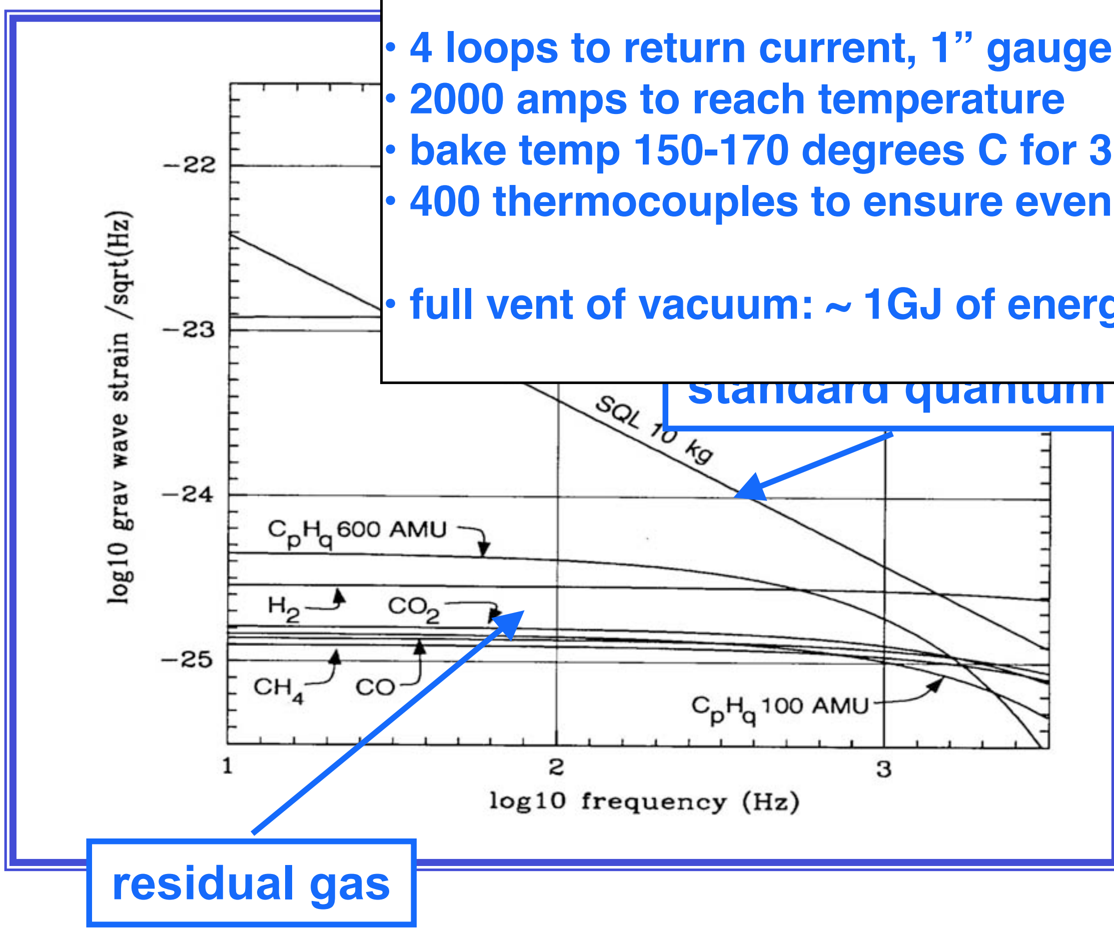
- **8km of 1.24m diameter 304L stainless tube**
- **65 foot-long spiral-welded sections**
- **welded stiffening rings, supports and bellows**
- **~10,000m^3, 10^{-9}Torr**

Beam Tube Bakeout

Bakeout facts:

- 4 loops to return current, 1” gauge
- 2000 amps to reach temperature
- bake temp 150-170 degrees C for 30 days
- 400 thermocouples to ensure even heating

- full vent of vacuum: ~ 1GJ of energy



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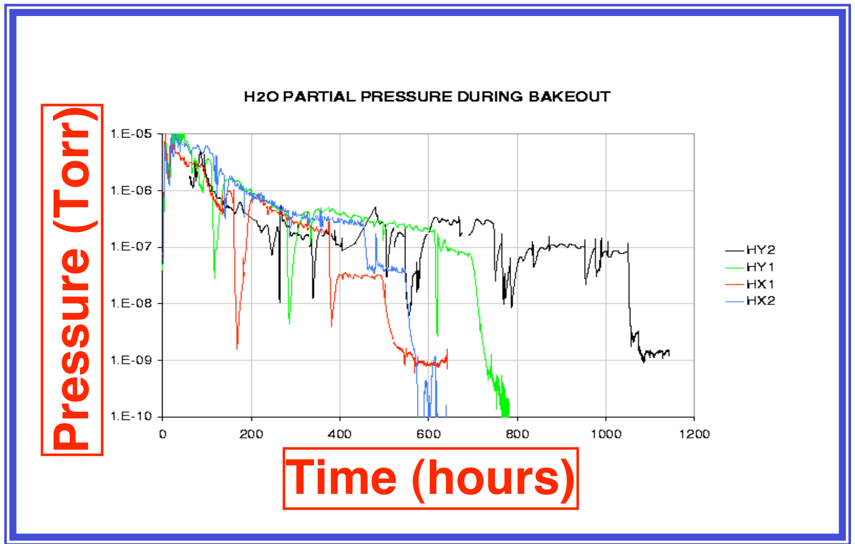
Bakeout

partial pressures during bakeout



Beam Tube Bakeout Results [a]

NOTE: All results except for H_2 are upper limits

		Hanford				Livingston	
Species	Goal [b]	HY2	HY1	HX1	HX2	LX2	
H_2	4.7	4.8	6.3	5.2	4.6	4.3	x 10^{-14} torr liters/sec/cm ^{2}
CH_4	48000	< 900	< 220	< 8.8	< 95	< 40	x 10^{-20} torr liters/sec/cm ^{2}
H_2O	1500	< 4	< 20	< 1.8	< 0.8	< 10	x 10^{-18} torr liters/sec/cm ^{2}
CO	650	< 14	< 9	< 5.7	< 2	< 5	x 10^{-18} torr liters/sec/cm ^{2}
CO_2	2200	< 40	< 18	< 2.9	< 8.5	< 8	x 10^{-19} torr liters/sec/cm ^{2}
NO+C_2H_6	7000	< 2	< 14	< 6.6	< 1.0	< 1.1	x 10^{-19} torr liters/sec/cm ^{2}
$H_nC_pO_q$	50-2 [c]	< 15	< 8.5	< 5.3	< 0.4	< 4.3	x 10^{-19} torr liters/sec/cm ^{2}
air leak	1000	< 20	< 10	< 3.5	< 16	< 7	x 10^{-11} torr liter/sec

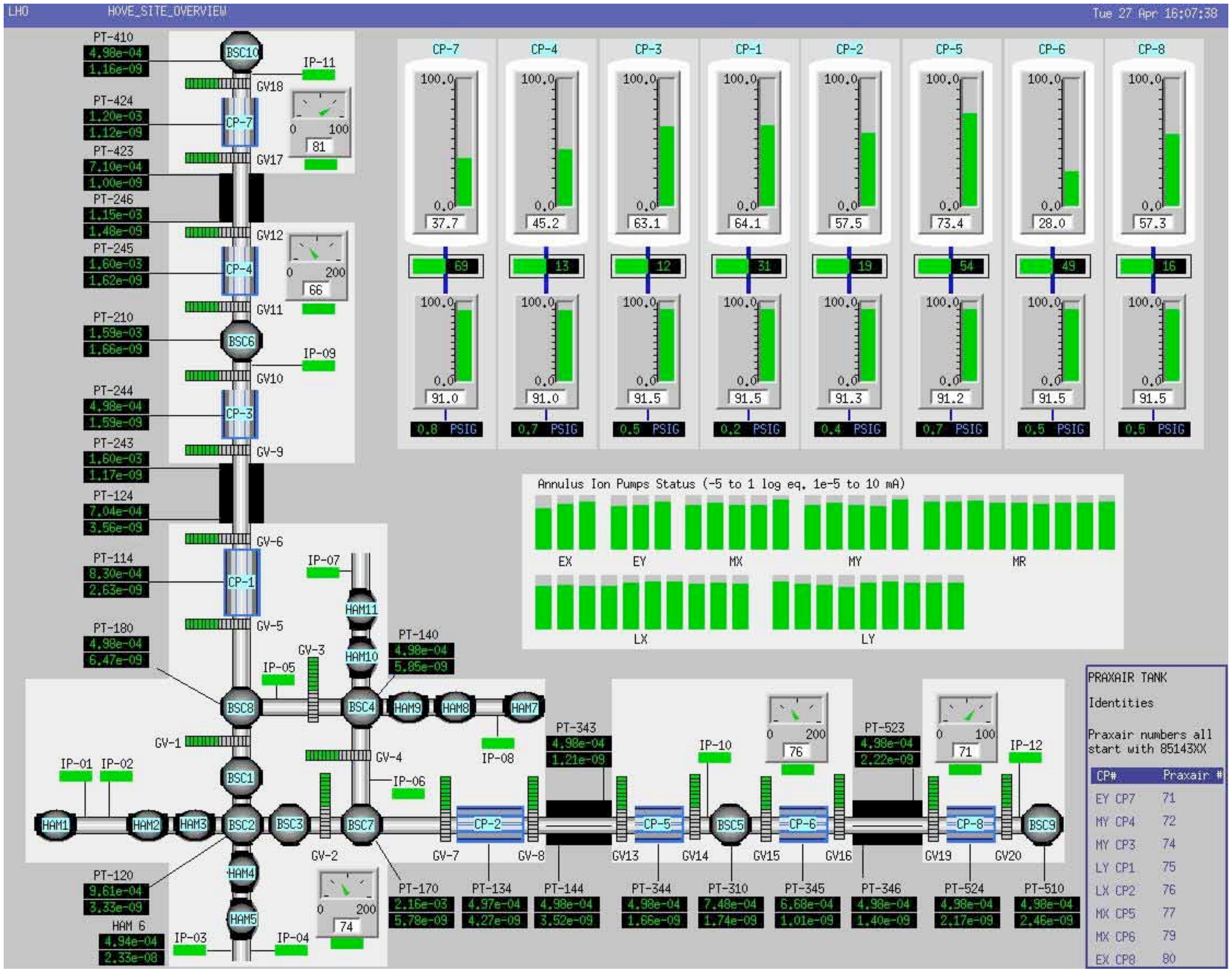
[a] Outgassing results correct to 23 C

[b] Goal: maximum outgassing to achieve pressure equivalent to 10^{-9} torr H_2 using only pumps at stations

[c] Goal for hydrocarbons depends on weight of parent molecule; range given corresponds with 100-300 AMU

Achieved Design Requirements (< 10^{-9} torr)

Vacuum overview



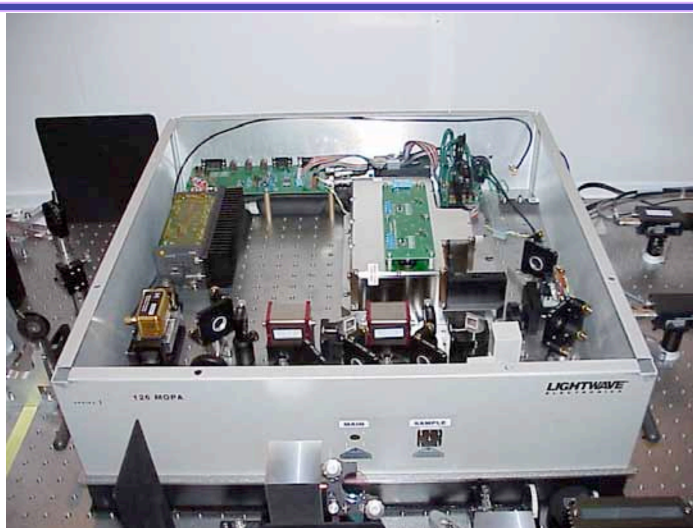
- Schematic of the Hanford vacuum layout
- Control and Data Systems (CDS) makes use of Epics
- Roughing achieved with roots blowers followed magnetically levitated turbos
- Seismically-quiet pumping via ion pumps, and LN2 cryo traps
- Isolation via 44” and 48” gate valves

Vertex at Hanford site

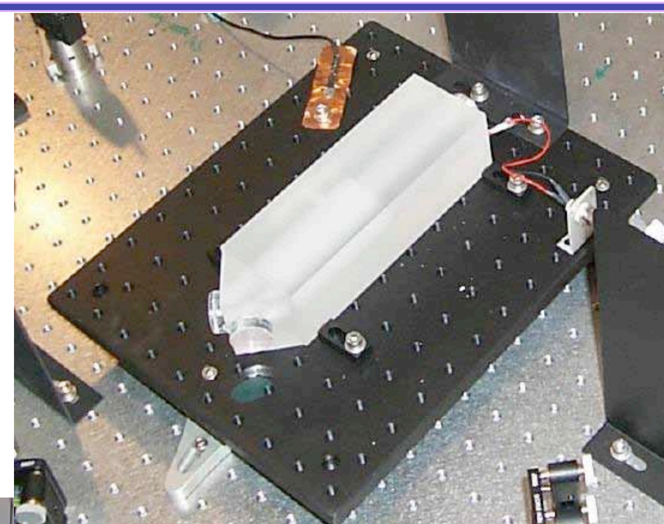
The 4k vertex

LIGO-G1000391-v1

All-Solid-State Nd:YAG Laser



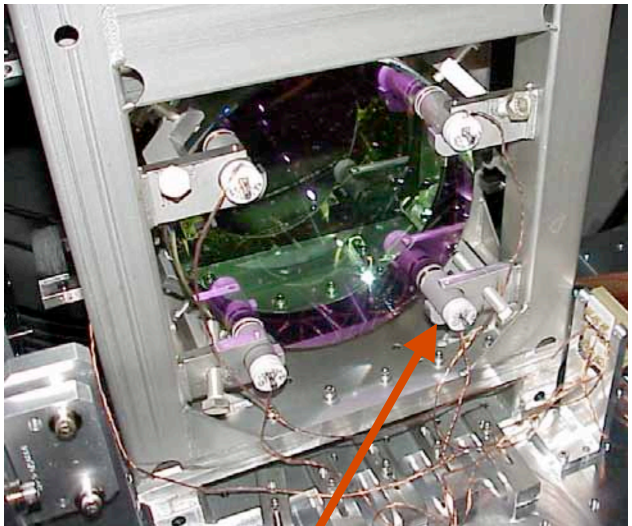
Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics
(now commercial product)

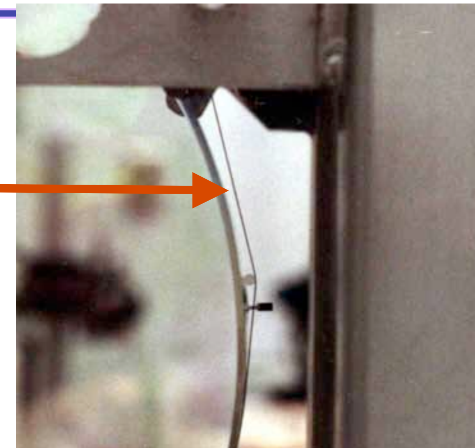


Cavity for
defining beam geometry,
joint development with
Stanford

Frequency reference
cavity (inside oven)

Core Optics Suspension and Control





Optics suspended as simple pendulums

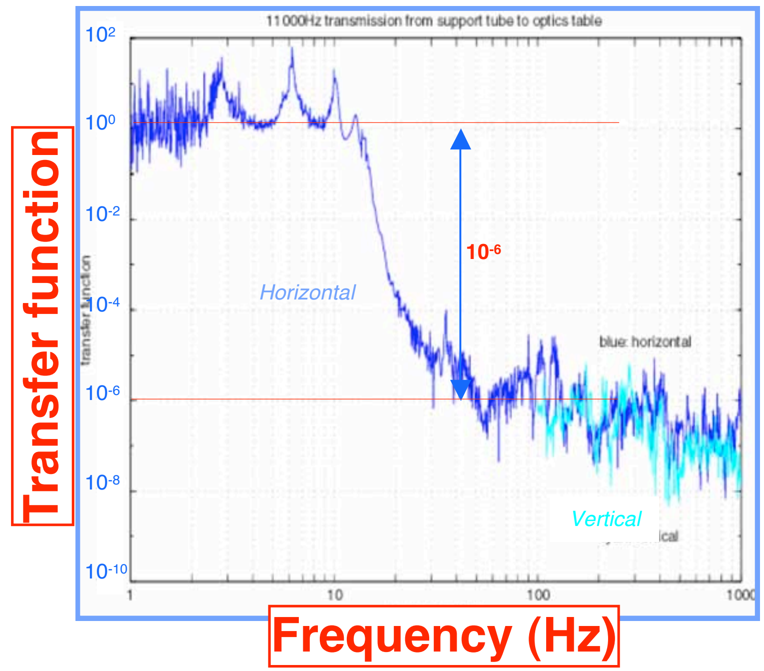
Shadow sensors & voice-coil actuators provide damping and control forces

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

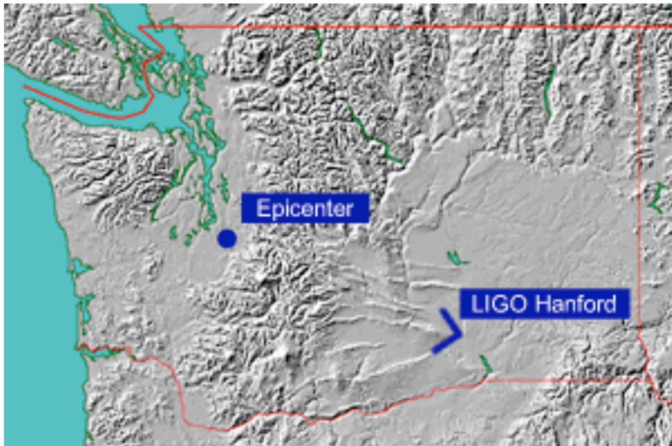
LIGO detector facilities

Seismic Isolation

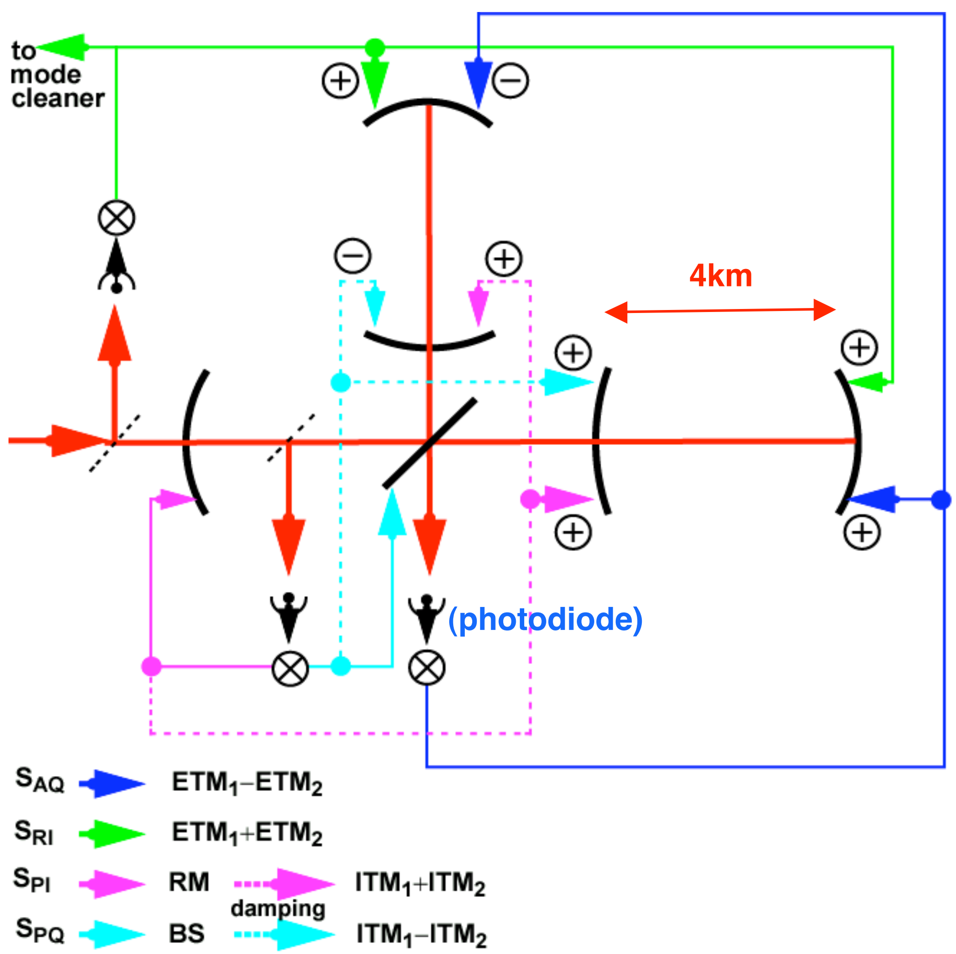
- Multi-stage (mass & springs) optical table support gives 10^6 suppression
- Pendulum suspension gives additional $1 / f^2$ suppression above ~1 Hz



The road to design sensitivity…



Fast servo example: length control



- Fast channel data acquired at 16384Hz
- Multiple Input / Multiple Output
- Three tightly coupled cavities
- Employs adaptive control system that evaluates plant evolution and reconfigures feedback paths and gains during lock acquisition

Slow servo example: tides

common mode differential mode

Tidal evaluation on 21-hour locked section of S1 data

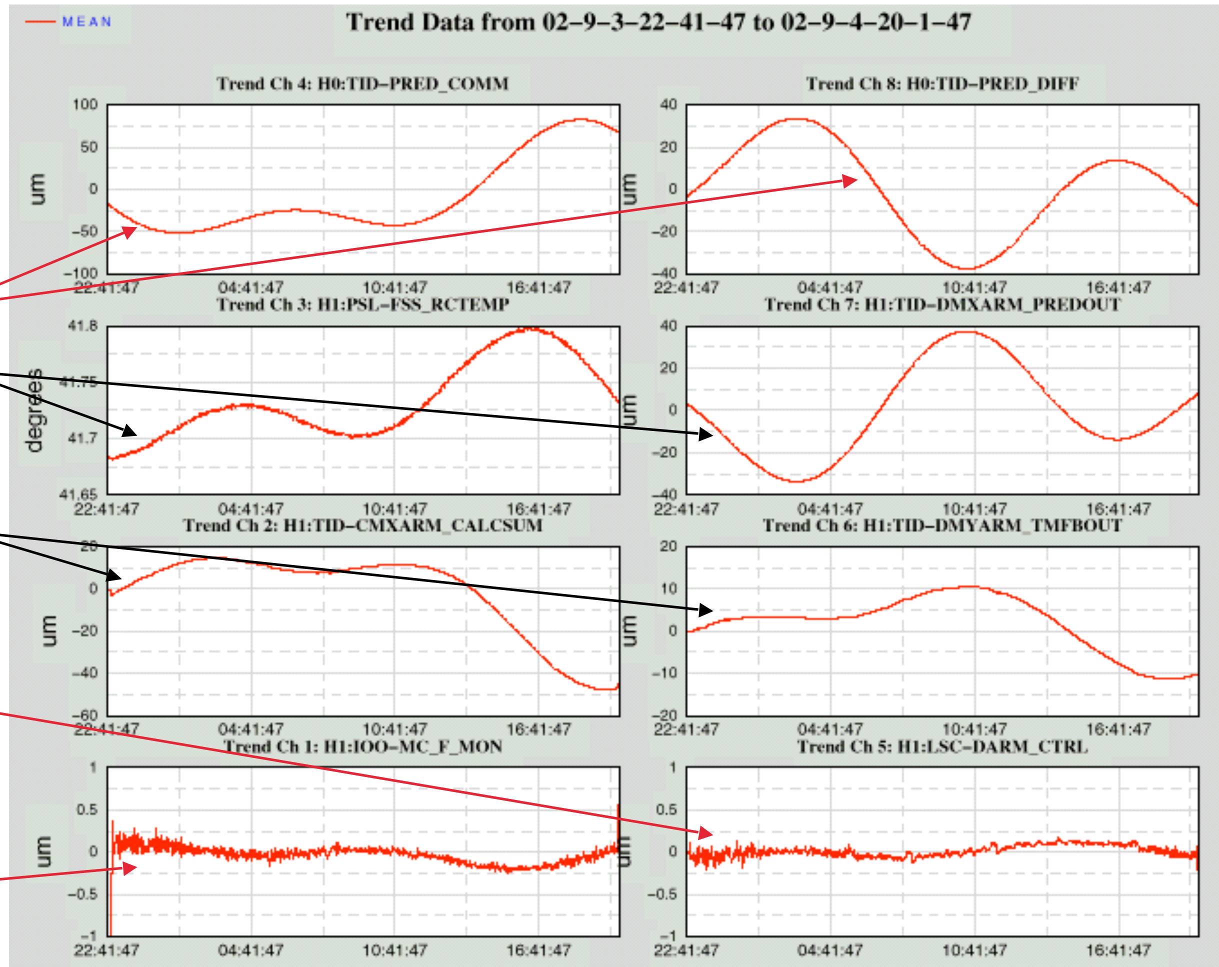
Predicted tides

Feedforward

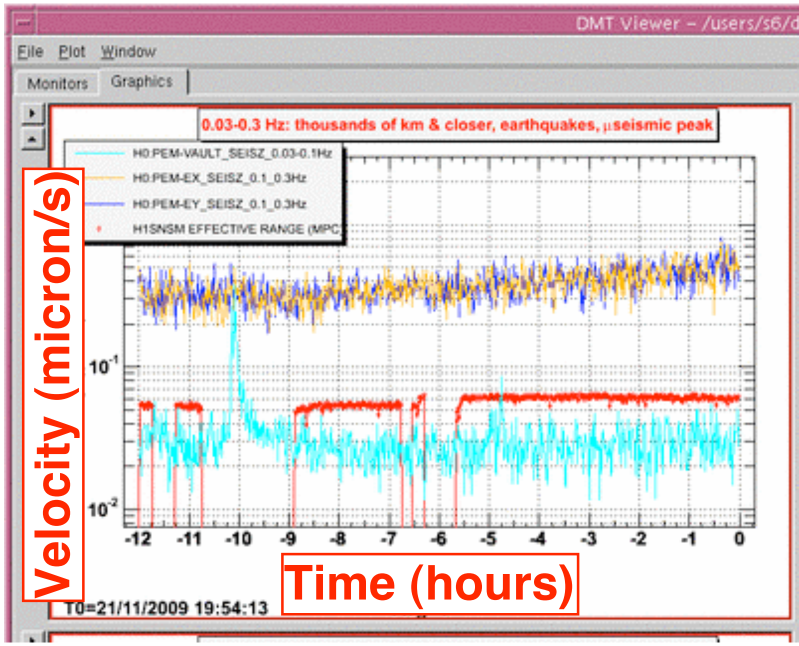
Feedback

Residual signal on coils

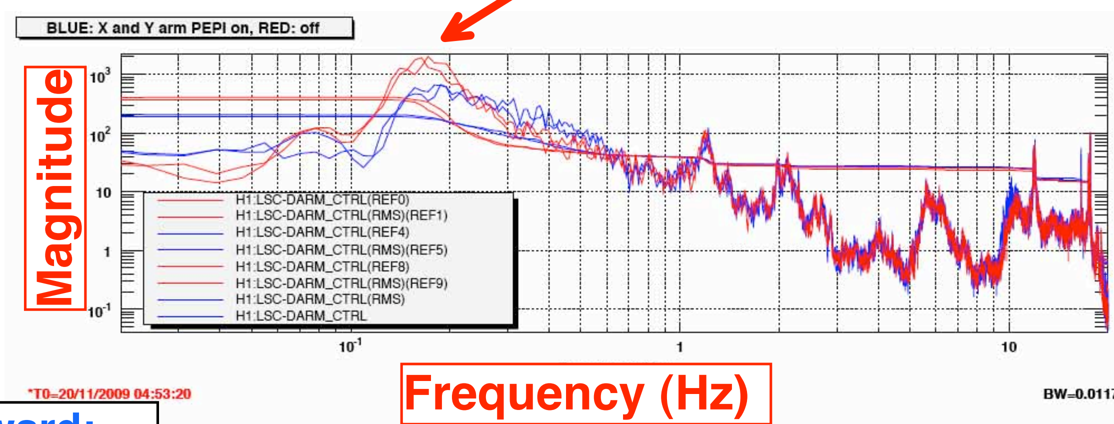
Residual signal on laser



Slow servo example: microseism

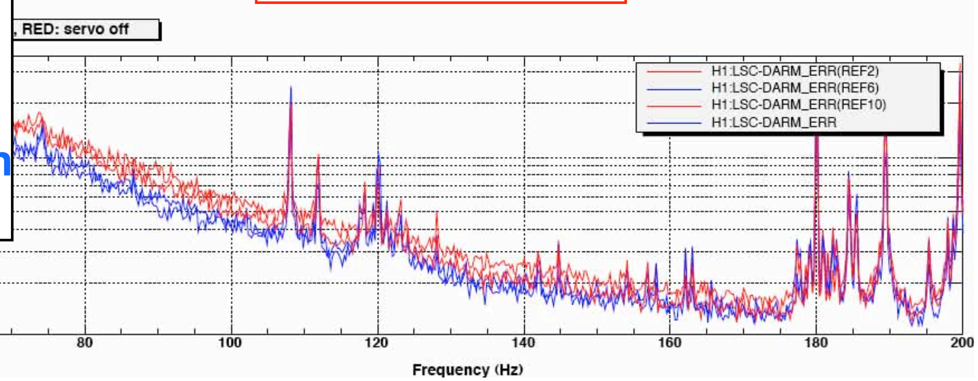


Need to supress microseismic peak at ~0.15Hz



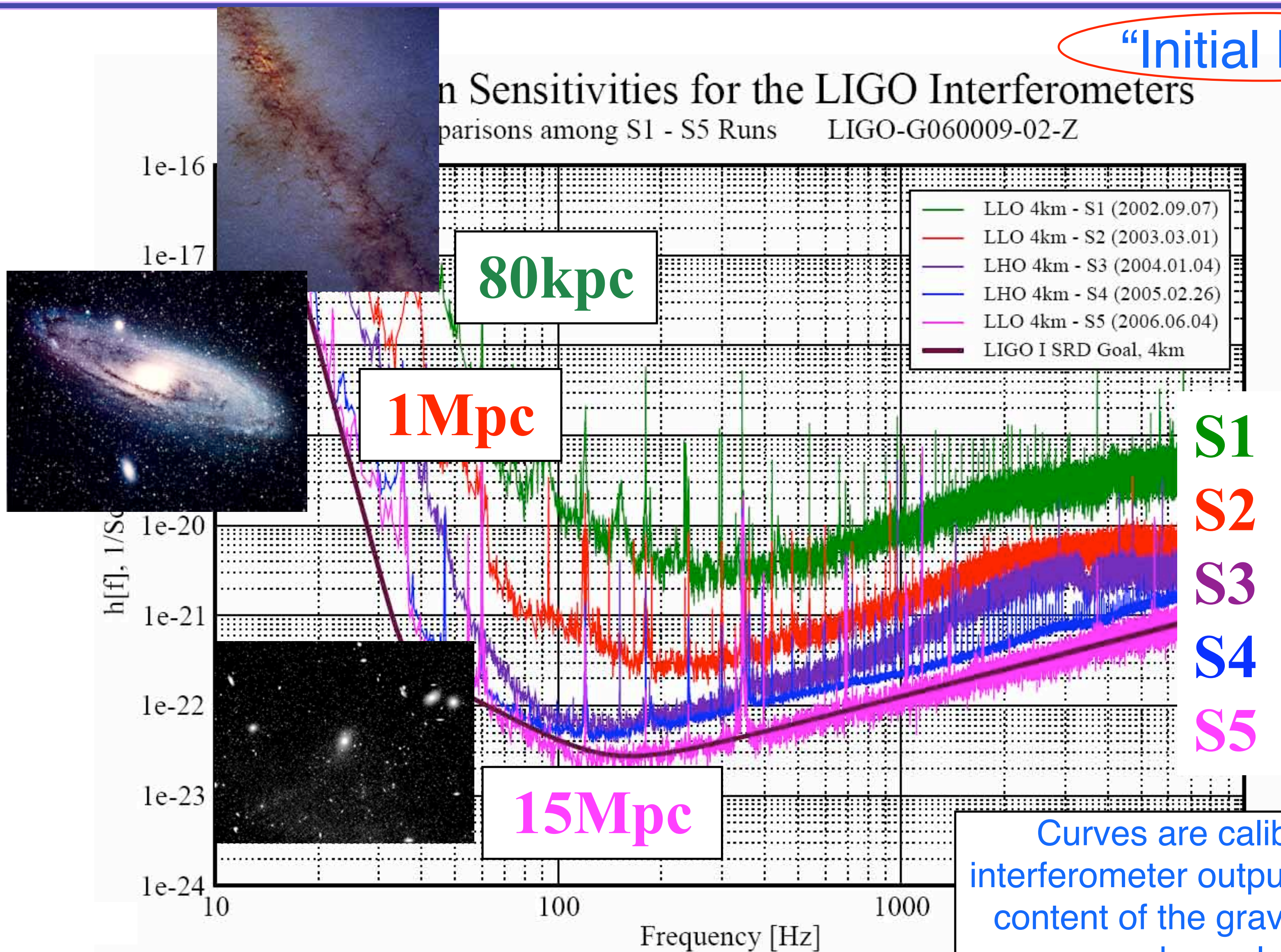
Microseismic feed back, and feed forward:

- **use seismometers in corner and ends**
- **actuate arm length to suppress low f motion**
- **can account for 1-2Mpc in inspiral range**



Calibrated output: LIGO noise history

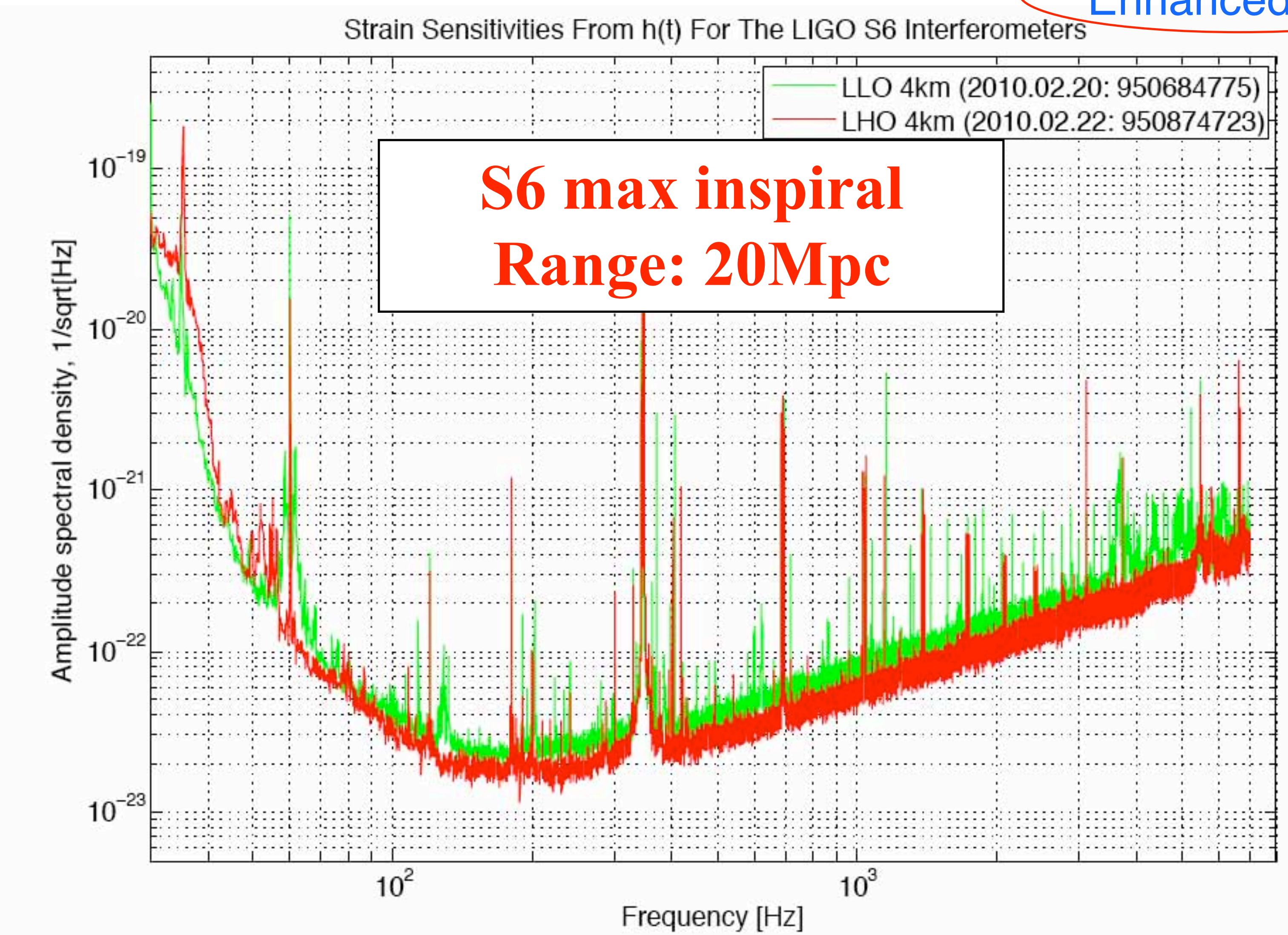
"Initial LIGO"



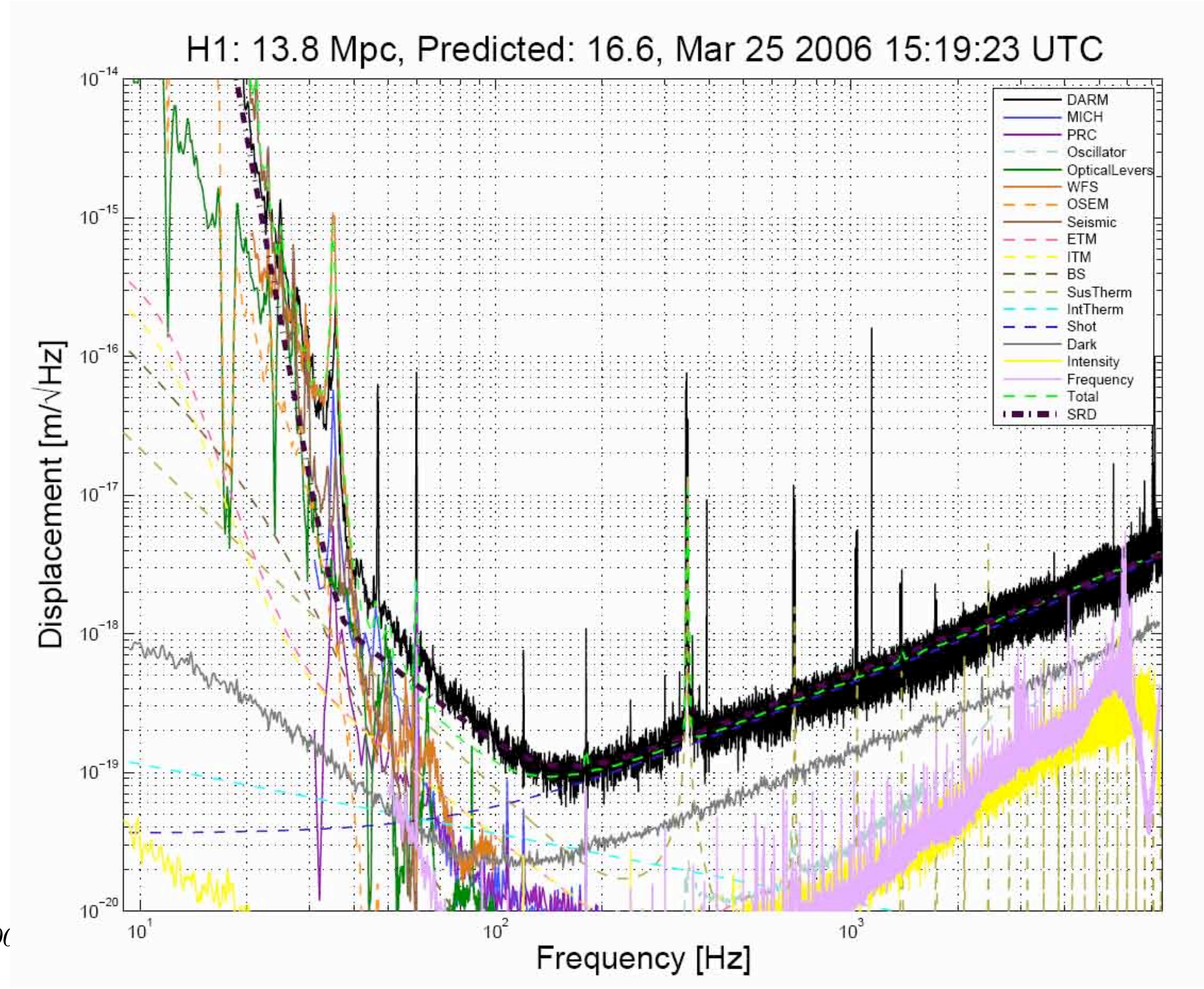
Curves are calibrated interferometer output: spectral content of the gravity-wave channel

Current science run: S6

“Enhanced LIGO”

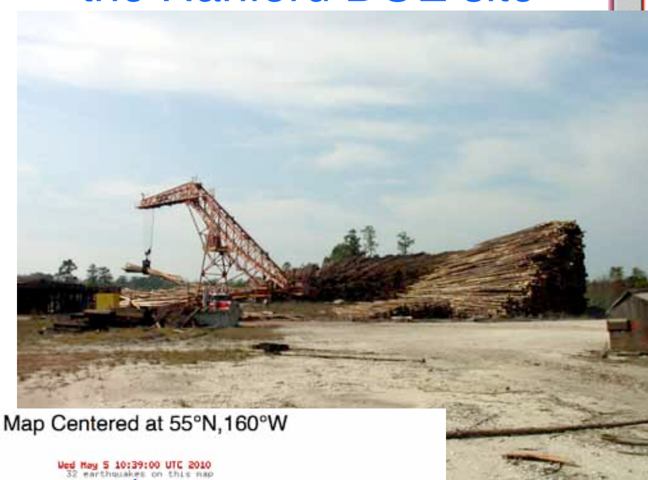


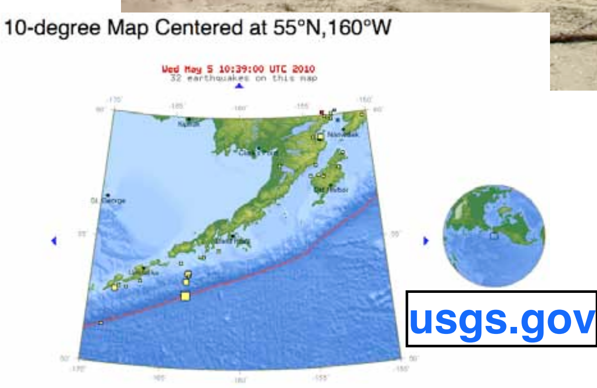
Noise budget

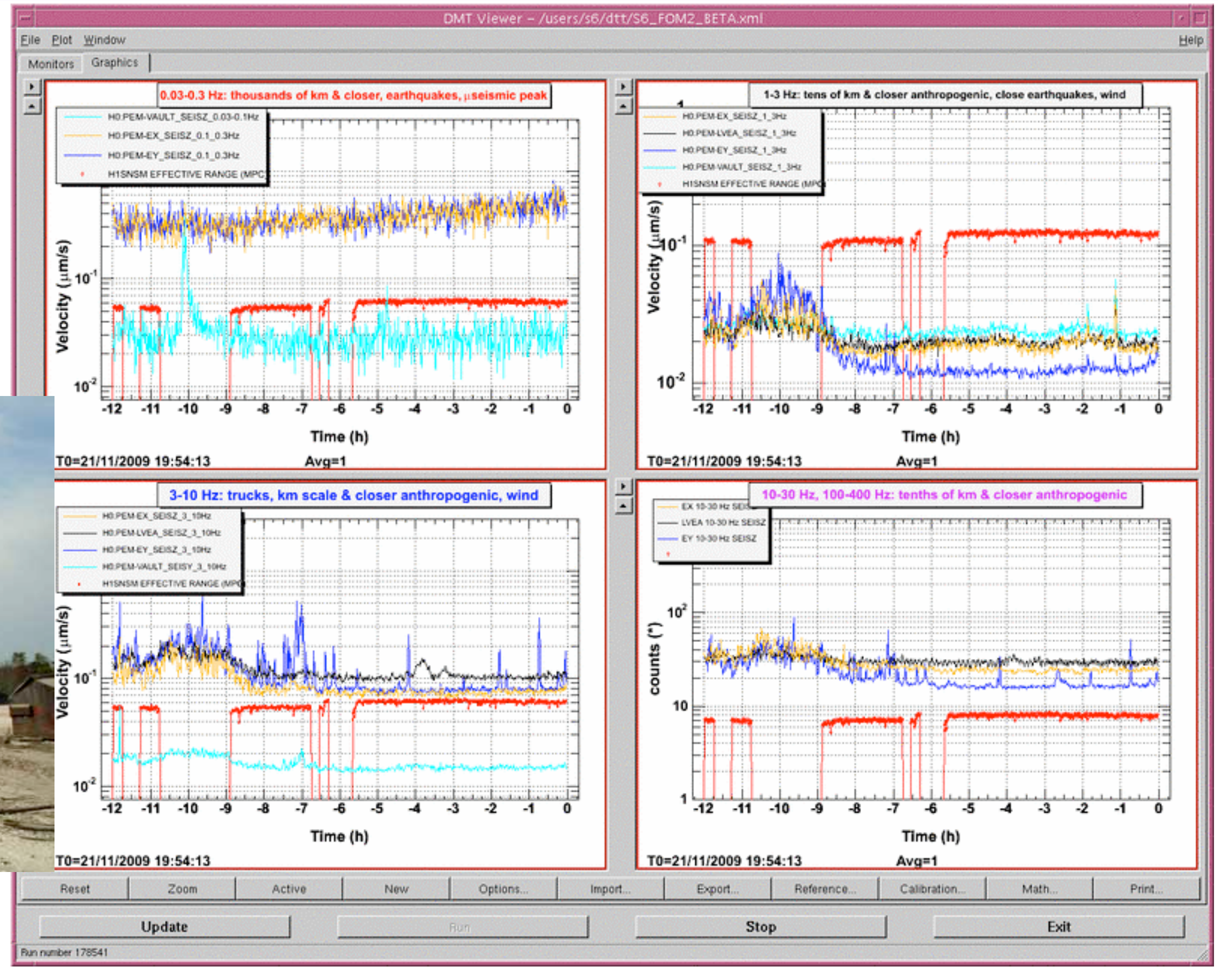


Environmental noise

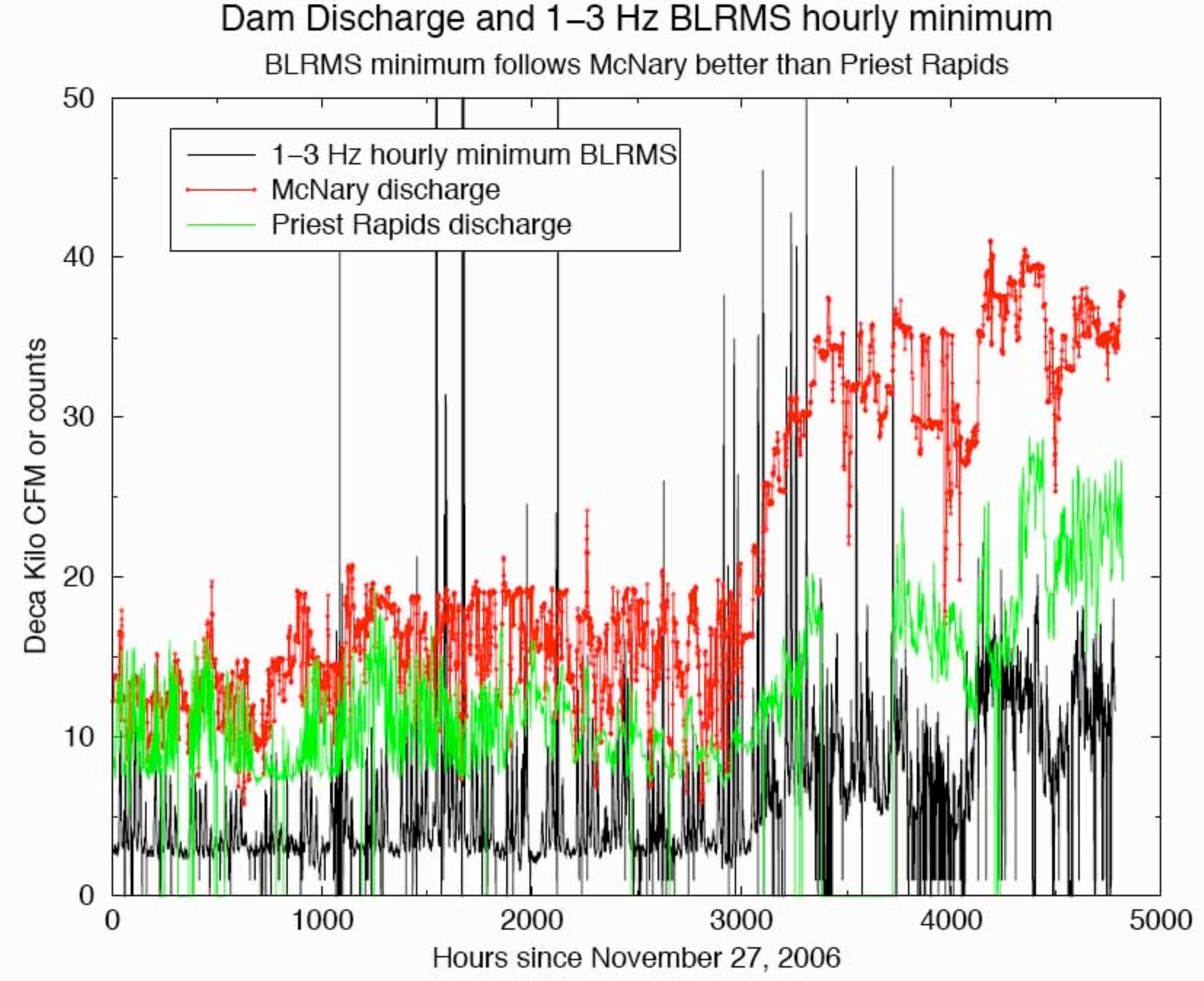
- Planes, trains and automobiles
- Logging in Livingston
- earthquakes
- Digging, burying on the Hanford DOE site







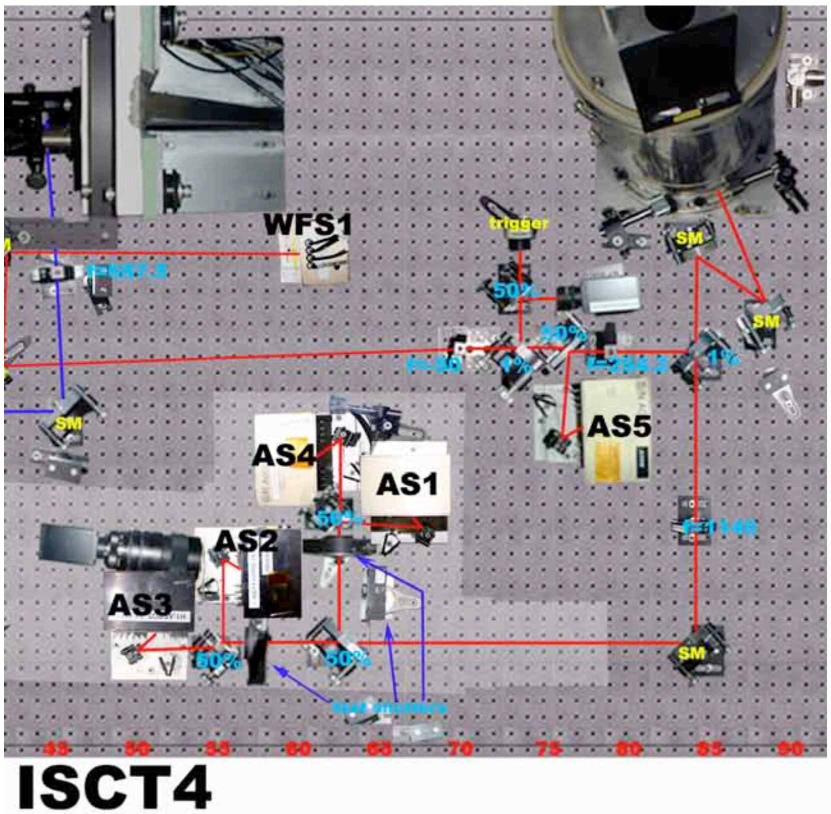
Dam noise

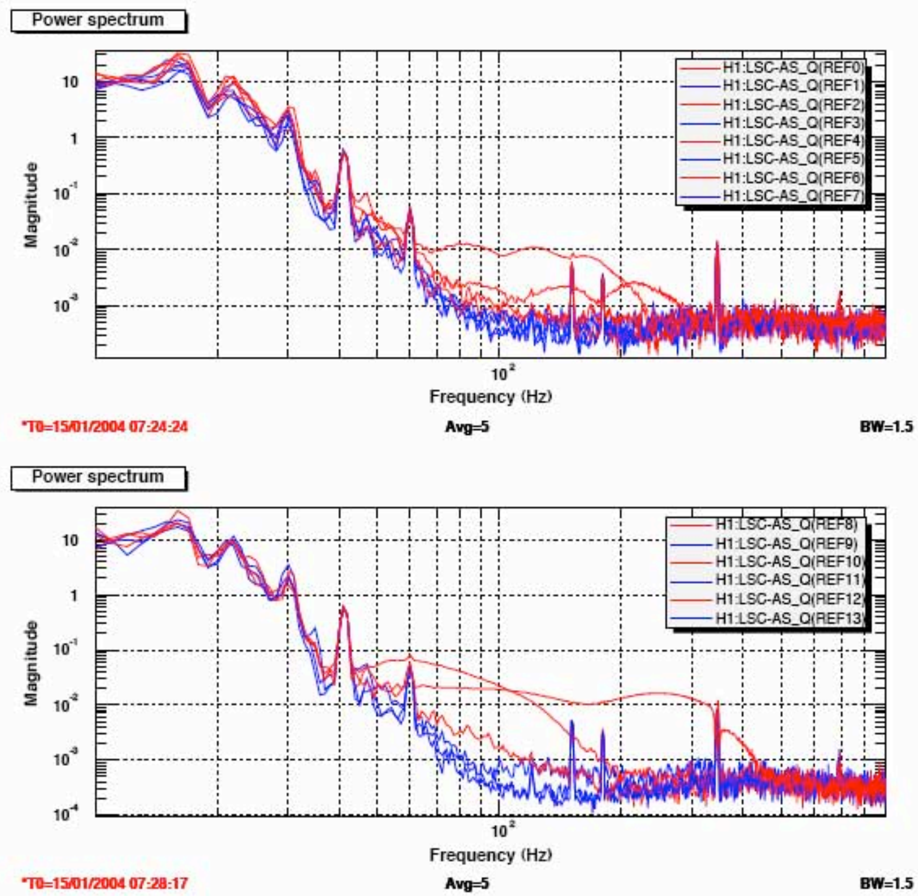


Dam Discharge and 1–3 Hz BLRMS hourly minimum
BLRMS minimum follows McNary better than Priest Rapids
1–3 Hz hourly minimum BLRMS
McNary discharge
Priest Rapids discharge
Deca Kilo CFM or counts
Hours since November 27, 2006
0
10
20
30
40
50
1000
2000
3000
4000
5000

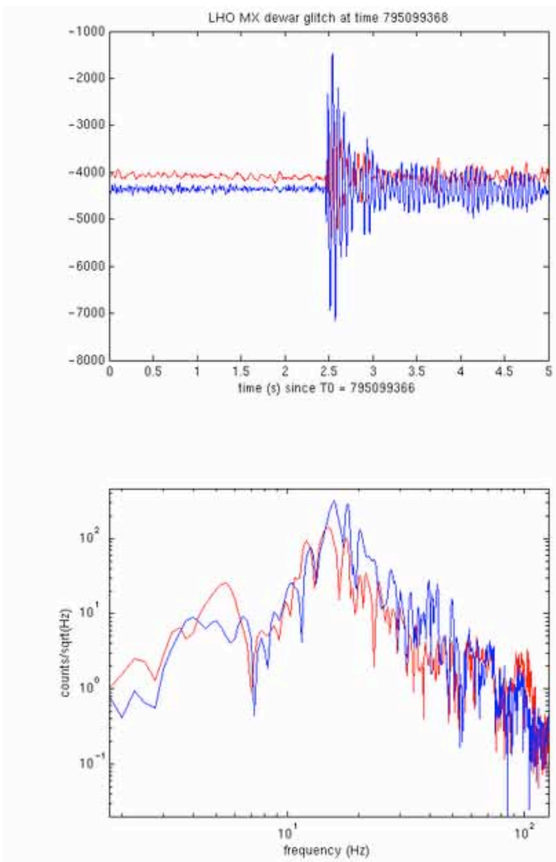
Dust glitches

RED: spectra for dust flash times on video tape of AS_Q photodiode region;
BLUE: spectra OFFSET +/- 10 s from dust flash on video tape





Dewar glitches



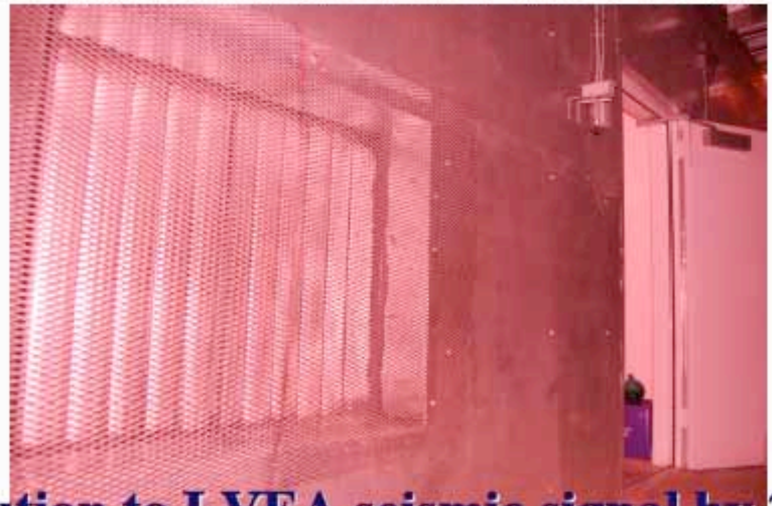
Original | Thermally insulated

HVAC noise

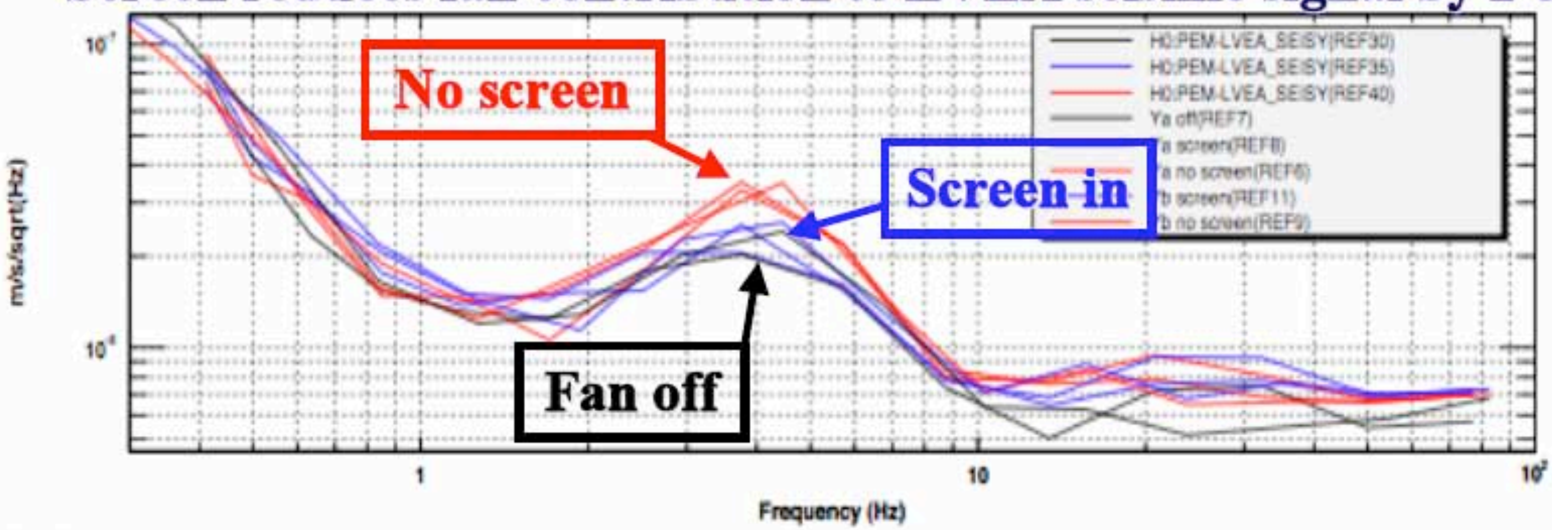
Screen reduces low-f noise from HVAC fans

Low frequency noise from large eddies.

Reduce eddy size with screen

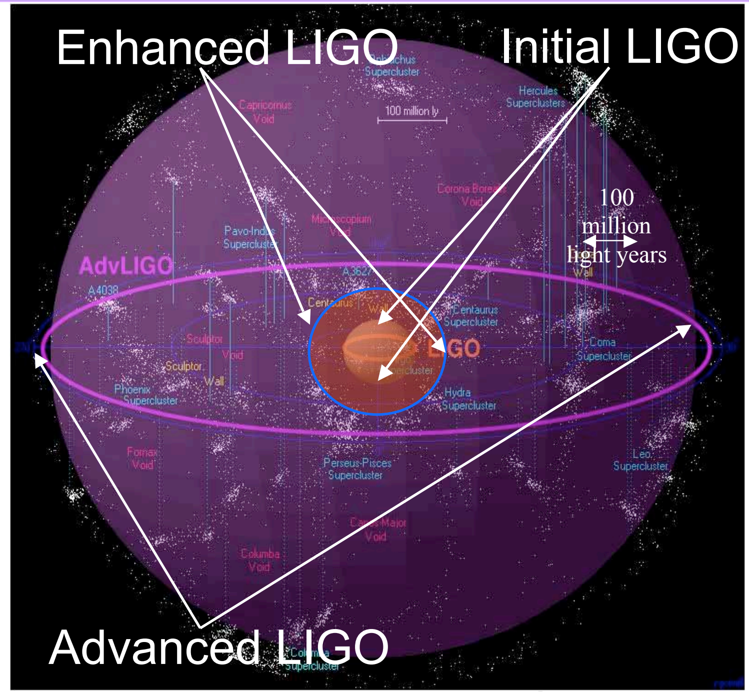


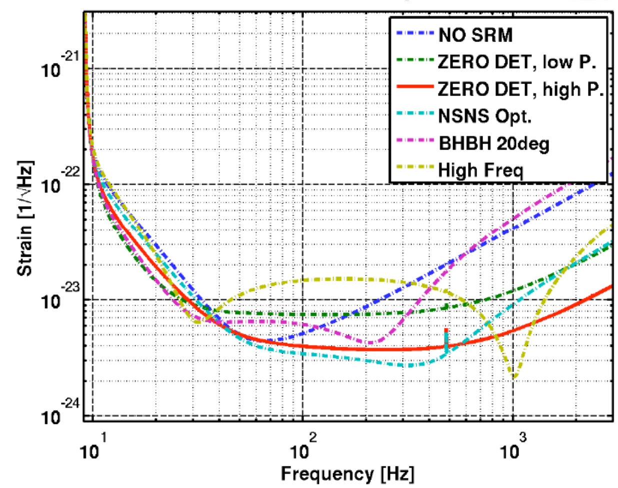
Screen reduces fan contribution to LVEA seismic signal by 2-3



Advanced LIGO

- Factor of 10 greater sensitivity than initial LIGO
- Factor 4 lower start to sensitive frequency range
  - ~10 Hz instead of ~40 Hz
  - More massive astrophysical systems, greater reach, longer observation of inspirals
- Intended to start gravitational-wave astronomy
- Frequent detections expected – exact rates to be determined, of course
  - Most likely rate for NS-NS inspirals observed: ~40/year





Summary

- Search for gravitational waves underway: no detections so far, S6 data being collected
- Facilities, including buildings, beamtubes and vacuum components designed for 20-year lifespan
- Advanced LIGO project underway, deinstall/install begins October 20 (Initial, Enhanced LIGO experience critical)
- Hope to usher in detection and transition to astronomy in the coming few years

LIGO Scientific Collaboration

LIGO

LSC

University of Maryland 1856

Michigan

University of Strathclyde

ACIGA

Montana State University

PAH

Loyola University New Orleans

University of Washington

Syracuse University Founded AD 1870 Suos Cultores Scientia Coronat

清華大学
Tsinghua University

Trinity University

San José State University

University of Wisconsin UW Milwaukee

ANU The Australian National University

UTB TSC

The University of Western Australia

1754

University of Glasgow

NASA
Goddard Space Flight Center

Università degli Studi del Sannio

LSU

California Institute of Technology 1891

Northwestern University

Andrews University

Massachusetts Institute of Technology

Southeastern Louisiana University

The University of Texas at Austin

Moscow State University

R·I·T

The University of Adelaide Australia

PAN

GEO 600

Embry-Riddle Aeronautical University

University of Massachusetts Amherst 1863

University of Southampton

PennState 1855

Carleton

Cardiff University

California State University Fullerton

Washington State University

UF University of Florida

The University of Mississippi 1848

Charles Sturt University

UIB Universitat de les Illes Balears

NAOJ

University of Rochester

Southern University Agricultural & Mechanical College

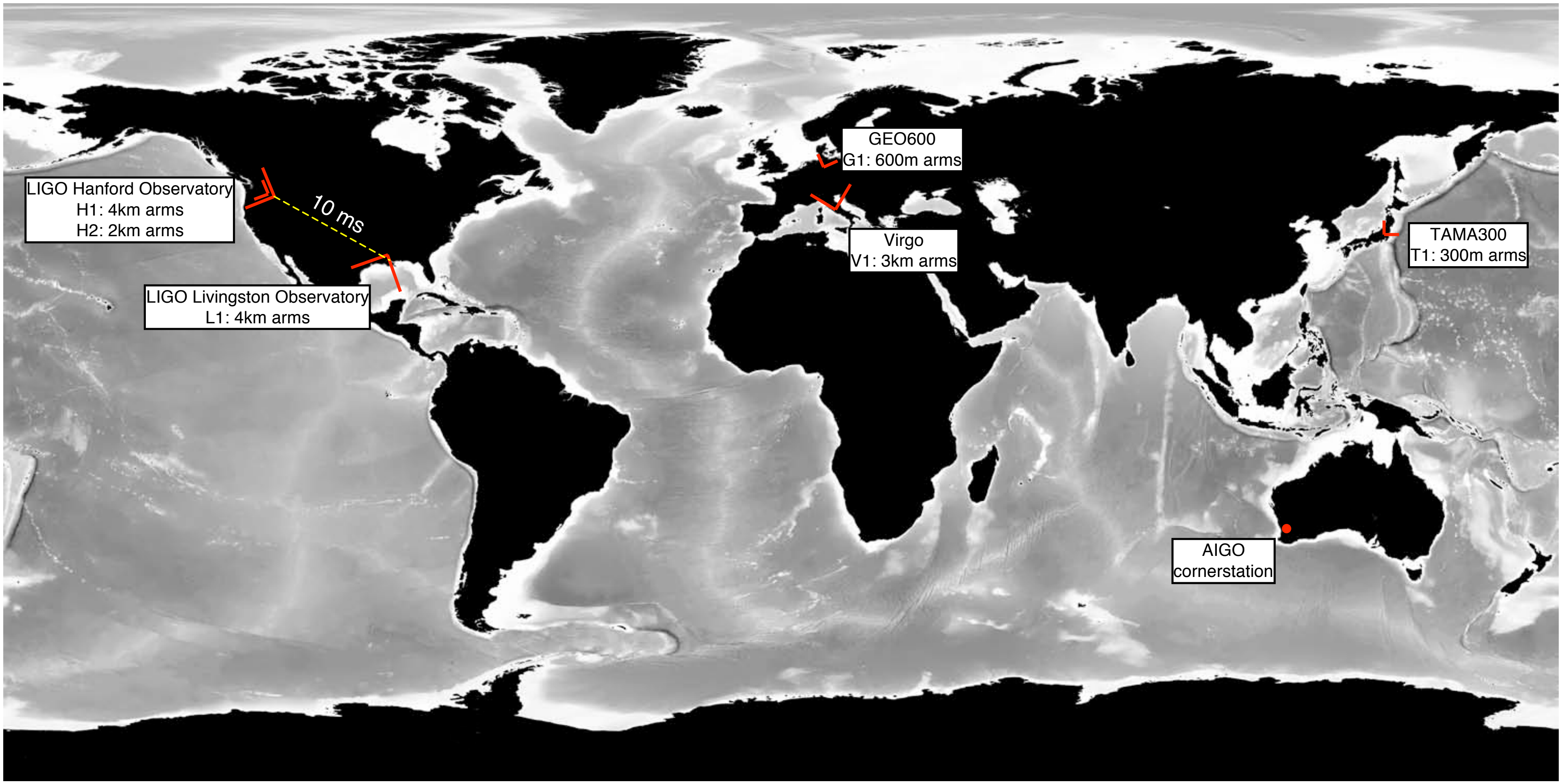
Hobart and William Smith Colleges

University of Minnesota

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Universität Hannover

Interferometer network



Credit: NASA's Earth Observatory