Vacuum for the Laser Interferometer Gravitational Wave Observatory

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IVS-2012, Kolkata, India

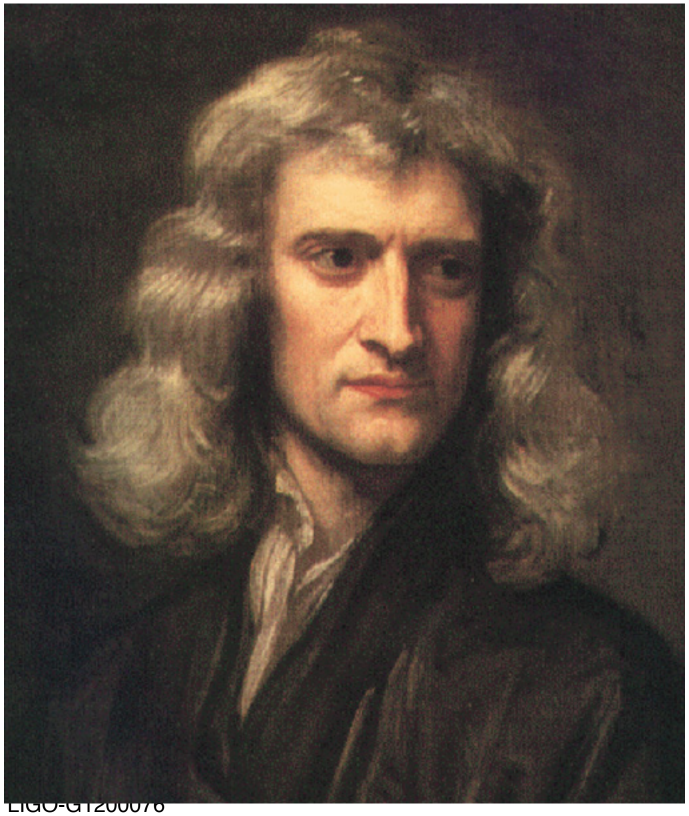
16 February 2012

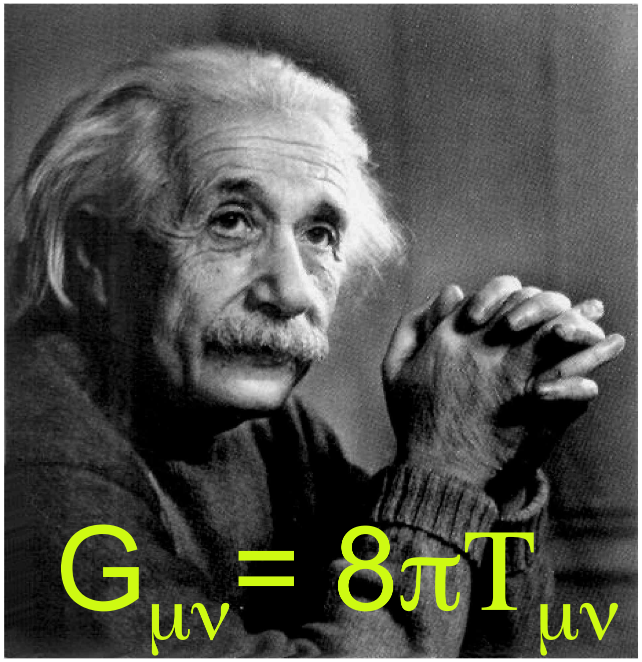
Outline

- About LIGO
- Vacuum Requirements & Constraints
- Beam Tubes
- Vacuum Chambers and Pumping
- Closing Remarks

Why must there be gravitational waves?

Newton's puzzle:
"instantaneous action at a distance"

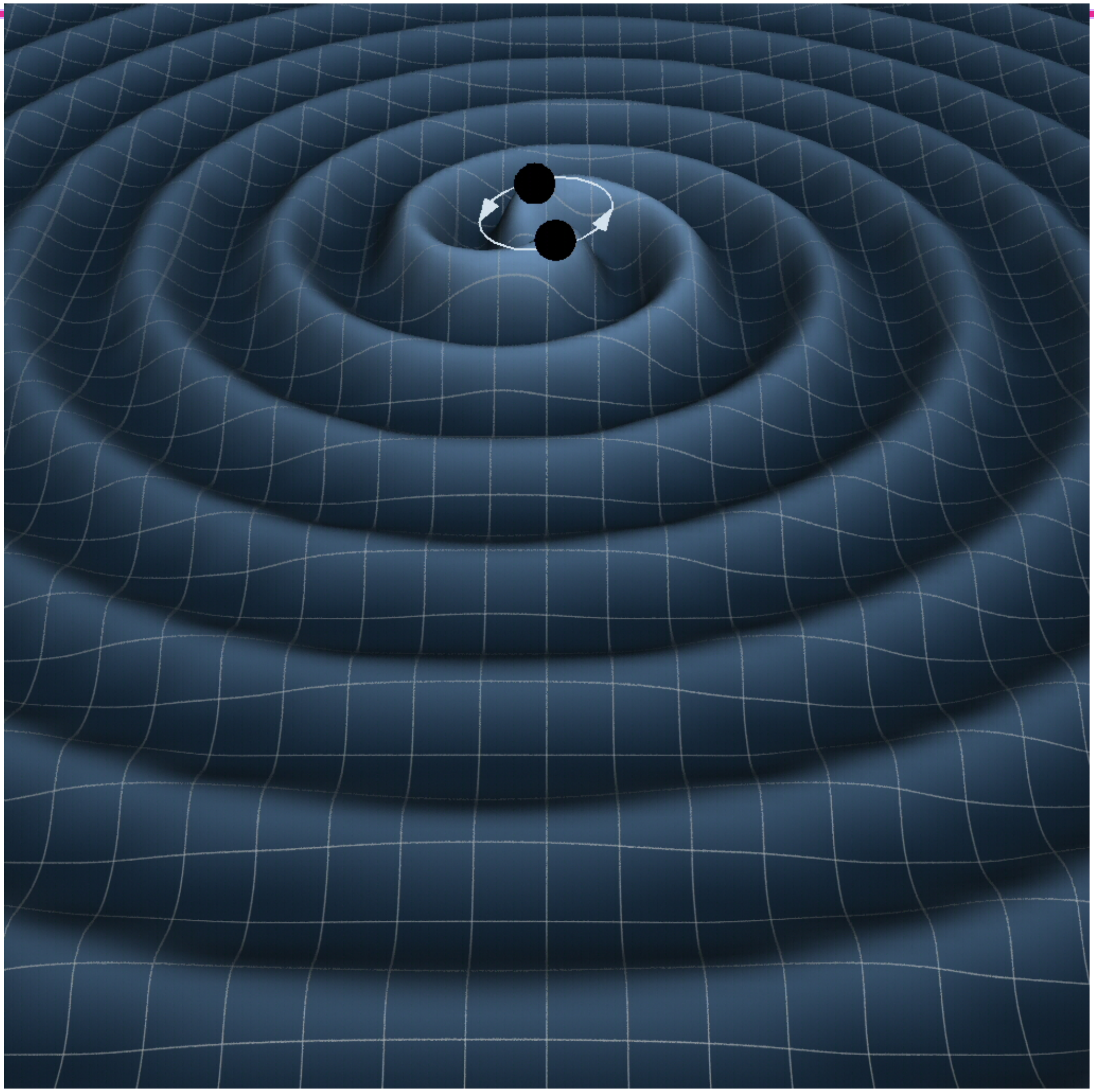




$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

General Relativity
Spacetime itself is a medium
Geometry carries information

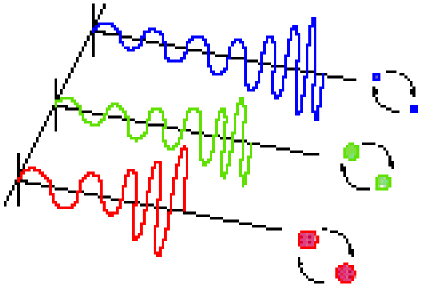
Gravitational Waves



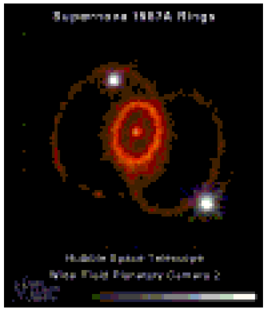
Changes of matter in one part of space affect geometry elsewhere

K. Thorne (Caltech) , T. Carnahan (NASA GSFC)

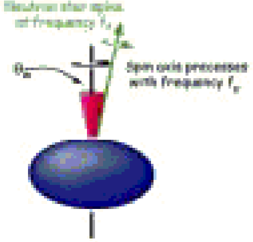
Some Expected Astrophysical Sources



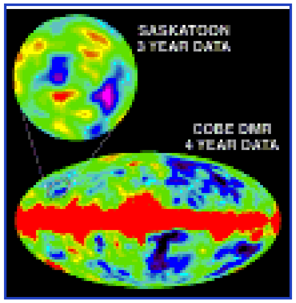
- Compact binary inspiral: “chirps”
  - NS-NS, NS-BH, BH-BH



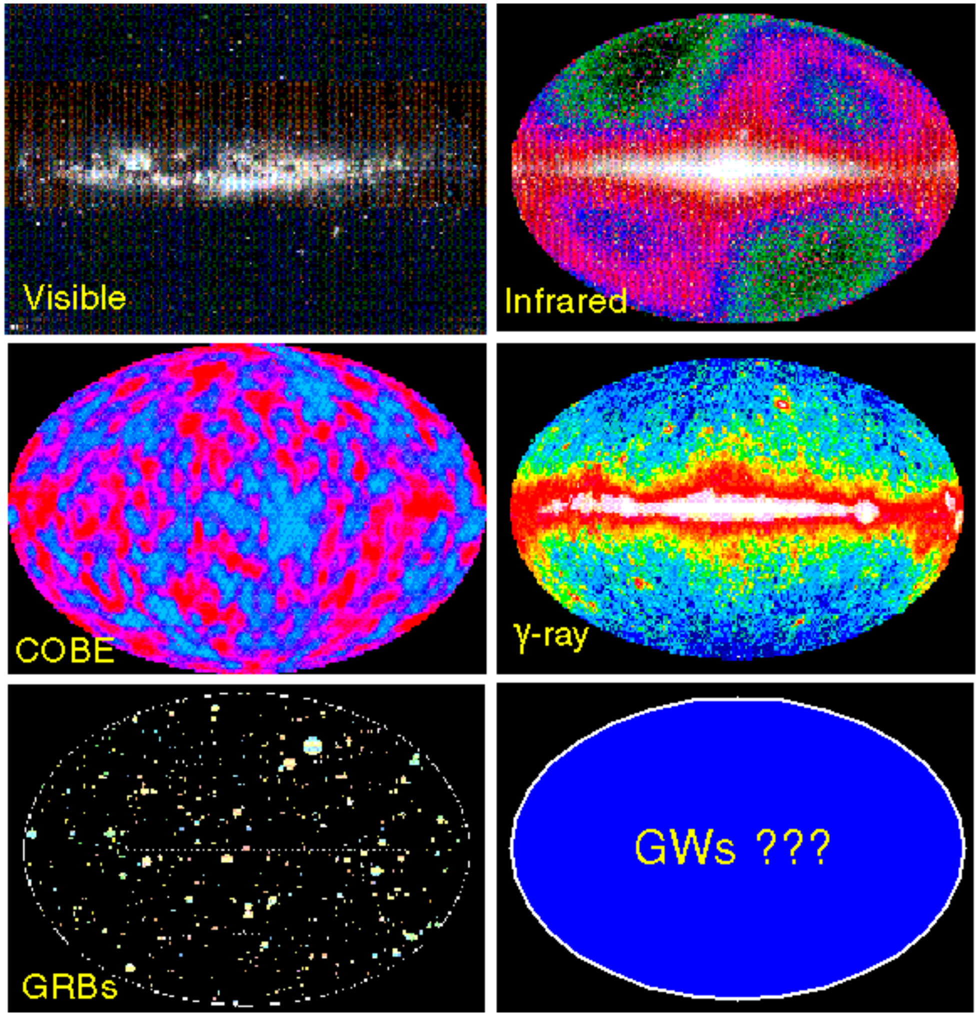
- Supernovas or GRBs: “bursts”
  - GW signals observed in coincidence with EM or neutrino detectors
- Pulsars in our galaxy: “periodic waves”
  - Rapidly rotating neutron stars
  - Modes of NS vibration

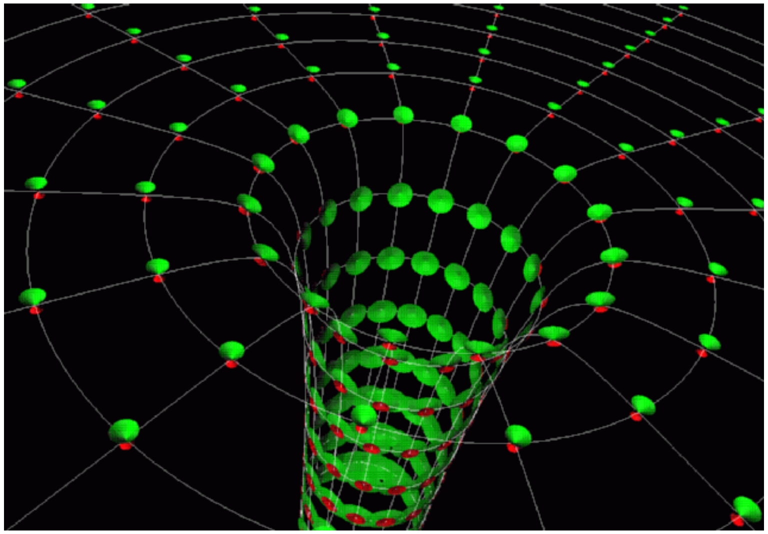


- Cosmological: “stochastic background”
  - Probe back to the Planck time (10^{-43} s)



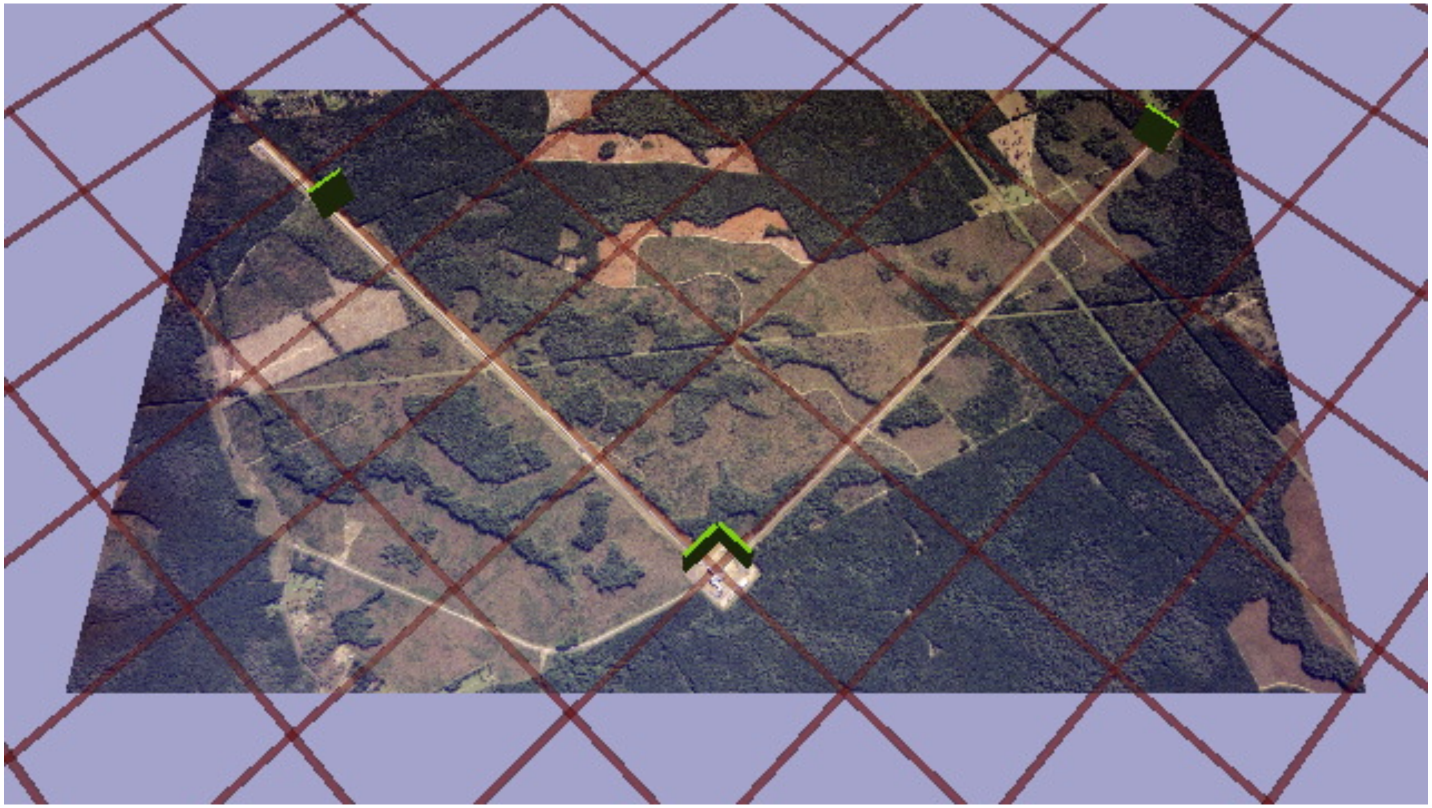
A New ‘Sense’- A New Universe





Gravitational Waves will provide complementary information, as different from what we know as sound is from sight.

On a small planet in a spiral galaxy far far away…



Great promise, but a great challenge…

A wave's strength is characterized by its *strain*

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

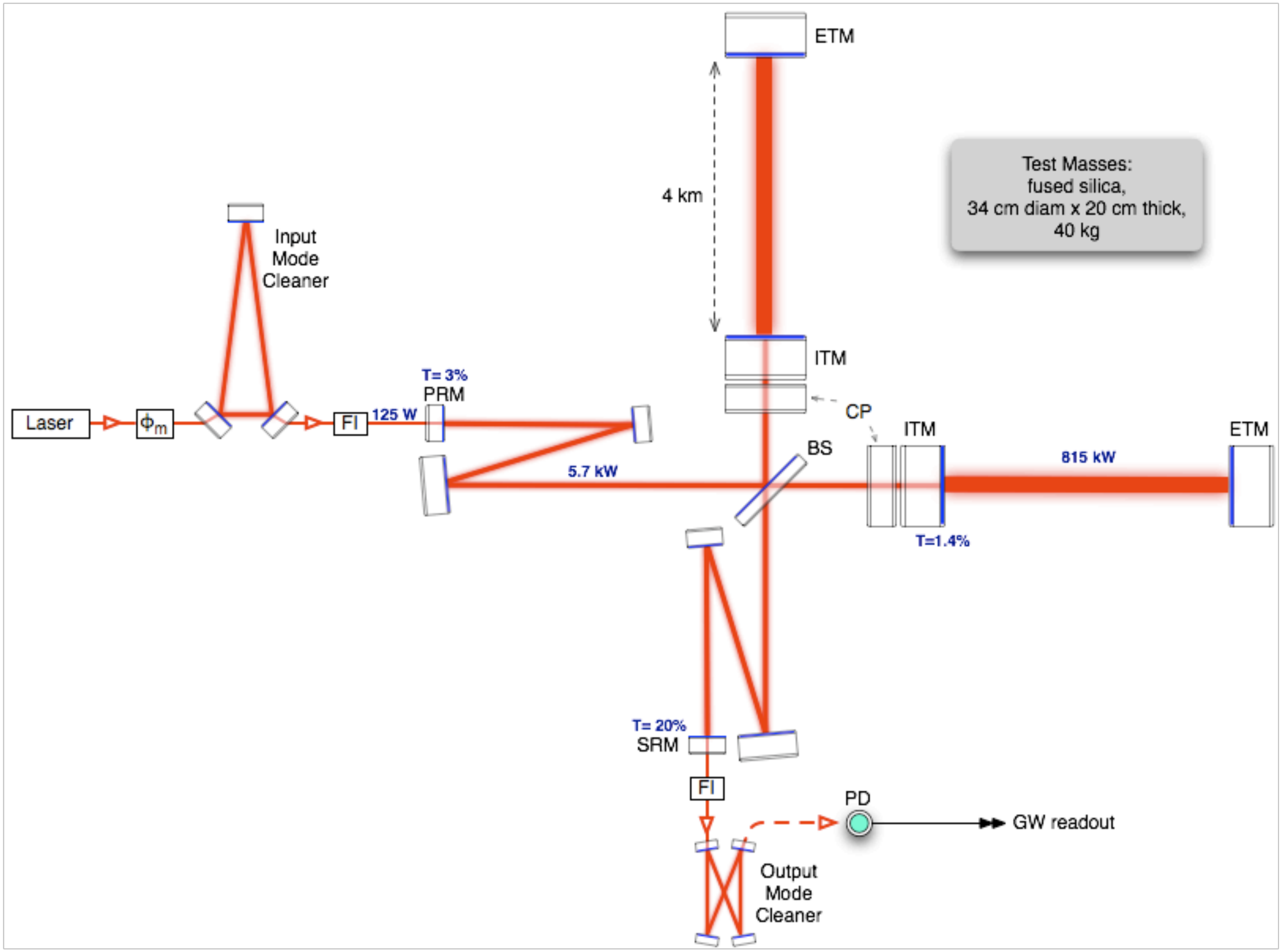
We can calculate the expected strain at Earth for, say, an orbiting binary system;

$$|h| \approx 4\pi^2 G M R^2 f_{orbit}^2 / c^4 r \approx 10^{-21} \left(\frac{R}{20\text{km}}\right)^2 \left(\frac{M}{M_\Theta}\right) \left(\frac{f_{orbit}}{400\,\text{Hz}}\right)^2 \left(\frac{10\text{Mpc}}{r}\right)$$

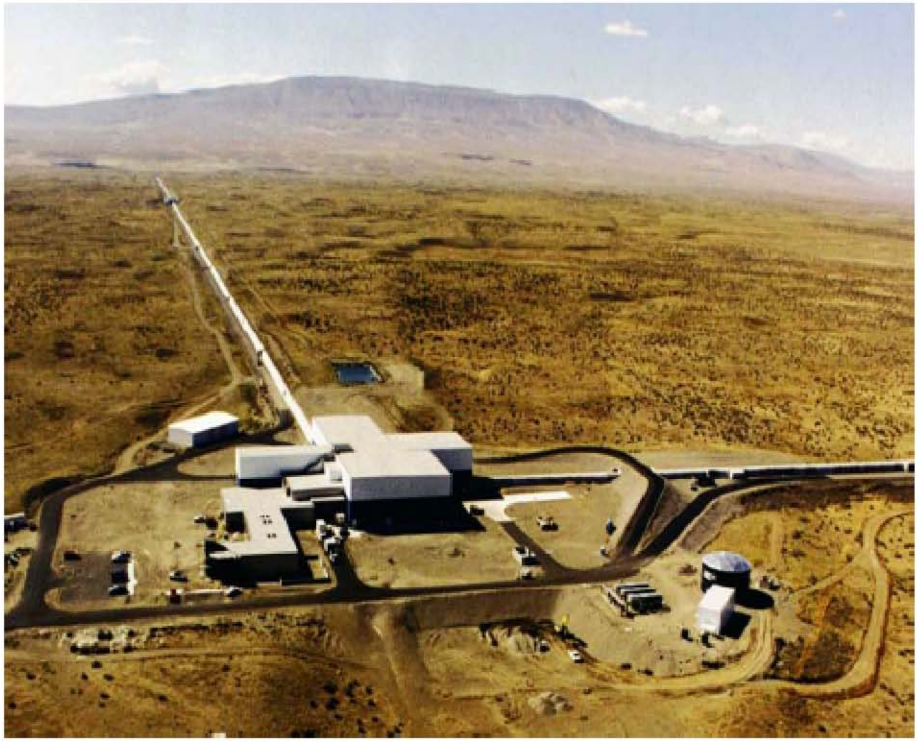
If we make our interferometer 4,000 meters long,

$$\Delta L = h \times L \approx 10^{-21} \times 4{,}000\, m \approx 10^{-18}\, m$$

LIGO Interferometer Schematic



LIGO Observatory Sites



LIGO Hanford Observatory [LHO]

26 km north of Richland, WA

2 km + 4 km interferometers in same vacuum envelope

LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

Single 4 km interferometer

LIGO Scientific Collaboration

LIGO

LSC

UNIVERSITY OF MARYLAND 18 56

MICHIGAN

UNIVERSITY OF STRATHCLYDE

ACIGA

LOYOLA UNIVERSITY NEW ORLEANS

LELAND STANFORD JUNIOR UNIVERSITY 1891

MONTANA STATE UNIVERSITY

РАН

UNIVERSITY OF WASHINGTON

IUCAA

SYRACUSE UNIVERSITY FOUNDED AD 1870

清華大學 Tsinghua University

TRINITY UNIVERSITY

RERUM COGNOSCERE CAUSAS

San José State UNIVERSITY

UNIVERSITY of WISCONSIN UWMILWAUKEE

ANU THE AUSTRALIAN NATIONAL UNIVERSITY

부산대학교 PUSAN NATIONAL UNIVERSITY

R·I·T

THE UNIVERSITY OF WESTERN AUSTRALIA

1754

UNIVERSITY of GLASGOW

NASA GODDARD SPACE FLIGHT CENTER

PER ARDUA AD ALTA

Università degli Studi del Sannio

LSU

UTB TSC

THE UNIVERSITY OF MELBOURNE

KiSTi

Andrews University

MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1861

SOUTHEASTERN LOUISIANA UNIVERSITY

Moscow State University

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

NORTHWESTERN UNIVERSITY

HANYANG UNIVERSITY 한양 1939

UNIVERSITY OF CAMBRIDGE

THE UNIVERSITY OF ADELAIDE AUSTRALIA

PAN

THE UNIVERSITY OF TEXAS AT AUSTIN

GEO 600

EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

UNIVERSITY OF MASSACHUSETTS AMHERST 1863

LUND UNIVERSITY

ISI

UNIVERSITY of NEW HAMPSHIRE

PENNSTATE 1855

CARLETON NORTHFIELD, MINN. A.D. 1866

CARDIFF UNIVERSITY

CALIFORNIA STATE UNIVERSITY FULLERTON

WASHINGTON STATE UNIVERSITY

국가수리과학연구소 National Institute for Mathematical Sciences

The University of Mississippi 1848

CHARLES STURT UNIVERSITY

UIB Universitat de les Illes Balears

UF UNIVERSITY of FLORIDA

PI PERIMETER INSTITUTE

CITA-ICAT

SEOUL NATIONAL UNIVERSITY

UNIVERSITY OF ROCHESTER

NAOJ

University of Southampton

HOBART COLLEGE

WILLIAM SMITH COLLEGE 1908

UNIVERSITY OF MINNESOTA

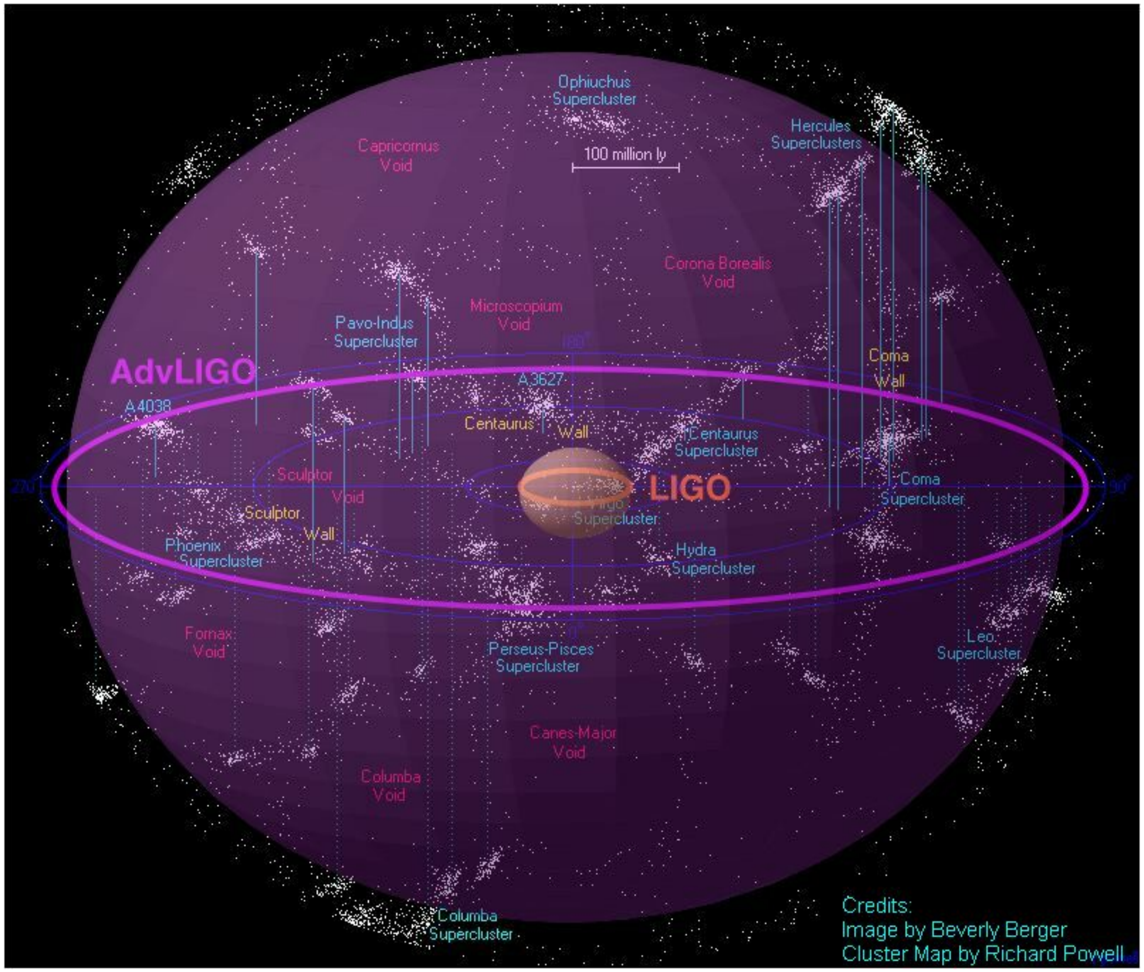
Universität Hannover

SOUTHERN UNIVERSITY And Agricultural & Mechanical College

Science & Technology Facilities Council Rutherford Appleton Laboratory

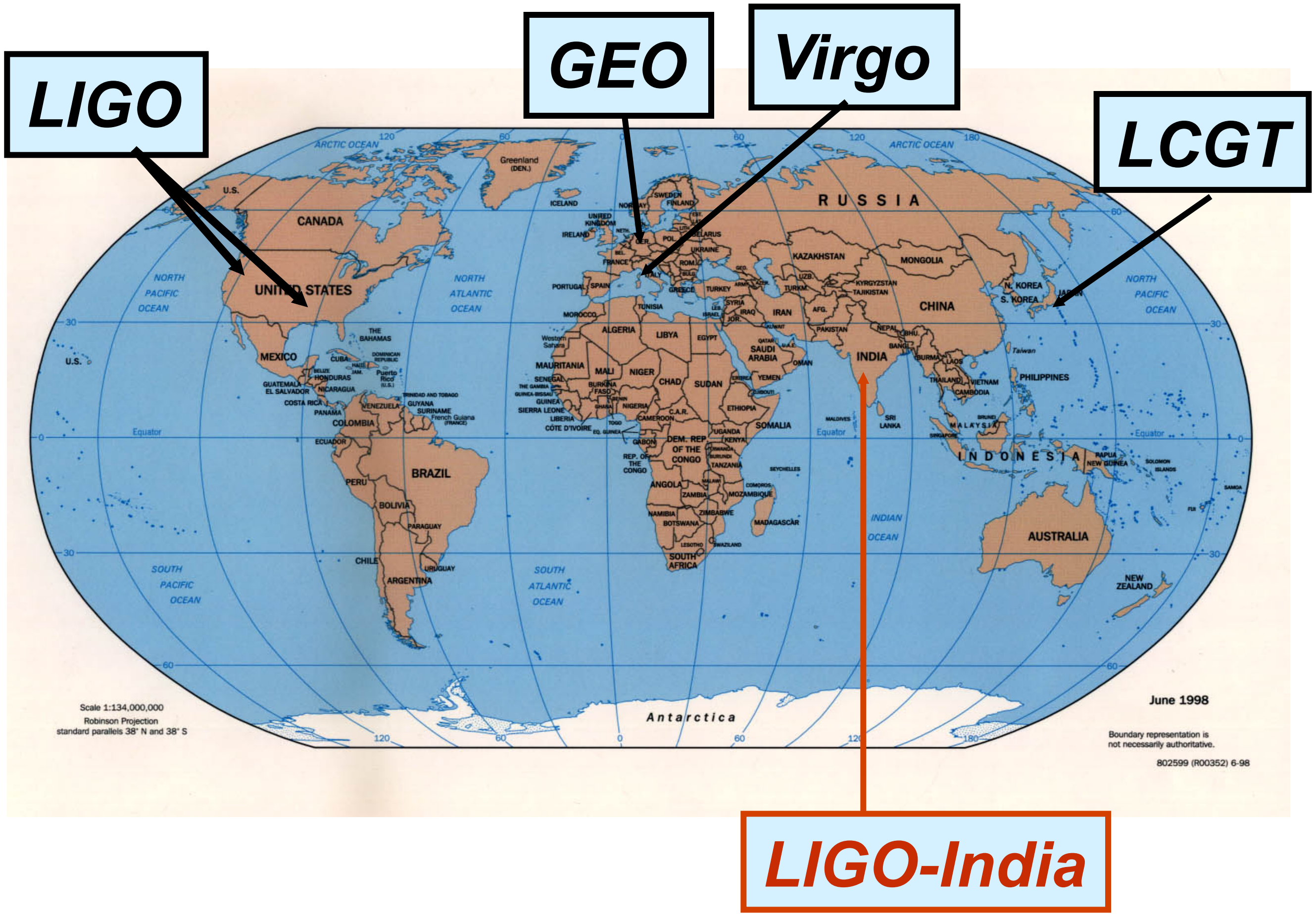
Now: Advanced LIGO

- Construction finished ‘00; reached initial design sensitivity in ‘05
- Ran ~ 2.5 years
  - No confirmed detection yet
- Facilities and vacuum system compatible with “ultimate” future interferometers
- Advanced LIGO detector upgrade funded ‘08, now being installed
  - Design 10x more sensitive
  - 1,000x greater observable volume (or event rate)



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

A Global Detector Network

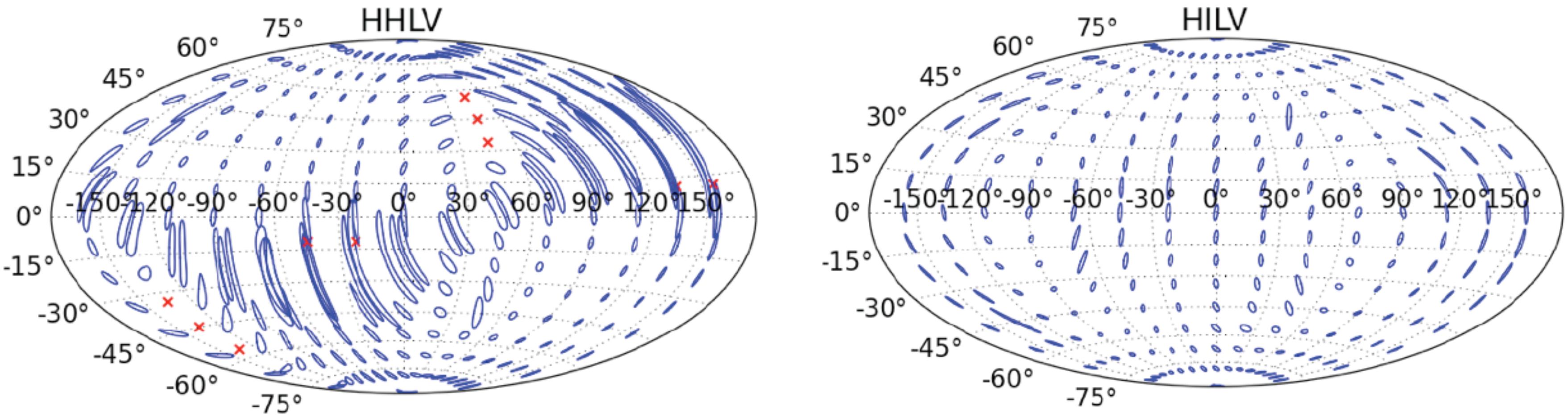


Current and planned detectors are close to co-planar—not optimal for sky coverage

Large science enhancement from a southern node in the network

Proposal pending to install third aLIGO interferometer at a new site in India

Astrophysical Source Localization: LIGO+Virgo without and with LIGO-India



Fairhurst 2011

Red crosses denote regions where the network has blind spots

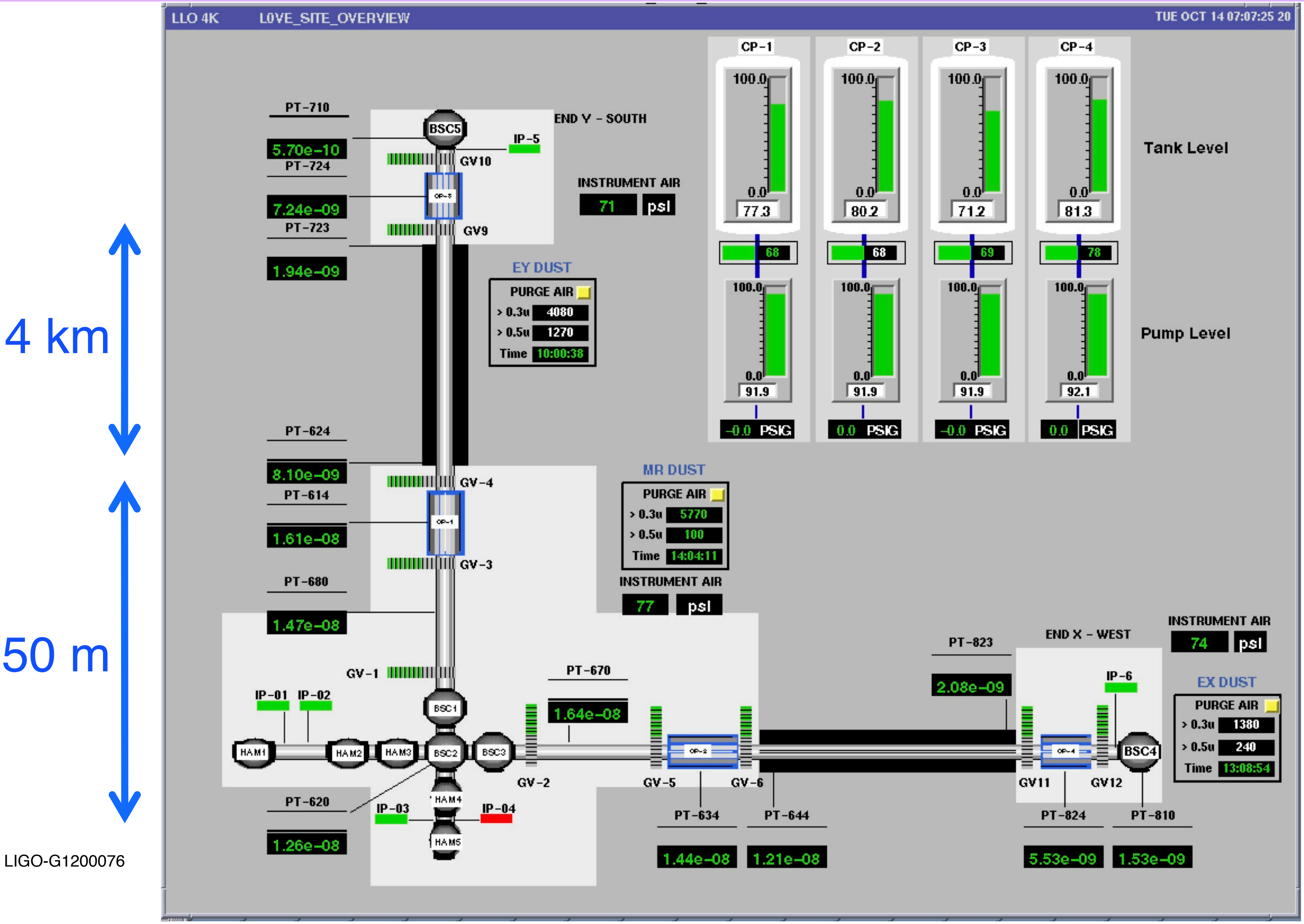
Fairhurst 2011
10

Greatly improved sky resolution with interferometer located in India

➔INDIGO consortium has submitted a proposal to build a third LIGO facility and vacuum system here

➔US would contribute complete interferometer system

Vacuum System Schematic



LLO 4K LOVE_SITE_OVERVIEW TUE OCT 14 07:07:25 20

PT-710 5.70e-10
PT-724 7.24e-09
PT-723 1.94e-09
PT-624 8.10e-09
PT-614 1.61e-08
PT-680 1.47e-08
PT-620 1.26e-08
PT-670 1.64e-08
PT-634 1.44e-08
PT-644 1.21e-08
PT-823 2.08e-09
PT-824 5.53e-09
PT-810 1.53e-09

INSTRUMENT AIR 71 psi

EY DUST
PURGE AIR
> 0.3u 4080
> 0.5u 1270
Time 10:00:38

MR DUST
PURGE AIR
> 0.3u 5770
> 0.5u 100
Time 14:04:11

INSTRUMENT AIR 77 psi

INSTRUMENT AIR 74 psi

EX DUST
PURGE AIR
> 0.3u 1380
> 0.5u 240
Time 13:08:54

	CP-1	CP-2	CP-3	CP-4
Tank Level	77.3	80.2	71.2	81.3
	68	68	69	78
Pump Level	91.9	91.9	91.9	92.1
PSIG	-0.0	0.0	-0.0	0.0

Really Two Vacuum Systems

Chambers

- Frequent access
- Isolation valves
- Large doors
- Electrical, mechanical support, optical penetrations
- Pumping & instrumentation
- Largely "conventional"
- *F:A* ~ 10^{-2} $ls^{-1}cm^{-2}$

Beam tubes

- A long hole in the air; *never vented*
- Very cost-sensitive
- Highly "unconventional"
  - 20 million liters (per site)
  - 600 million cm^2 (per site)
  - 200 l/s char. conductance
  - *F:A* ~ 10^{-5} $ls^{-1}cm^{-2}$

LIGO Vacuum Requirements

(partial list)

- Light scattering phase noise from residual gas
  - Function of molecular polarizability, transit speed and partial pressure
  - Primary goals for beam tubes:
    - ➔$P(H_2) < 10^{-9}$ Torr
    - ➔$P(H_2O) < 10^{-10}$ Torr
- Contamination of optics
  - Mirror absorption < 0.1 ppm
  - Hydrocarbons: < 1 monolayer/10 years
    - ➔Aggressive cleaning and vacuum bake of every component
  - Particles: < one 10 μm particle on any mirror
    - ➔ISO Class 5 or better cleanroom protocol for worker access, internal components, surface exposure
- Vibration-free environment
    - ➔No mechanical, turbo or closed-cycle cryo pumps in steady state operation

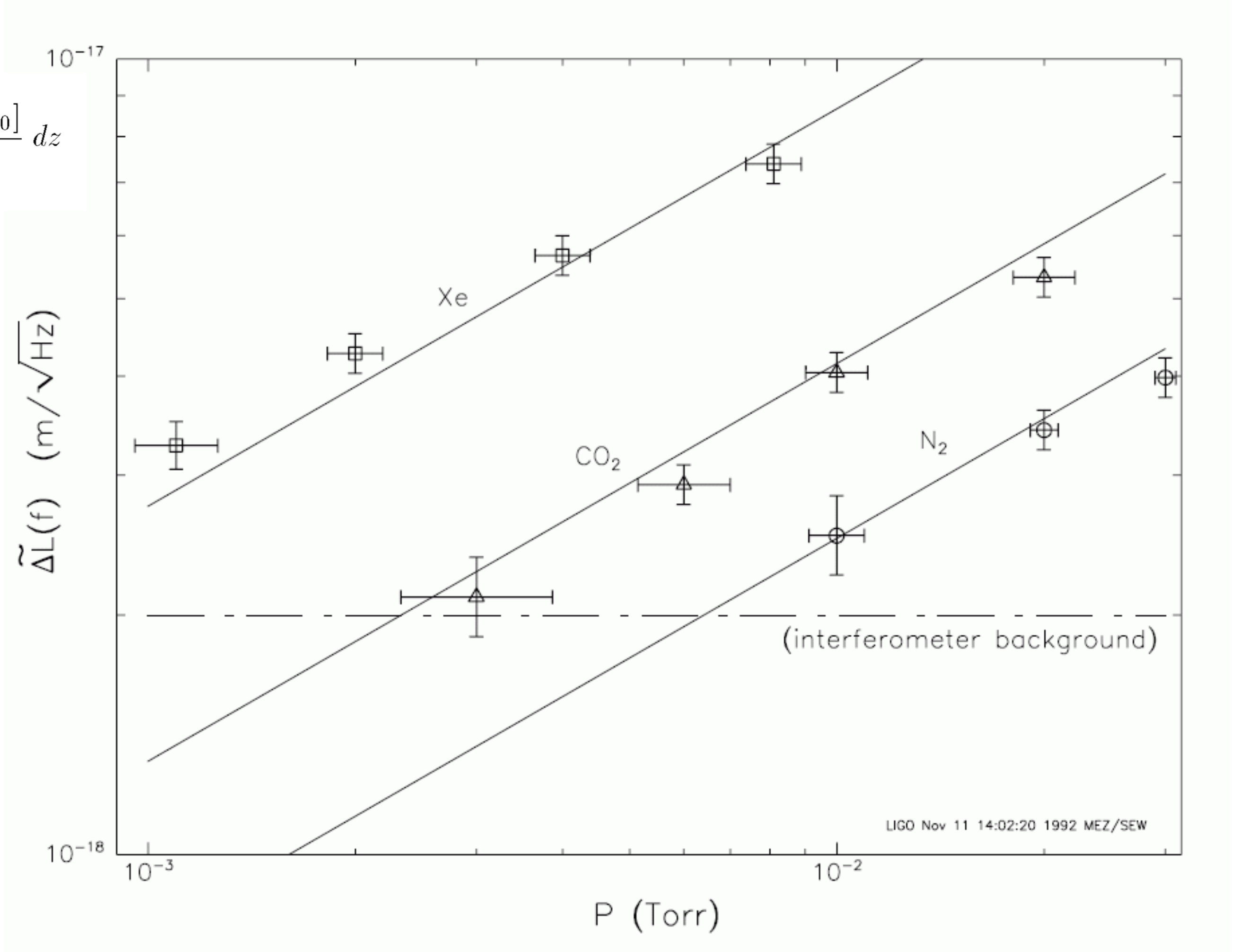
NB: Unlike accelerator, plasma, or aerospace applications, we have no radiation, thermal, or ion loading ; in LIGO outgassing is passive at ambient temperature

Residual Gas Index Fluctuation Noise

$$S_L(f) = \frac{4\rho(2\pi\alpha)^2}{v_0} \int_0^{L_0} \frac{\exp\left[-2\pi f\, w(z)/v_0\right]}{w(z)}\, dz$$

$$\Delta\tilde{L}(f) \equiv \sqrt{\bar{S}_{\Delta L}(f)} = \sqrt{2 S_L(f)}$$

ϱ = gas number density (~ pressure)
α = optical polarizability (~ index)
w = beam radius
v_0 = most probable thermal speed
L_0 = arm length
ΔL = arm optical path difference



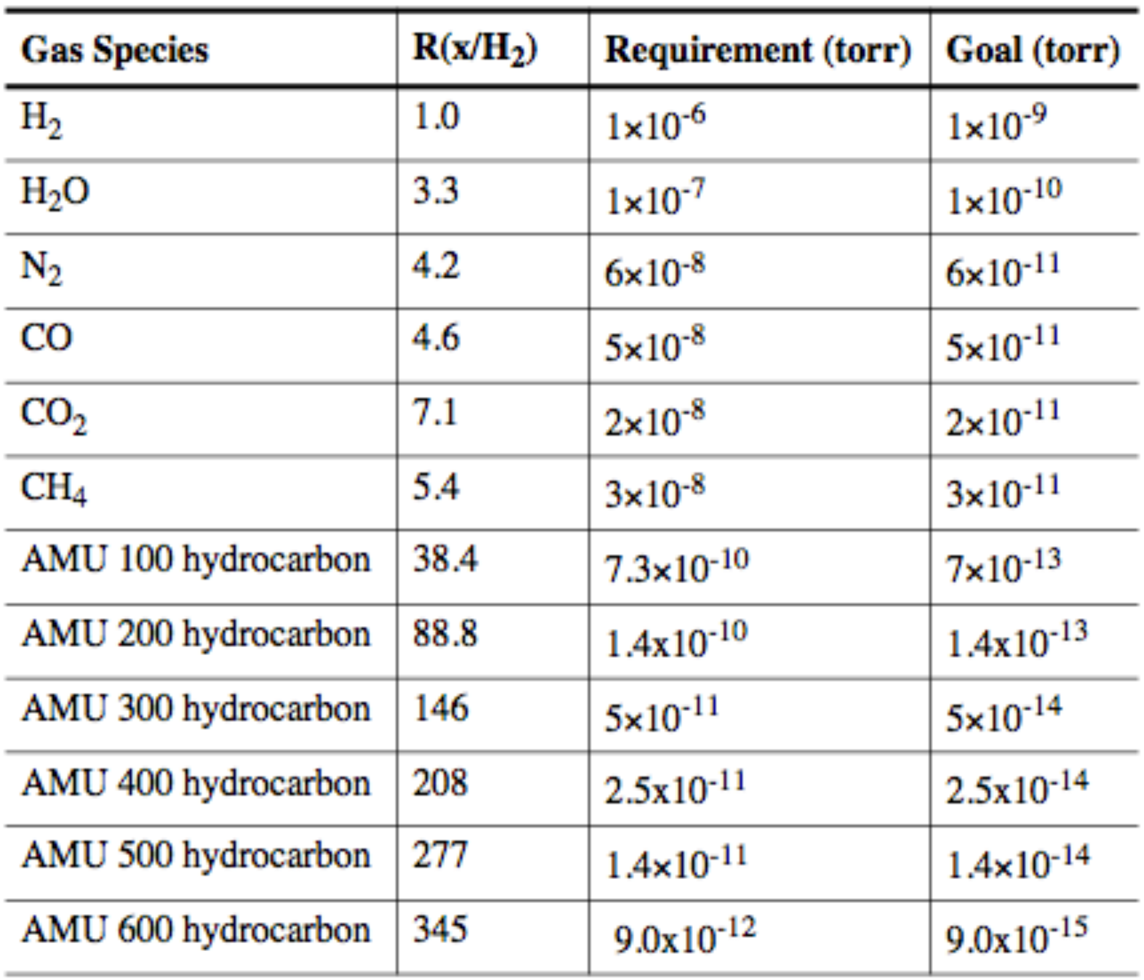
Statistical model verified by interferometer experiment

S. Whitcomb and MZ, *Proc. 7th Marcel Grossmann Meeting on GR,* R. Jantzen and G. Keiser, eds. World Scientific, Singapore (1996).

Residual Gas Pressure Limits

$$h(f) = 4.8\times10^{-21} R\left(\frac{x}{H_2}\right)\sqrt{\langle P(torr)\rangle_L}$$

Table 1: Residual gas phase noise factor and average pressure

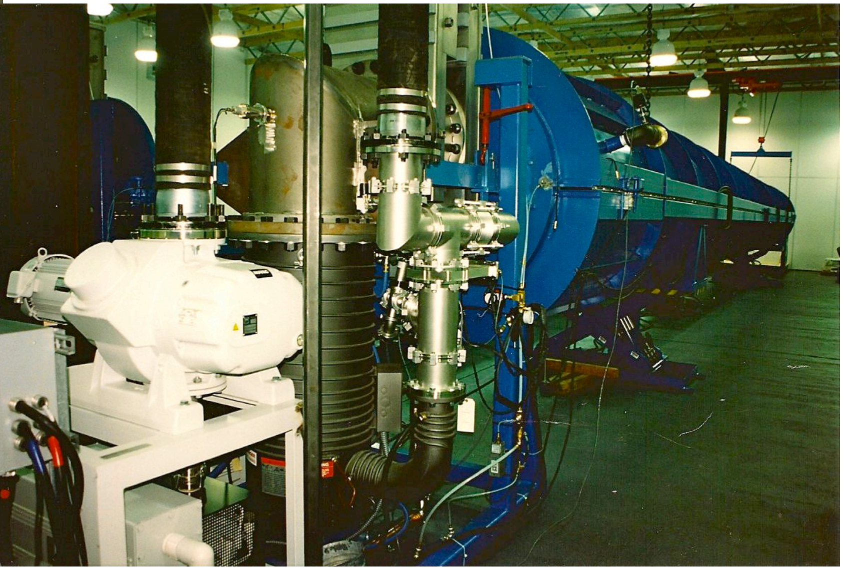


Gas Species	$R(x/H_2)$	Requirement (torr)	Goal (torr)
H_2	1.0	1×10^{-6}	1×10^{-9}
H_2O	3.3	1×10^{-7}	1×10^{-10}
N_2	4.2	6×10^{-8}	6×10^{-11}
CO	4.6	5×10^{-8}	5×10^{-11}
CO_2	7.1	2×10^{-8}	2×10^{-11}
CH_4	5.4	3×10^{-8}	3×10^{-11}
AMU 100 hydrocarbon	38.4	7.3×10^{-10}	7×10^{-13}
AMU 200 hydrocarbon	88.8	$1.4x10^{-10}$	$1.4x10^{-13}$
AMU 300 hydrocarbon	146	5×10^{-11}	5×10^{-14}
AMU 400 hydrocarbon	208	$2.5x10^{-11}$	$2.5x10^{-14}$
AMU 500 hydrocarbon	277	1.4×10^{-11}	1.4×10^{-14}
AMU 600 hydrocarbon	345	$9.0x10^{-12}$	$9.0x10^{-15}$

Tube Fabrication

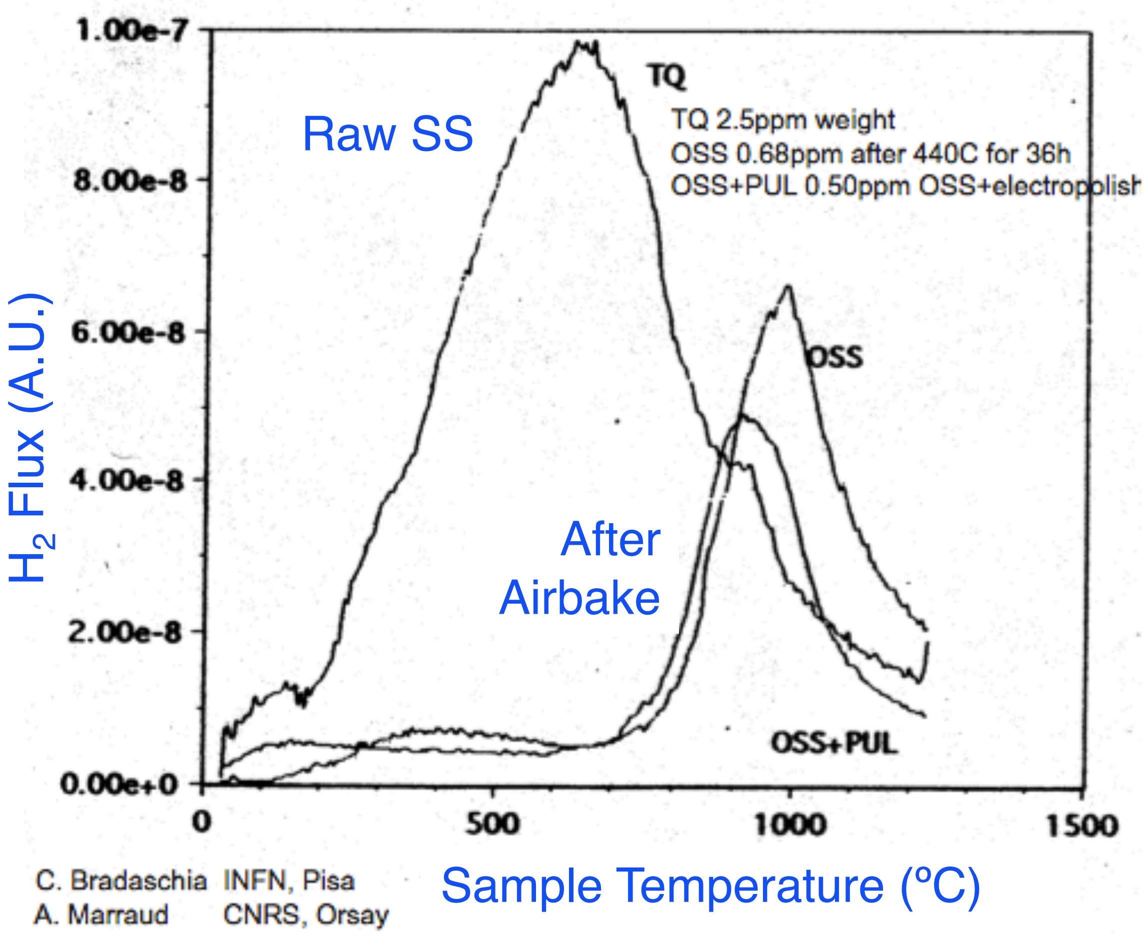
- 304L SS, 3.2 mm thick with external stiffeners
- raw coiled stock air baked 36h @ 455C to deplete hydrogen
  - » $J_{H2} < 1e\text{-}13\ Tl/s/cm^2$
  - » permits ultimate P without distributed pumps
  - » process developed by LIGO
- prepared coil spiral-welded into 1.2m tube on modified culvert mill
- 16m sections cleaned, leak checked, and capped
- FTIR analysis to confirm HC-free
- sections field butt-welded together in travelling clean room
- Over 50 linear km of weld—

  not one leak



Depleting H from raw SS before fabrication: An economical alternative to high T vacuum bakeout

- SS sheet from mill is baked in air 36 hours at 455 °C
- (Hotter treatment deemed inadvisable due to carbide formation)
- Total dissolved hydrogen is reduced ~ 3x
- Remaining H is tightly bound, high activation T
- Care is required in welding to avoid re-introduction of H



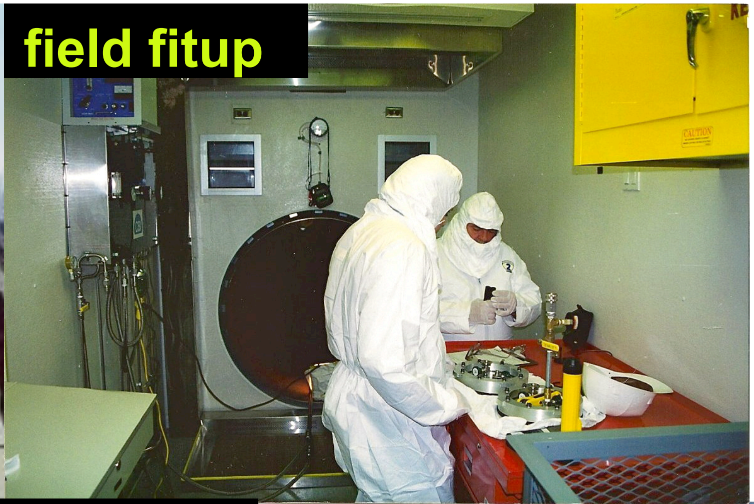
C. Bradaschia INFN, Pisa
A. Marraud CNRS, Orsay

data courtesy of Virgo

Beam Tube Field Assembly


transport


position


field fitup

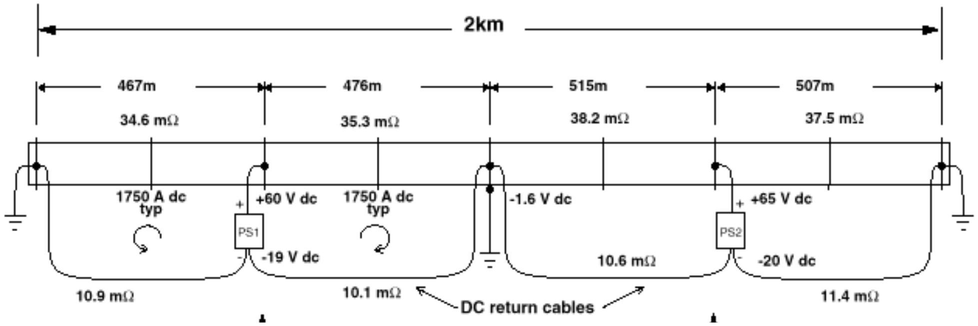

butt weld

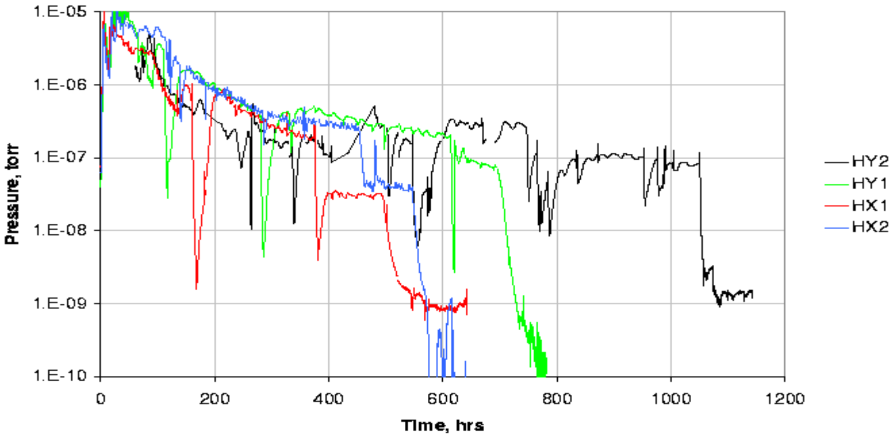

leak check


next section

Tube I^2R Bakeout to Desorb Water

- Glass wool insulation
- I_{DC} = 2,000 A
- ~ 3 weeks @ 160ºC
- Final $J_{H20} < 2e\text{-}17$ Tl/s/cm^2
- Tubes never to be vented





Beam Tube Bakeout Results

	Outgassing Rate corrected to 23 °C torr liters/sec/cm^2 (All except H_2 are upper limits)					
molecule	**Goal***	**HY2**	**HY1**	**HX1**	**HX2**	
H_2	4.7	4.8	6.3	5.2	4.6	$\times 10^{-14}$
CH_4	48000	< 900	< 220	< 8.8	< 95	$\times 10^{-20}$
H_2O	1500	< 4	< 20	< 1.8	< 0.8	$\times 10^{-18}$
CO	650	< 14	< 9	< 5.7	< 2	$\times 10^{-18}$
CO_2	2200	< 40	< 18	< 2.9	< 8.5	$\times 10^{-19}$
$NO+C_2H_6$	7000	< 2	< 14	< 6.6	< 1.0	$\times 10^{-19}$
$H_nC_pO_q$	50–2†	< 15	< 8.5	< 5.3	< 0.4	$\times 10^{-19}$

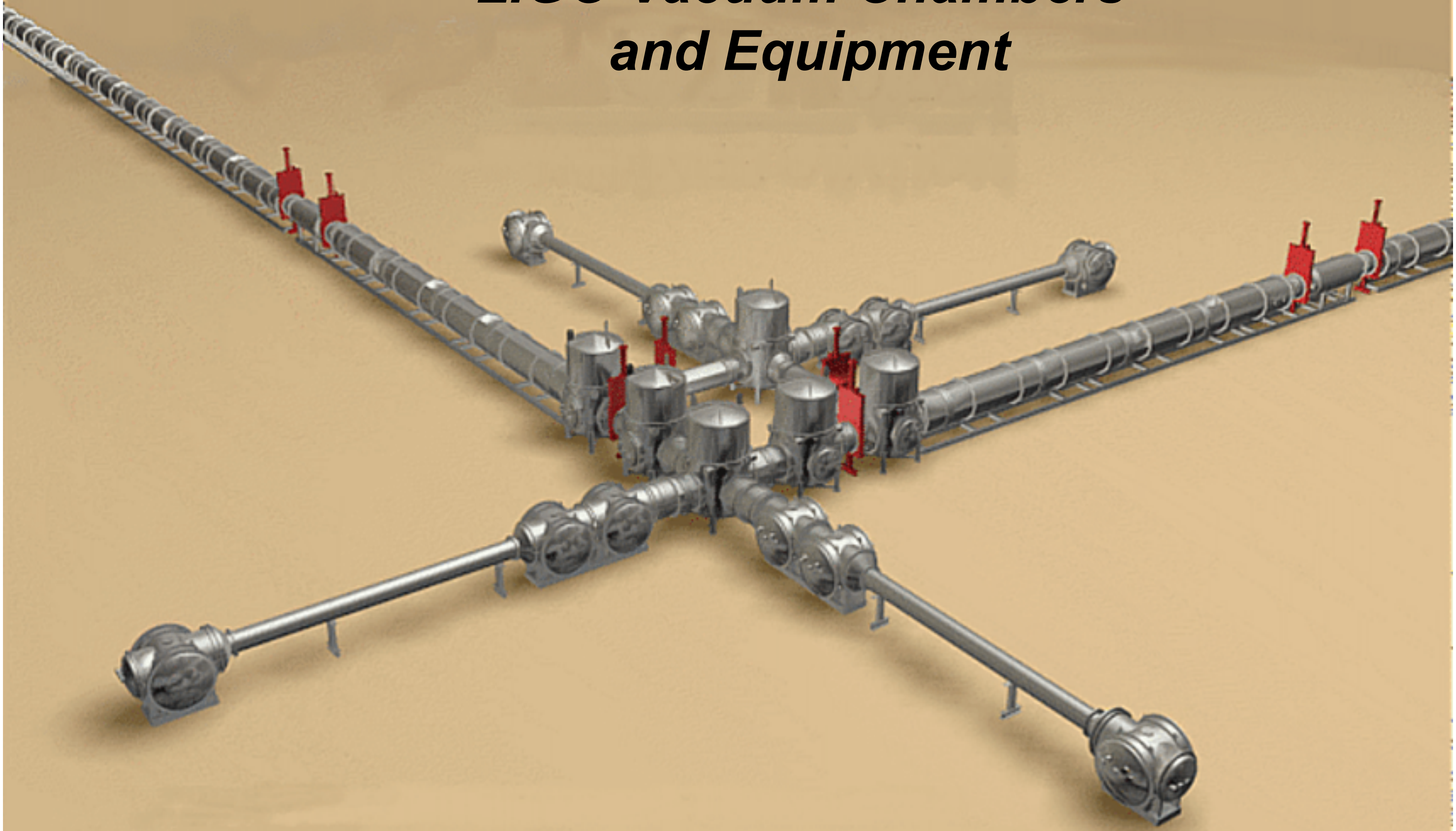
air leak	1000	< 20	< 10	< 3.5	< 16	$\times 10^{-11}$ torr liter/sec

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

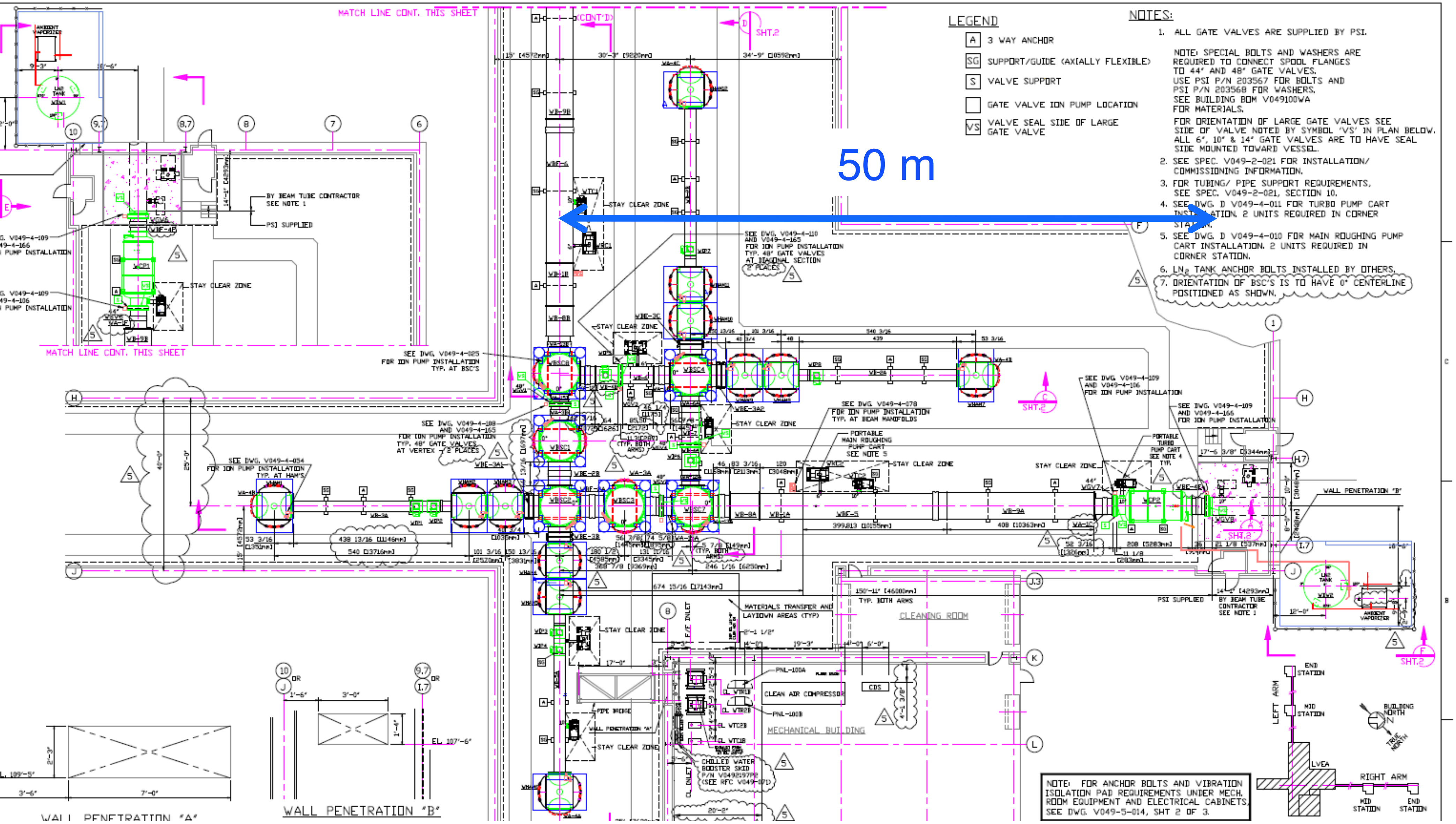
†Goal for hydrocarbons depends on weight of parent molecule; range given corresponds with 100–300 AMU

5/24/99 wea

LIGO Vacuum Chambers and Equipment



Corner Station Layout



LEGEND

A	3 WAY ANCHOR
SG	SUPPORT/GUIDE (AXIALLY FLEXIBLE)
S	VALVE SUPPORT
☐	GATE VALVE ION PUMP LOCATION
VS	VALVE SEAL SIDE OF LARGE GATE VALVE

NOTES:

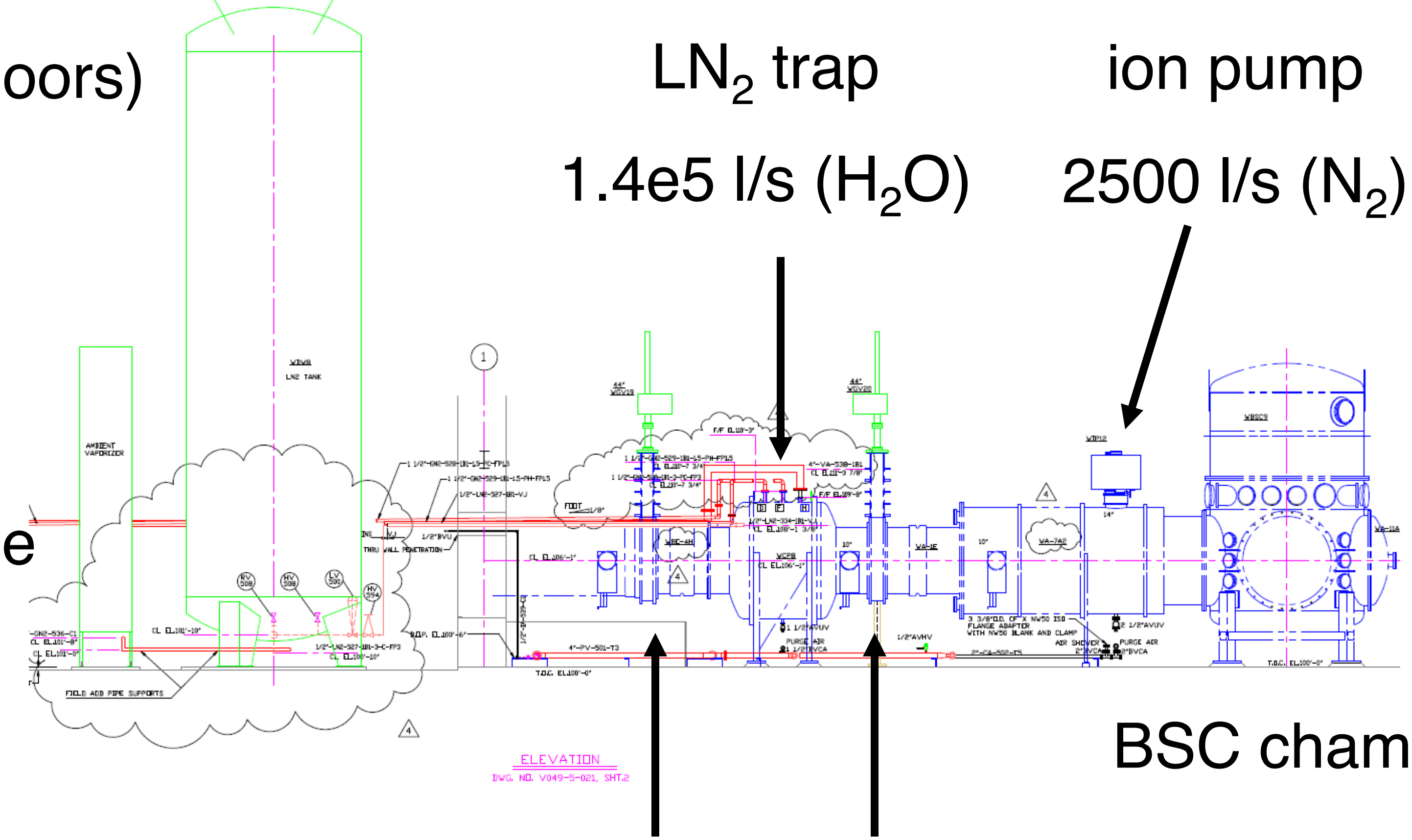
1. ALL GATE VALVES ARE SUPPLIED BY PSI.

   NOTE: SPECIAL BOLTS AND WASHERS ARE REQUIRED TO CONNECT SPOOL FLANGES TO 44" AND 48" GATE VALVES. USE PSI P/N 203567 FOR BOLTS AND PSI P/N 203568 FOR WASHERS. SEE BUILDING BOM V049100WA FOR MATERIALS.

   FOR ORIENTATION OF LARGE GATE VALVES SEE SIDE OF VALVE NOTED BY SYMBOL 'VS' IN PLAN BELOW. ALL 6", 10" & 14" GATE VALVES ARE TO HAVE SEAL SIDE MOUNTED TOWARD VESSEL.
2. SEE SPEC. V049-2-021 FOR INSTALLATION/ COMMISSIONING INFORMATION.
3. FOR TUBING/ PIPE SUPPORT REQUIREMENTS, SEE SPEC. V049-2-021, SECTION 10.
4. SEE DWG. D V049-4-011 FOR TURBO PUMP CART INSTALLATION. 2 UNITS REQUIRED IN CORNER STATION.
5. SEE DWG. D V049-4-010 FOR MAIN ROUGHING PUMP CART INSTALLATION. 2 UNITS REQUIRED IN CORNER STATION.
6. LN_2 TANK ANCHOR BOLTS INSTALLED BY OTHERS.
7. ORIENTATION OF BSC'S IS TO HAVE 0° CENTERLINE POSITIONED AS SHOWN.

NOTE: FOR ANCHOR BOLTS AND VIBRATION ISOLATION PAD REQUIREMENTS UNDER MECH. ROOM EQUIPMENT AND ELECTRICAL CABINETS, SEE DWG. V049-5-014, SHT 2 OF 3.

End Station Arrangement



LN_2 storage

(outdoors)

Coaxial

LN_2 trap

1.4e5 l/s (H_2O)

ion pump

2500 l/s (N_2)

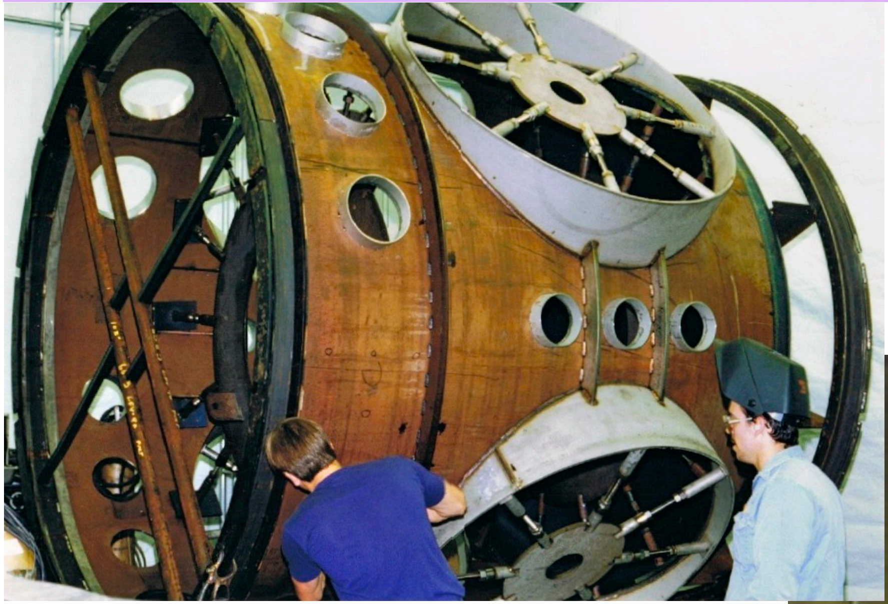
beamtube

BSC chamber

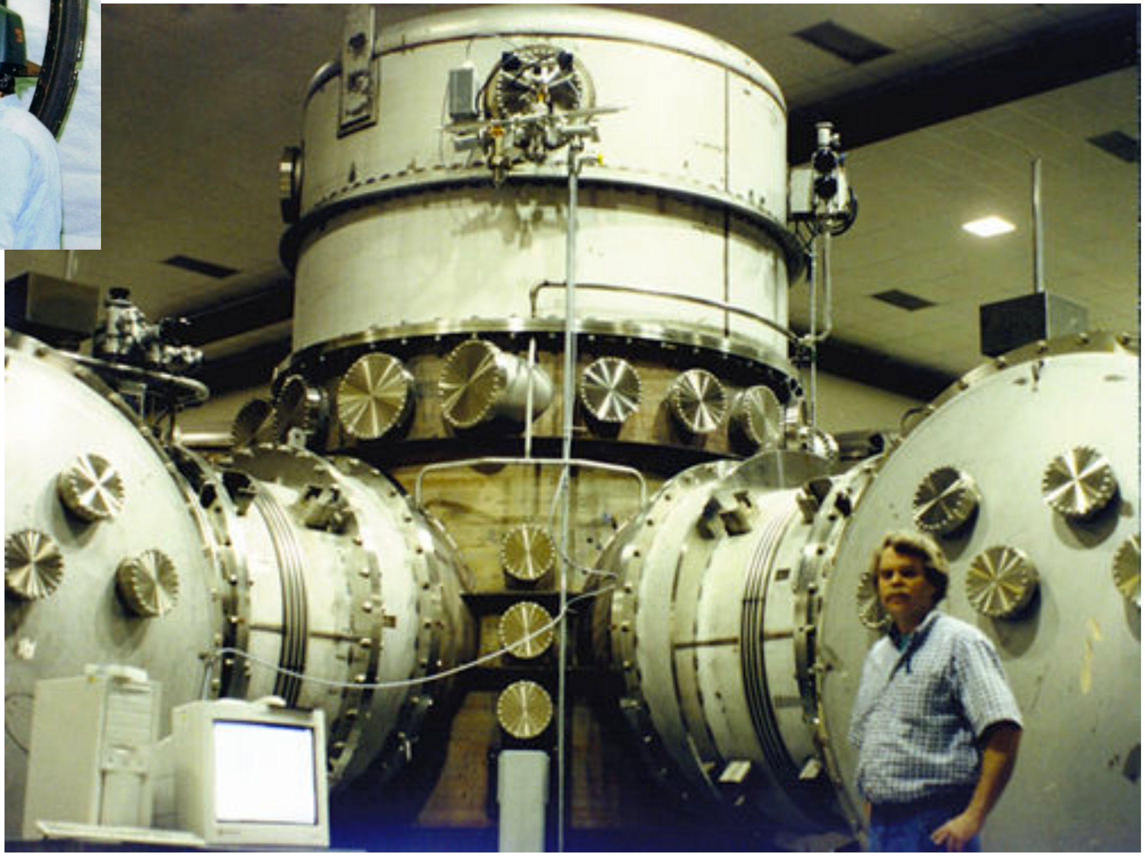
1.2m Ø gate valves

BSC chamber

(Basic Symmetric Chamber)



- House large cavity optics & beamsplitter
- 2.8m Ø x 5.5m h
- upper third removable dome



- Ports < 35cm Ø: ConFlat^{TM}
- Ports > 35cm Ø: Dual O-ring
  - Treated Viton elastomer
  - Isolated pumped annulus between inner and outer seal
  - Permeation and damage tolerant

In Situ Chamber Bakeout

BSC Equipment Installation

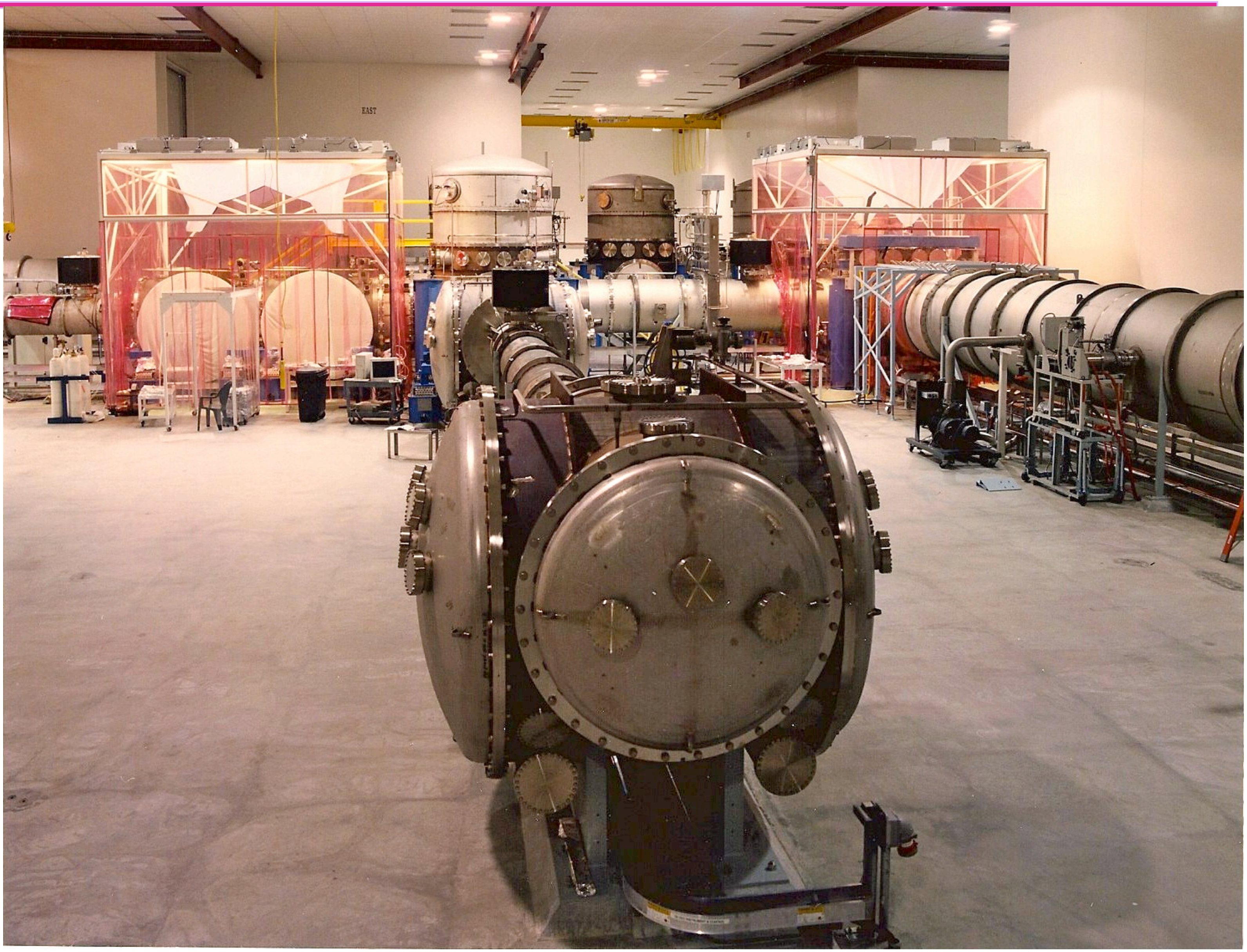
HAM chamber

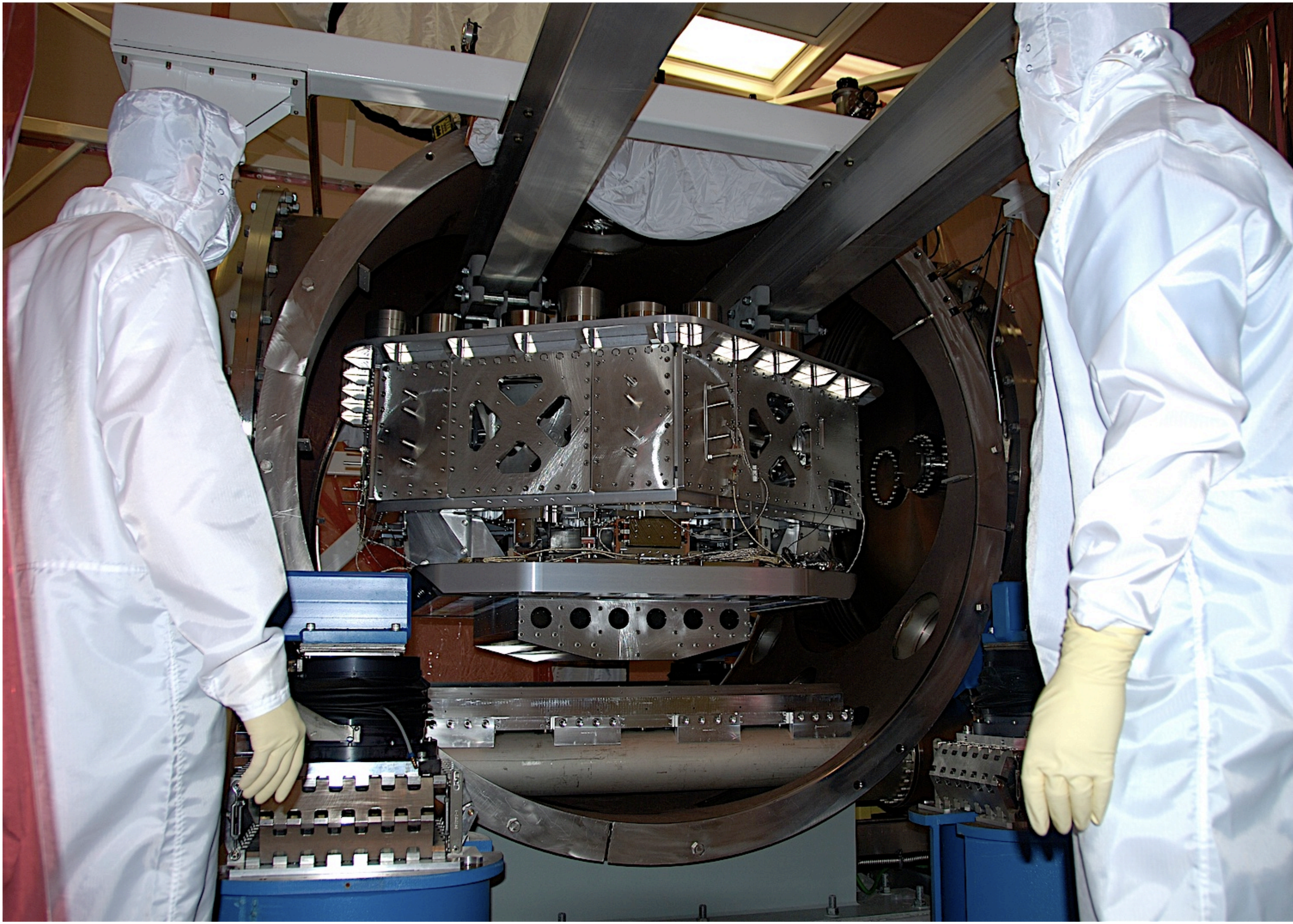
(Horizontal Access Module)

- House complex input/output optics

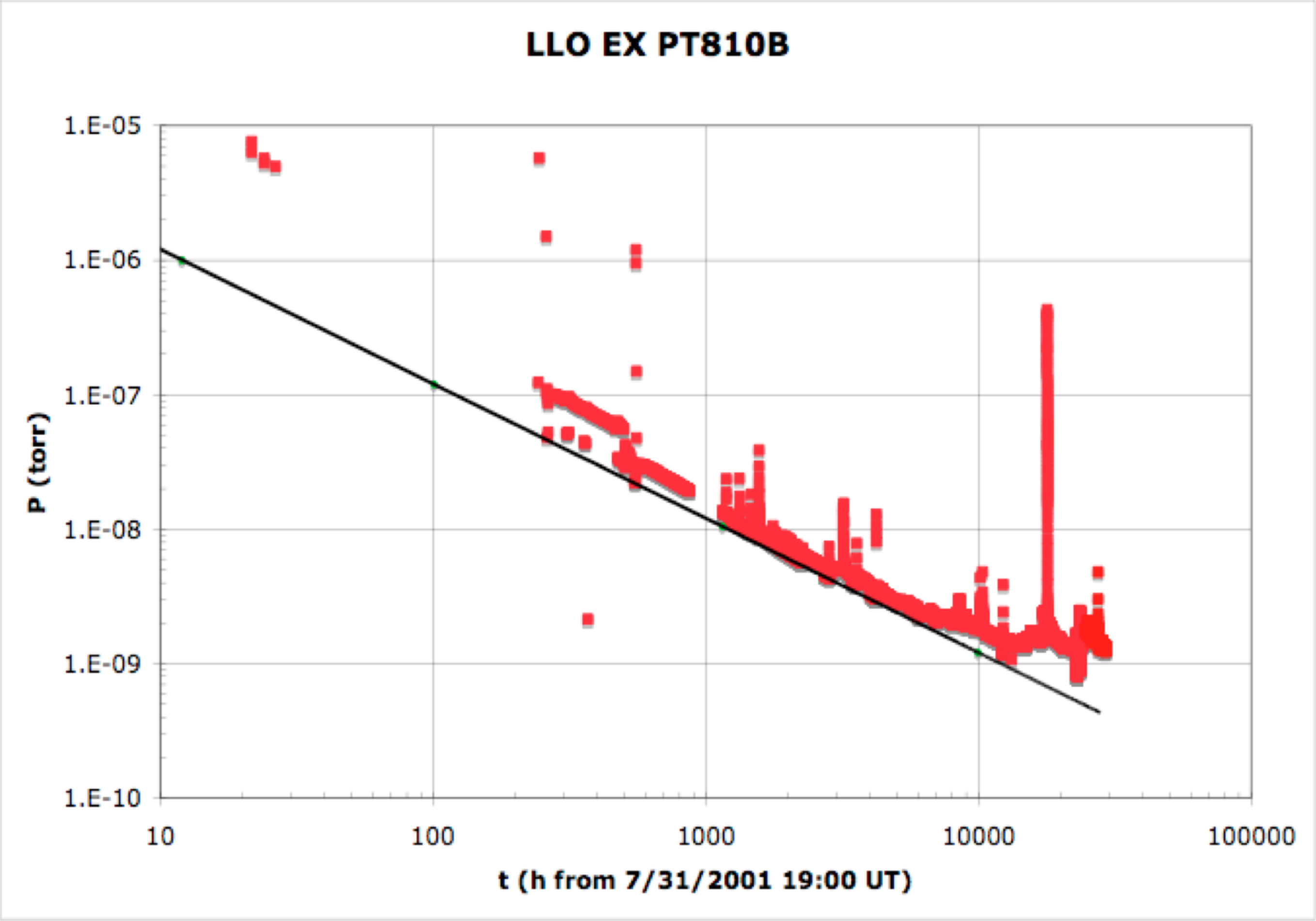
- 2.1m Ø x 2m w

- More than 70% of area is removable access doors





End Station Pressure Evolution after Backfill



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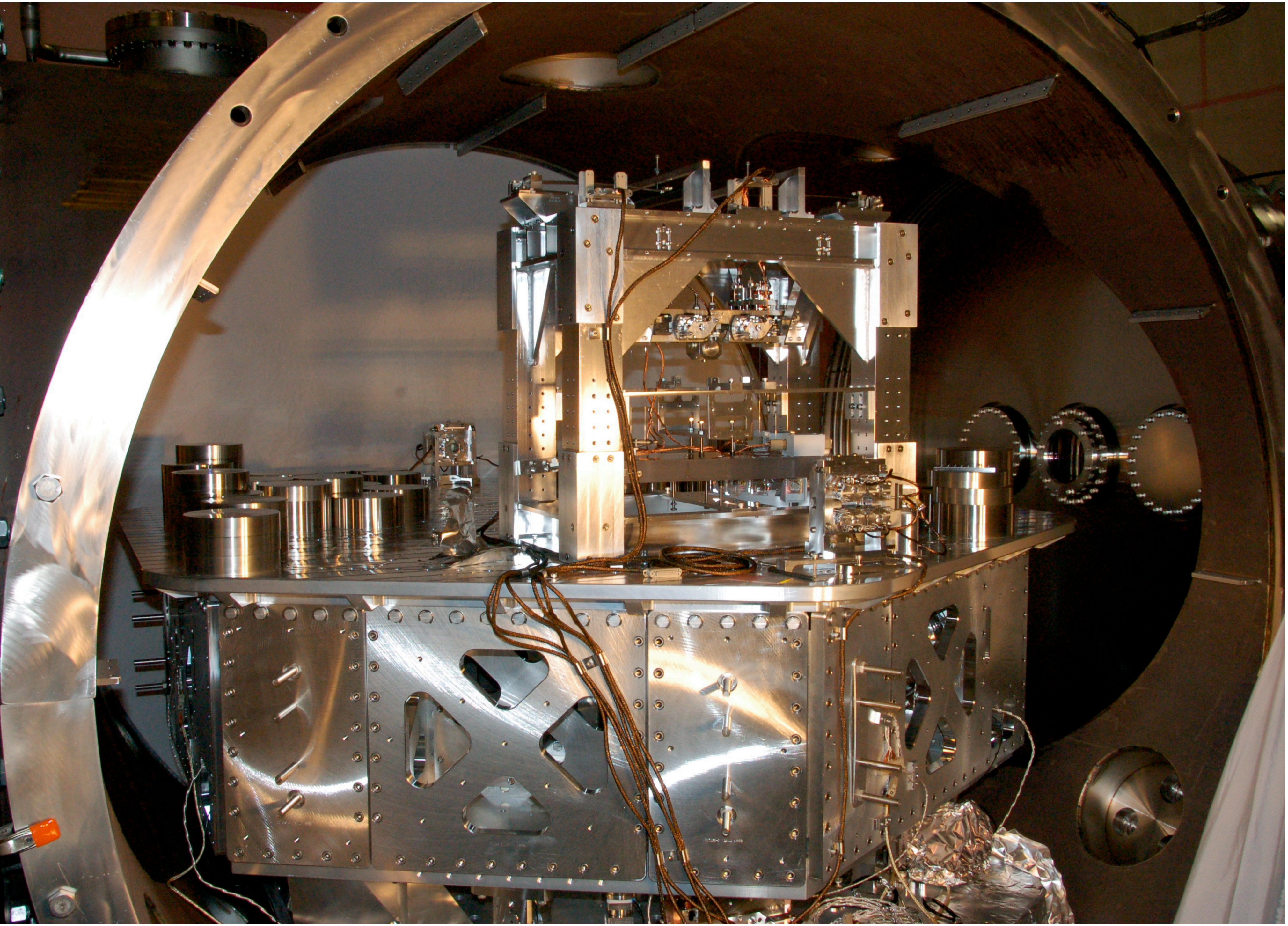
Final Remarks

- LIGO facilities are among the largest high-vacuum systems ever built, and have stringent requirements
- Novel and cost-effective methods were developed to meet these challenges
- In operation over a decade, LIGO is now installing its second-generation instruments
- We look forward to helping the **IndIGO** consortium achieve comparable success in this country if LIGO-India is approved!

Thank you IVS and VECC!

--Reference Slides--

LIGO Vacuum Equipment



Fabrication and Installation

- Fabricated and cleaned off-site
- Delivered in sealed condition for alignment and installation


View of the LVEA (corner station)

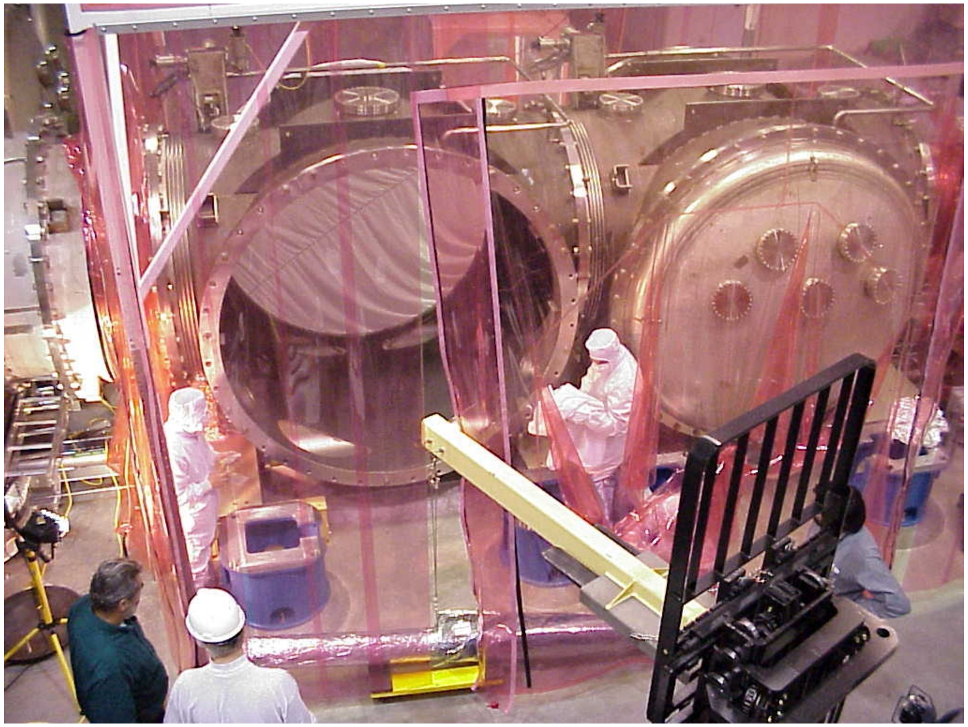
Pumps and Manifolds

- Roughing pumps (Roots blowers) located remotely
- Ion pumps and LN2 traps located on vacuum system

Beamtube Gate Valves

- Large gate valves to isolate beamtubes, LN2 traps

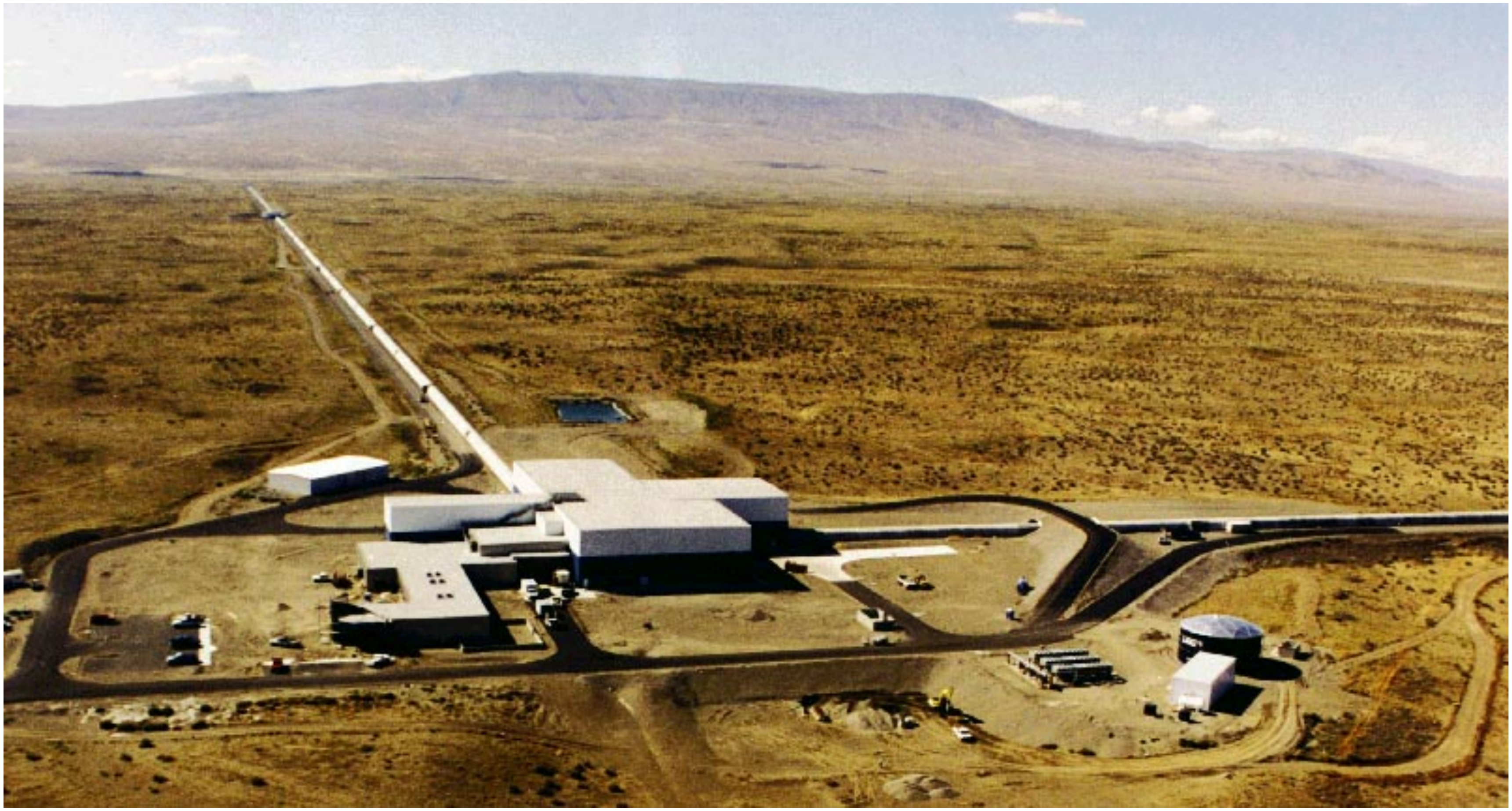
Particulate control: movable ISO Class 5 cleanrooms



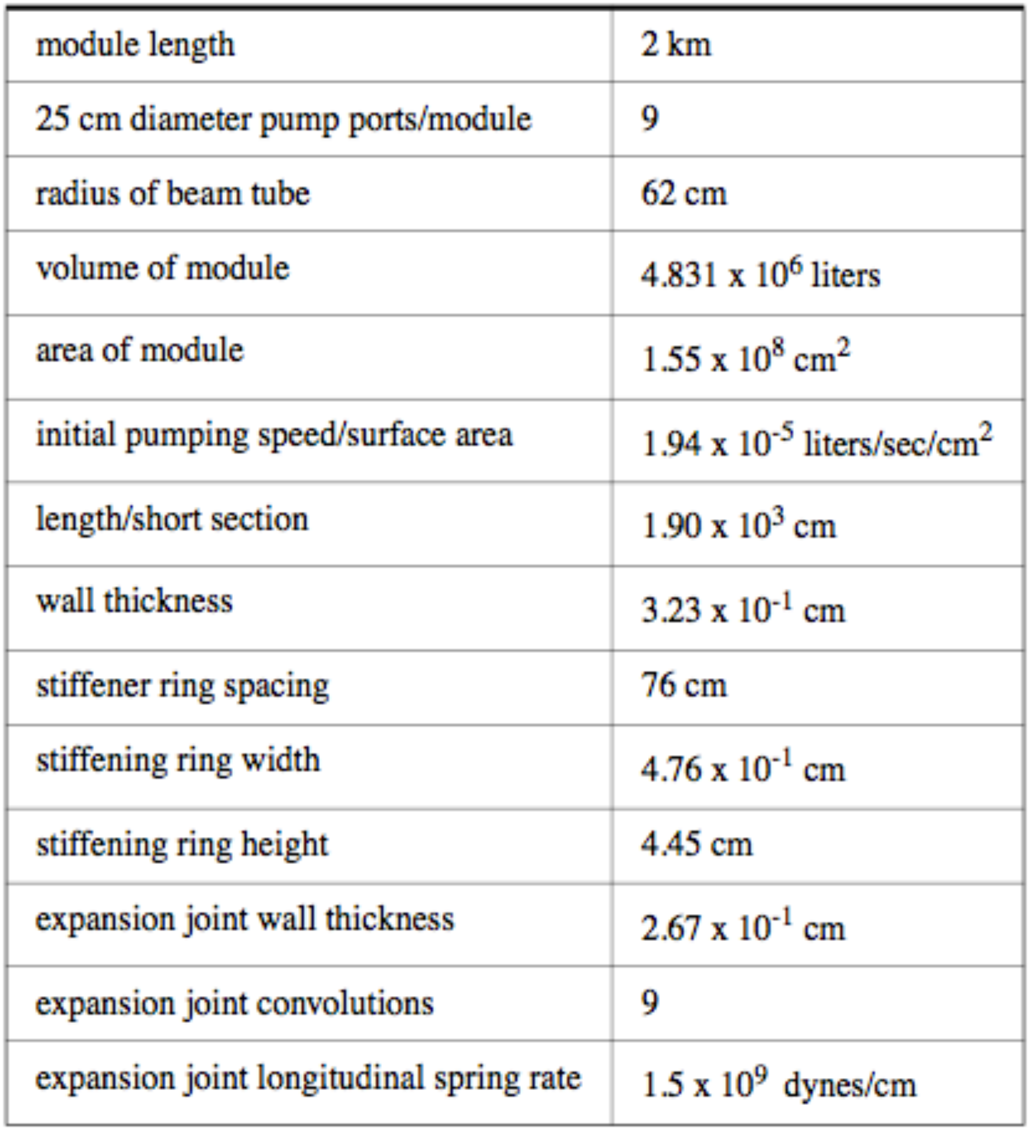
LIGO
Livingston Observatory

LIGO

Hanford Observatory

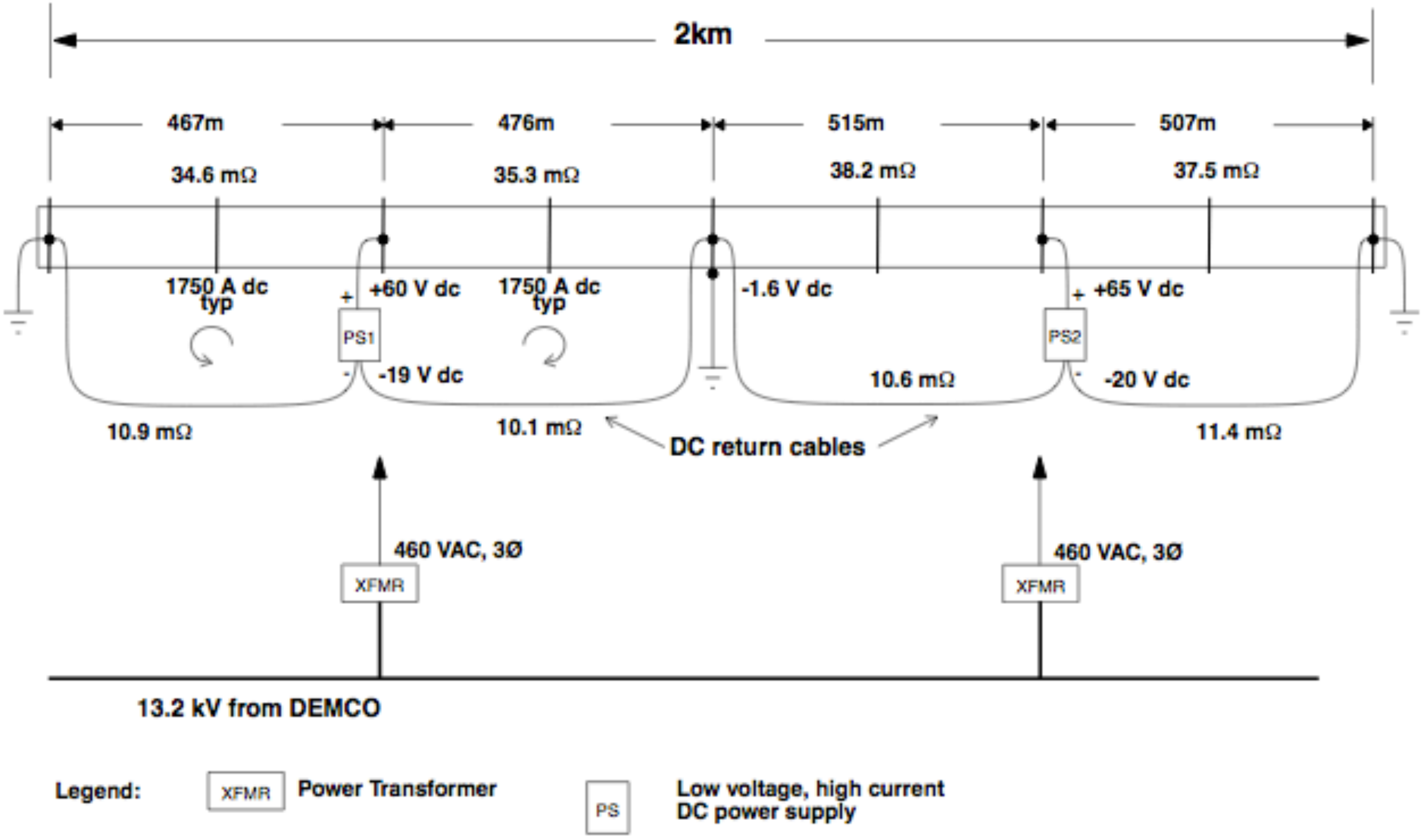


Beam Tube Properties

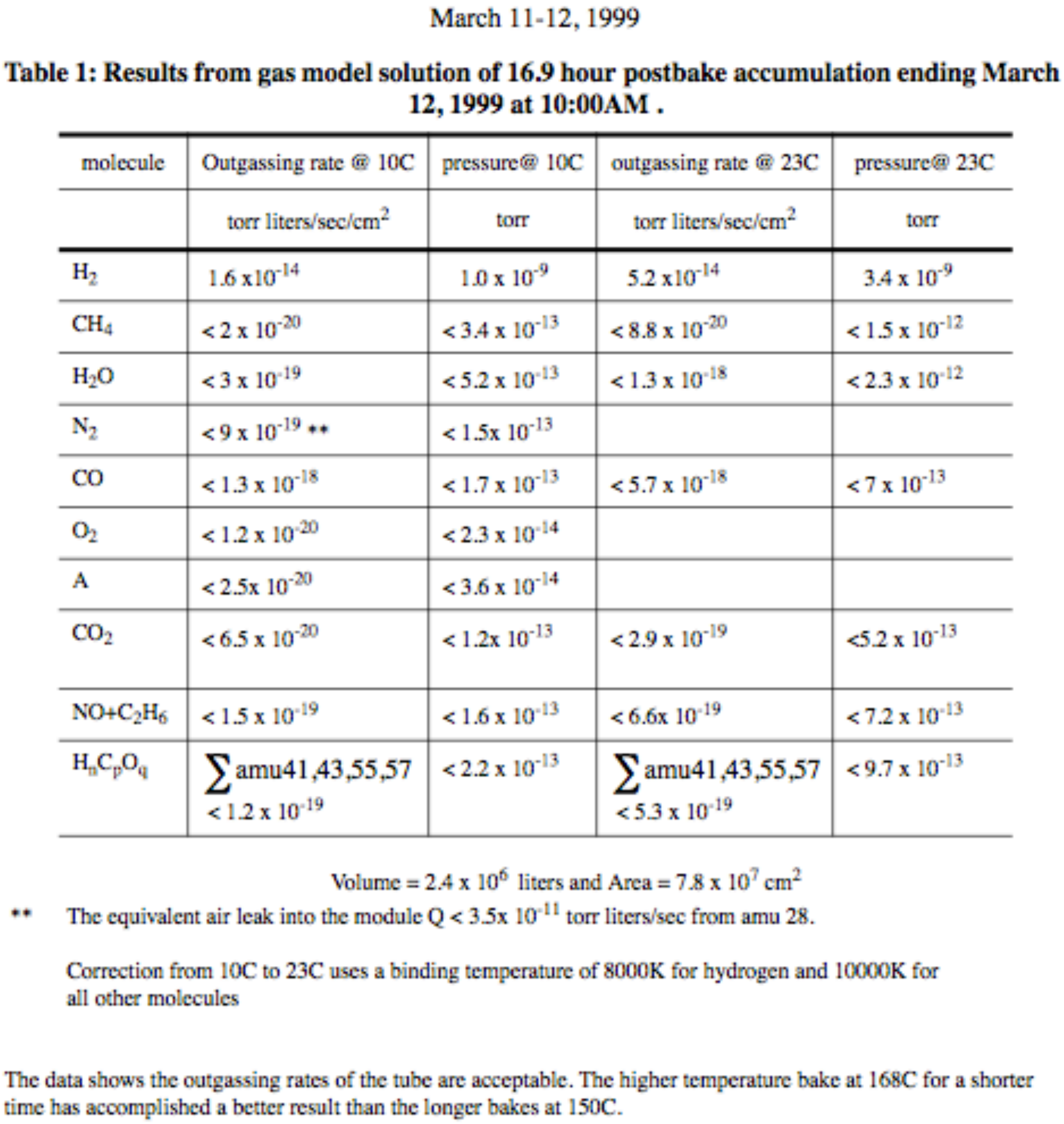


module length	2 km
25 cm diameter pump ports/module	9
radius of beam tube	62 cm
volume of module	4.831×10^{6} liters
area of module	1.55×10^{8} cm^{2}
initial pumping speed/surface area	1.94×10^{-5} liters/sec/cm^{2}
length/short section	1.90×10^{3} cm
wall thickness	3.23×10^{-1} cm
stiffener ring spacing	76 cm
stiffening ring width	4.76×10^{-1} cm
stiffening ring height	4.45 cm
expansion joint wall thickness	2.67×10^{-1} cm
expansion joint convolutions	9
expansion joint longitudinal spring rate	1.5×10^{9} dynes/cm

BEAM TUBE BAKEOUT ELECTRICAL HEATING POWER



Postbake measurements of module X1 at Hanford



March 11-12, 1999

Table 1: Results from gas model solution of 16.9 hour postbake accumulation ending March 12, 1999 at 10:00AM .

molecule	Outgassing rate @ 10C	pressure@ 10C	outgassing rate @ 23C	pressure@ 23C
	torr liters/sec/cm^2	torr	torr liters/sec/cm^2	torr
H_2	1.6×10^{-14}	1.0×10^{-9}	5.2×10^{-14}	3.4×10^{-9}
CH_4	$< 2 \times 10^{-20}$	$< 3.4 \times 10^{-13}$	$< 8.8 \times 10^{-20}$	$< 1.5 \times 10^{-12}$
H_2O	$< 3 \times 10^{-19}$	$< 5.2 \times 10^{-13}$	$< 1.3 \times 10^{-18}$	$< 2.3 \times 10^{-12}$
N_2	$< 9 \times 10^{-19}$ **	$< 1.5 \times 10^{-13}$		
CO	$< 1.3 \times 10^{-18}$	$< 1.7 \times 10^{-13}$	$< 5.7 \times 10^{-18}$	$< 7 \times 10^{-13}$
O_2	$< 1.2 \times 10^{-20}$	$< 2.3 \times 10^{-14}$		
A	$< 2.5 \times 10^{-20}$	$< 3.6 \times 10^{-14}$		
CO_2	$< 6.5 \times 10^{-20}$	$< 1.2 \times 10^{-13}$	$< 2.9 \times 10^{-19}$	$< 5.2 \times 10^{-13}$
$NO+C_2H_6$	$< 1.5 \times 10^{-19}$	$< 1.6 \times 10^{-13}$	$< 6.6 \times 10^{-19}$	$< 7.2 \times 10^{-13}$
$H_nC_pO_q$	$\sum$ amu41,43,55,57 $< 1.2 \times 10^{-19}$	$< 2.2 \times 10^{-13}$	$\sum$ amu41,43,55,57 $< 5.3 \times 10^{-19}$	$< 9.7 \times 10^{-13}$

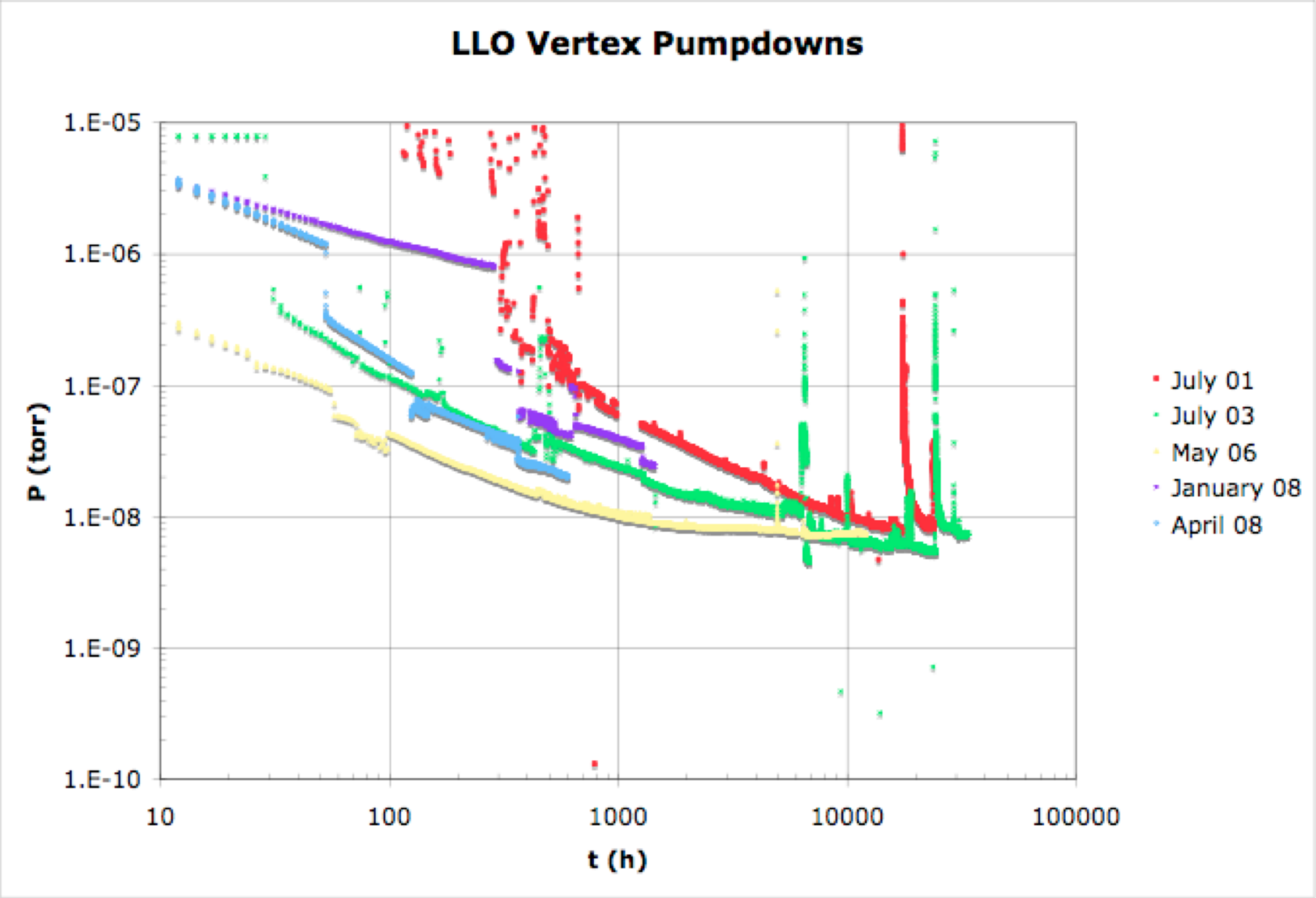
Volume = 2.4×10^6 liters and Area = 7.8×10^7 cm^2

** The equivalent air leak into the module $Q < 3.5 \times 10^{-11}$ torr liters/sec from amu 28.

Correction from 10C to 23C uses a binding temperature of 8000K for hydrogen and 10000K for all other molecules

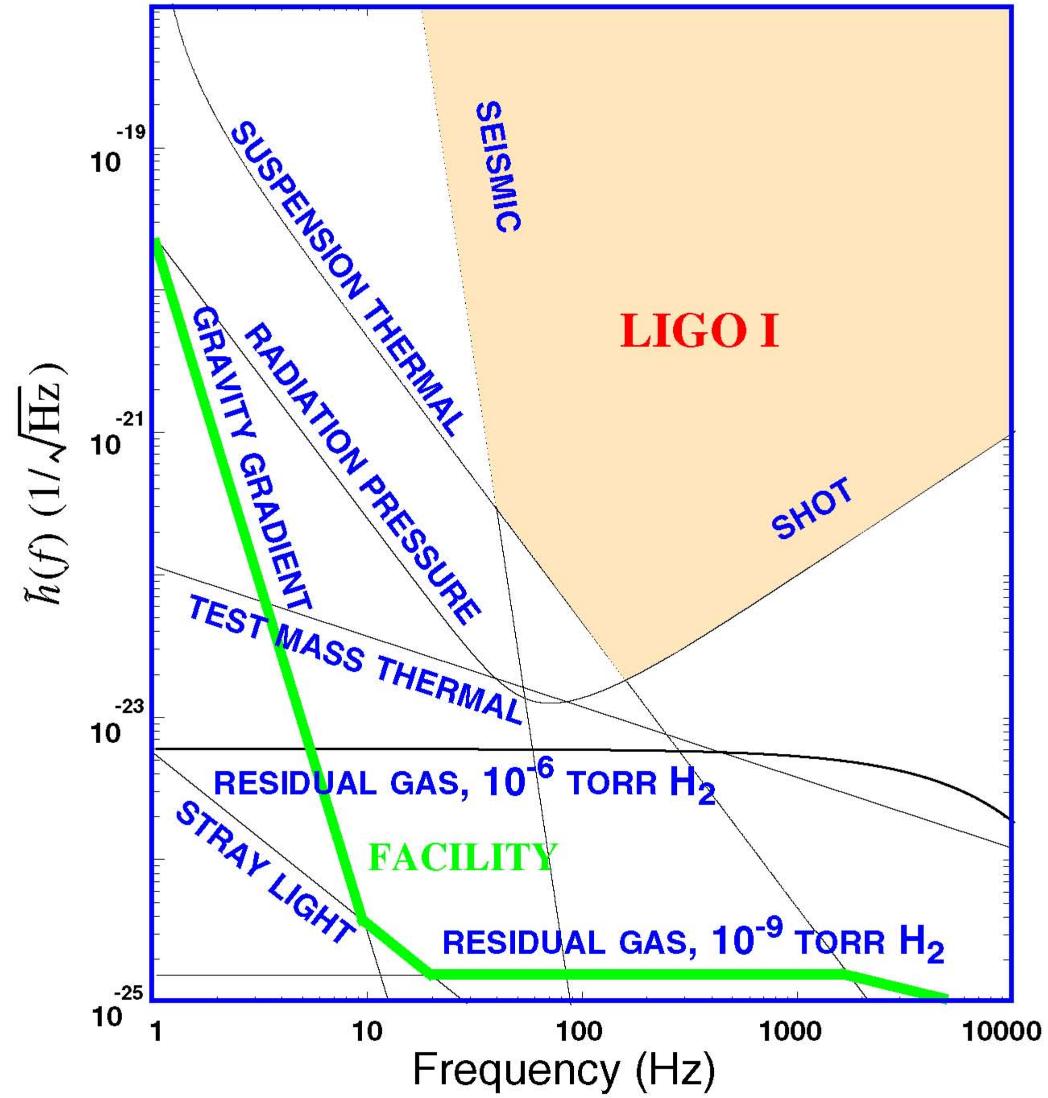
The data shows the outgassing rates of the tube are acceptable. The higher temperature bake at 168C for a shorter time has accomplished a better result than the longer bakes at 150C.

Vertex Pressure Evolution after Backfill

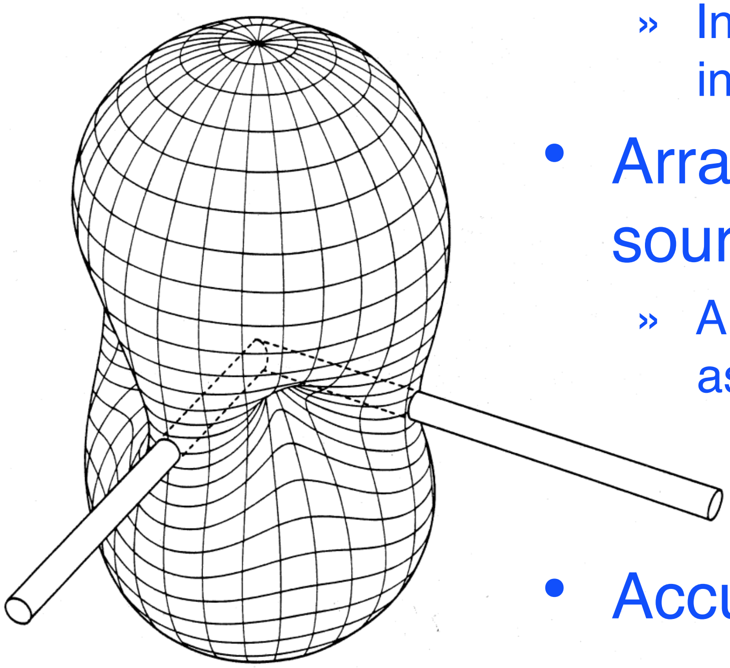


Limits to Sensitivity

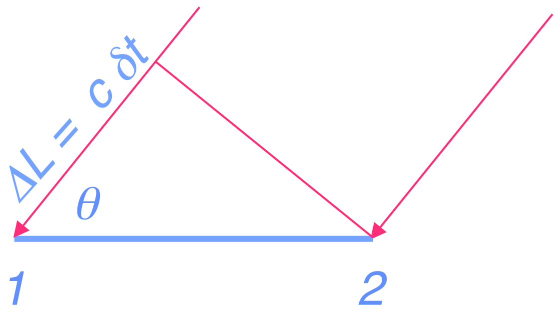
- First detectors reached design sensitivity in 2005
- Now installing Advanced detectors
- Vacuum requirement $<10^{-9}$ torr H_2 $<10^{-10}$ torr H_2O



A Global Array of GW Detectors: Source Localization



- Detectors are nearly omni-directional
  - Individually they provide almost no directional information
- Array working together can determine source location
  - Analogous to “aperture synthesis” in radio astronomy
- Accuracy tied to diffraction limit



Pressure evolution for major species during 160ºC beam tube module bakeout