# Einstein Telescope: vacuum considerations

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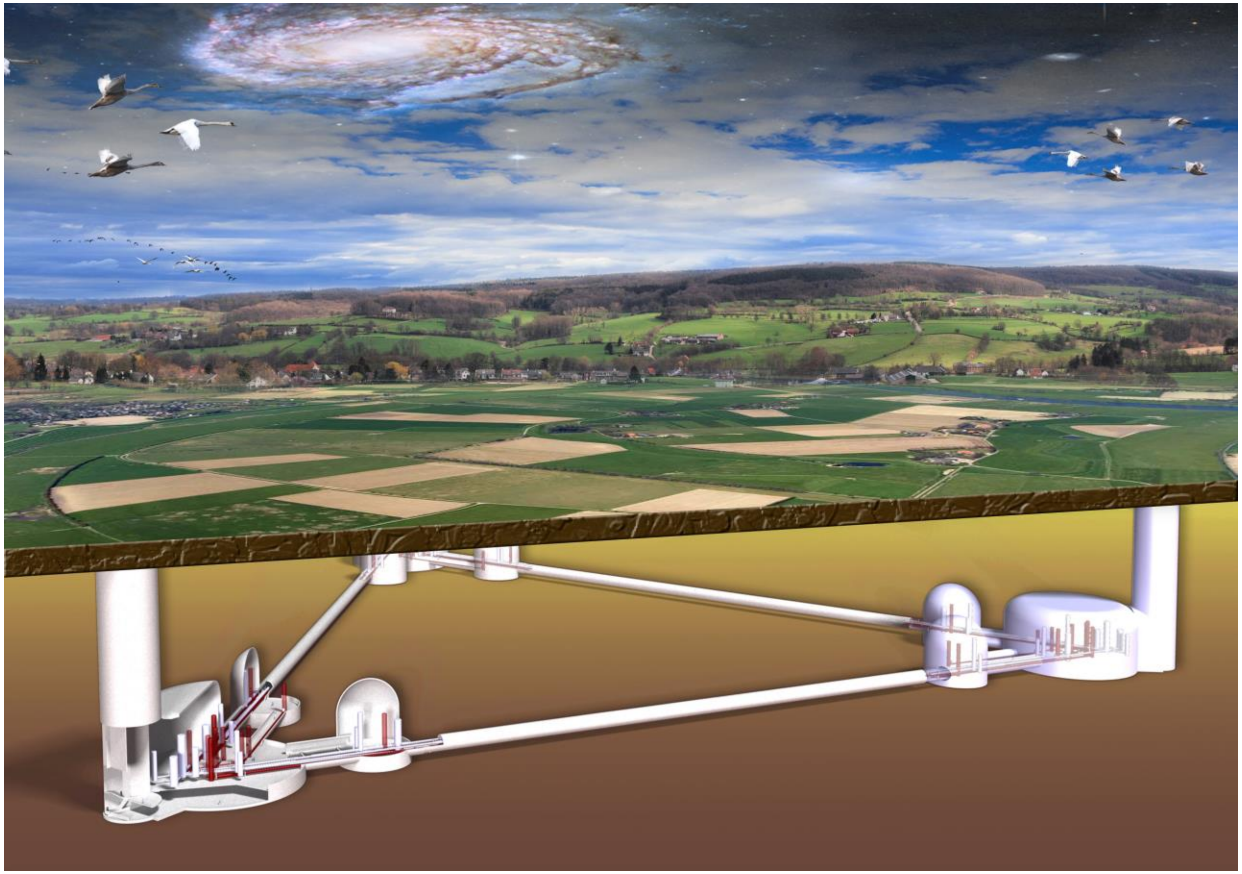
Webinar Technical Challenges Einstein Telescope, July 15, 2020



LIGO Scientific Collaboration

Advanced Virgo

# Contents

Motivation and overview of the vacuum system of Einstein Telescope

Examples from LIGO and Virgo

- Vacuum equipment construction
- Tube construction, cleaning & bake out procedure
- Performance, experience and hindsight

Research topics

- Conservative approach
- Some perhaps “wild” ideas

Acknowledgments:

1. LIGO-G1900137, Mike Zucker LIGO Caltech & MIT, NSF Workshop on Large UHV Systems for Frontier Scientific Research, LIGO Livingston Observatory, 29-31 January, 2019
2. Workshop report by Fulvio Ricci, Sapienza University of Rome, ET-KAGRA-meeting-Perugia-2019
3. Virgo Vacuum System - 3G detector challenges, C. Bradaschia, A. Buggiani , A. Pasqualetti, D. Sentenac, T. Zelenova, Orosei, May 3, 2019
4. Gravitational wave detector vacuum systems, Harald Lueck, Aachen, June 2019

# Einstein Telescope vacuum system

Three detectors that each consist of two interferometers: 6 ITFs in total

Each ITF has 20 km of main vacuum tube + several km of filter cavities

About 3 * (2 * 30 + 2) ≈ 130 km of vacuum tube of about 1 m diameter (assumption)

**Total volume: about 120,000 $m^3$**

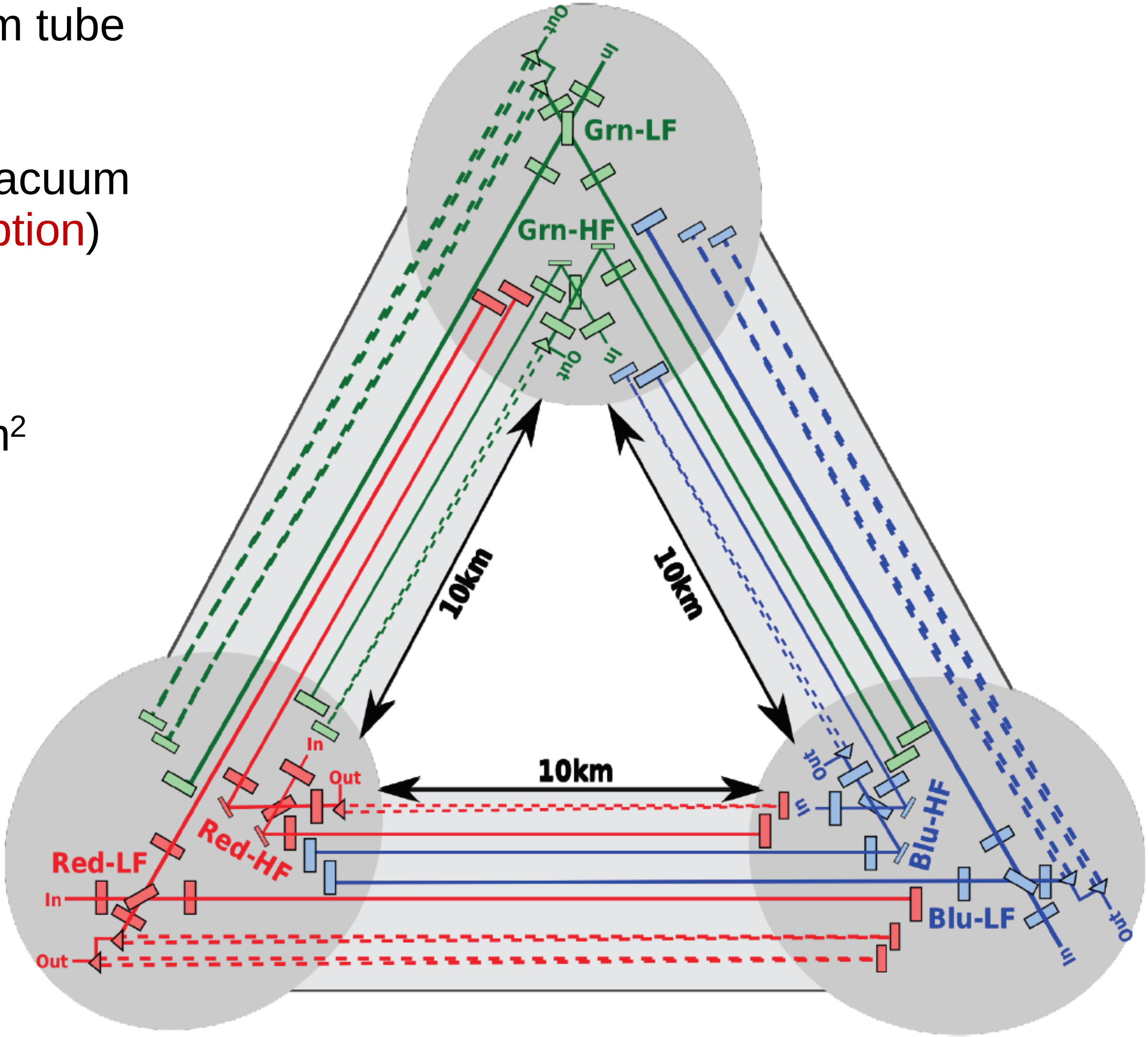
Total surface area: about 420,000 $m^2$

Target pressure of < $10^{-10}$ hPa

Hydrocarbon pressure < $10^{-14}$ hPa

For comparison LHC at CERN:

- **Beam tubes: 2,000 $m^3$**
- Cryo-magnet insulation: 9,000 $m^3$
- Cryo distribution line: 5,000 $m^3$



# Why do we need an ultra-high vacuum system?

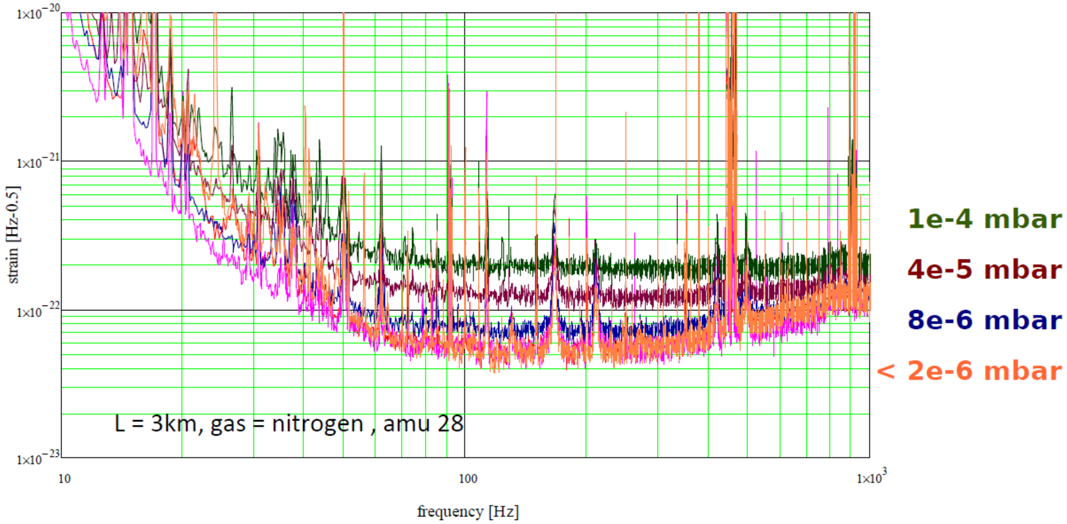
- Reduce the **phase noise due to residual gas density fluctuations** along the beam path to an acceptable level
- Isolate test masses and other optical elements from **acoustic noise**
- Reduce **test mass motion** excitation due to residual gas fluctuations
- Reduce friction losses in the mirror suspensions → **suspension thermal noise**
- Contribute to **thermal isolation of test masses** and of their support structures
- Contribute to preserve the **cleanliness** of optical elements

Virgo design values

| Gas species | Pressure [ mbar ] | Noise [ $\sqrt{\text{Hz}}$ ] |
|---|---|---|
| Hydrogen | $1 \times 10^{-9}$ | $9.7 \times 10^{-26}$ |
| Water | $1.5 \times 10^{-10}$ | $2.5 \times 10^{-25}$ |
| Air | $5 \times 10^{-10}$ | $5.6 \times 10^{-25}$ |
| Hydrocarbons | $1 \times 10^{-13}$ | $2.9 \times 10^{-26}$ |
| Total | $1.7 \times 10^{-9}$ | $6.2 \times 10^{-25}$ |

Einstein Telescope aims at an order of magnitude improvement

$$S_L(f) = \frac{4\rho\,(2\pi\alpha)^2}{v_0}\int_0^{L_0}\frac{1}{w(z)}e^{-2\pi f w(z)/v_0}dz$$

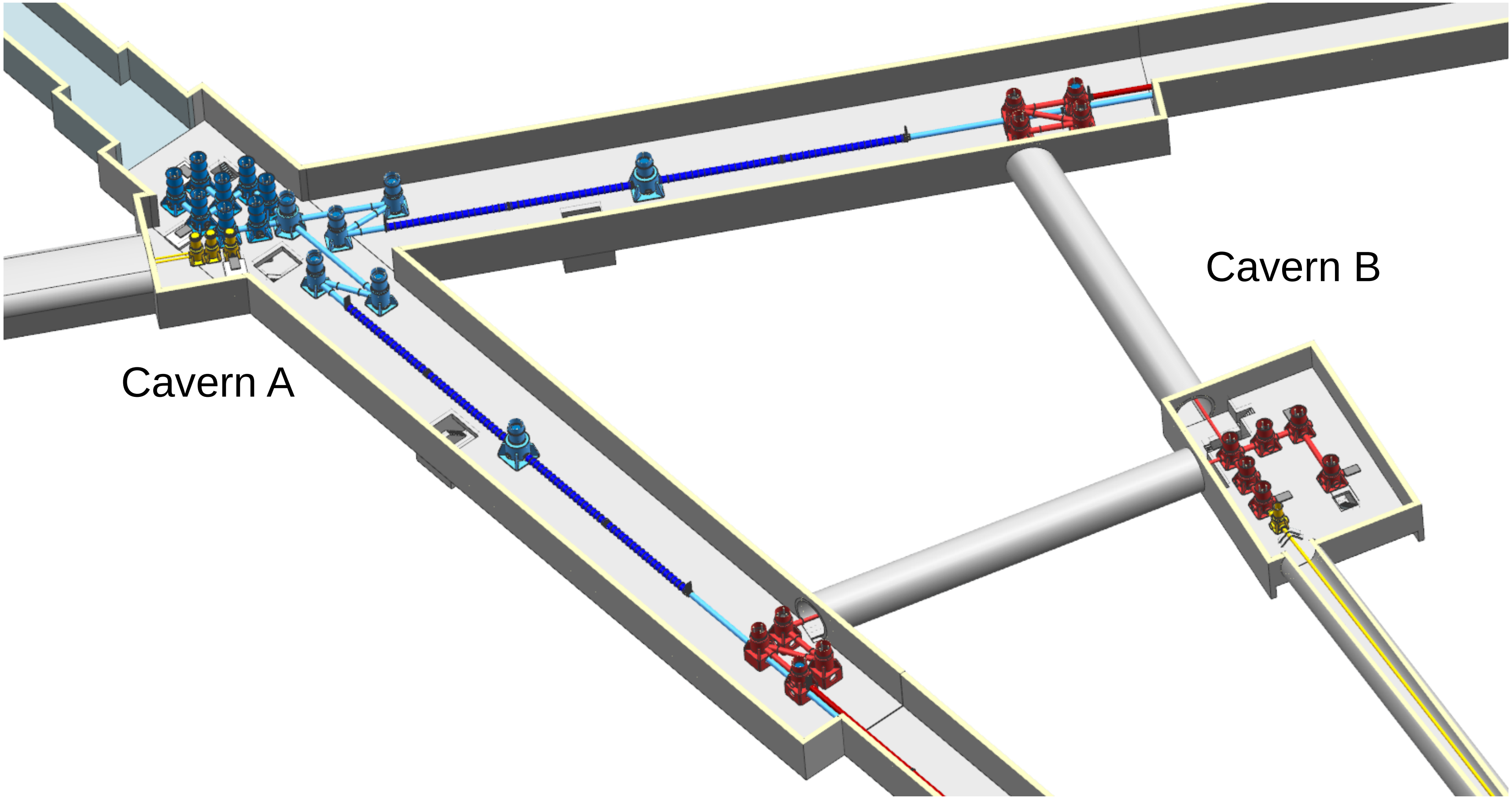


Fluctuations of the refractive index of residual gas limits sensitivity

# Einstein Telescope layout: corner station

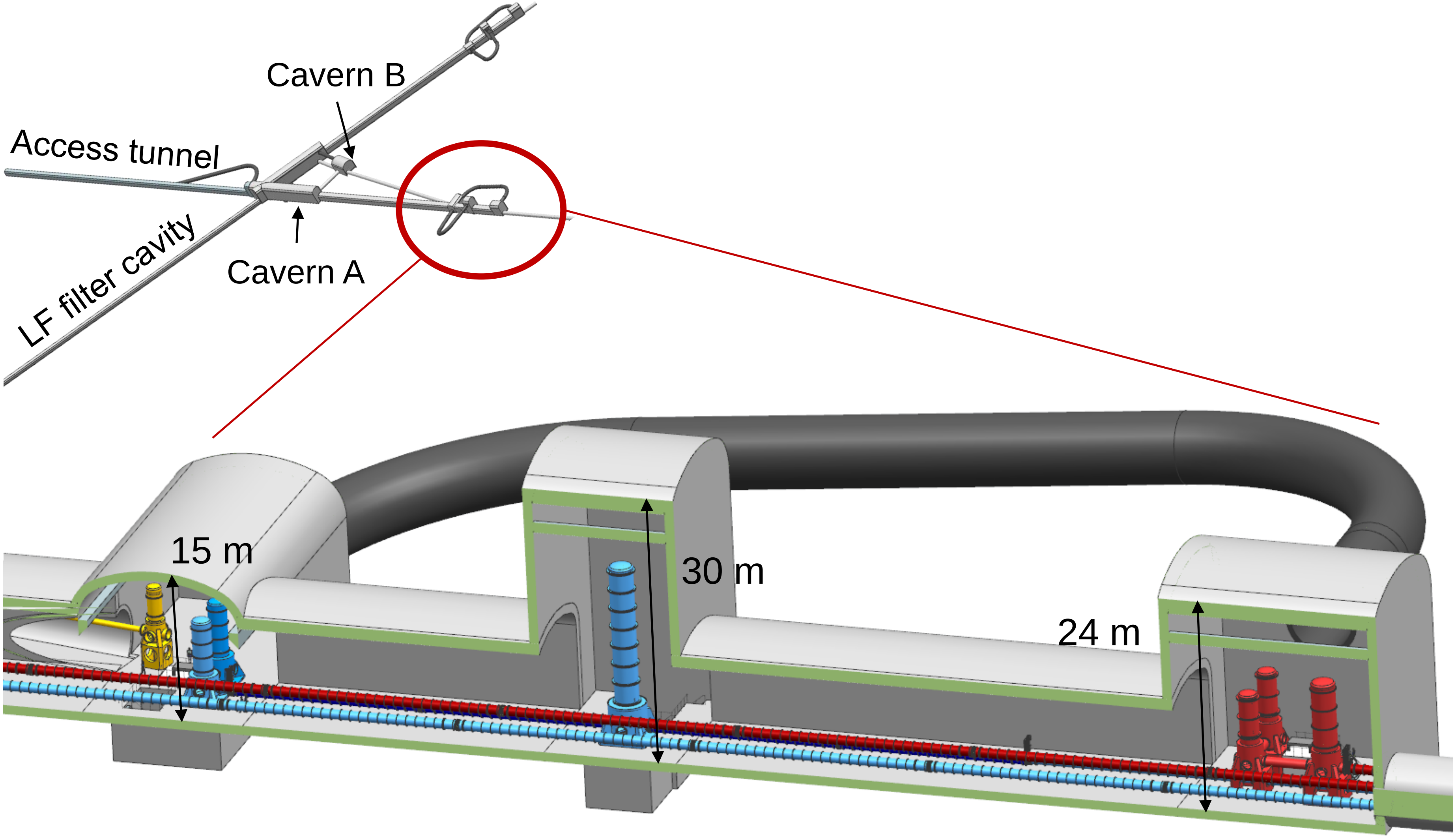
Low frequency towers (blue): height ≈ 20 m

High frequency towers (red): height ≈ 10 m



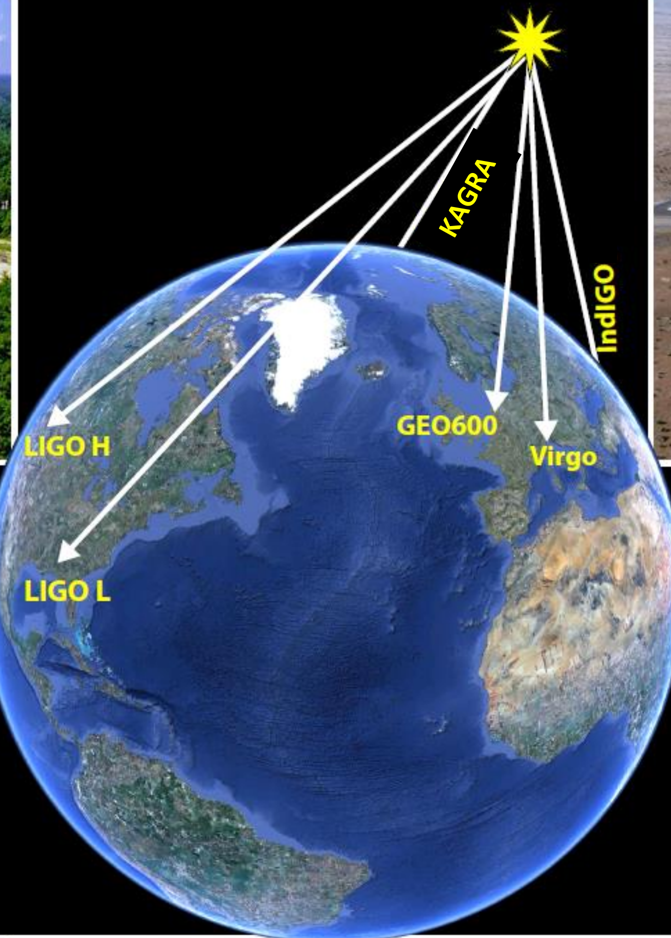
Towers for filter cavities and pick-off beams (yellow)

# Einstein Telescope layout: arm cavities



# Examples from LIGO, Virgo, GEO600 and KAGRA


LIGO Livingston, LA




LIGO Hanford, WA

Advanced LIGO and Virgo
run simultaneously

Kagra joined in 2020
LIGO India approved


GEO600, Hannover, Germany


Virgo, Cascina, Italy


Kagra, Kamioka, Hida, Japan

Virgo interferometer

Virgo vacuum system

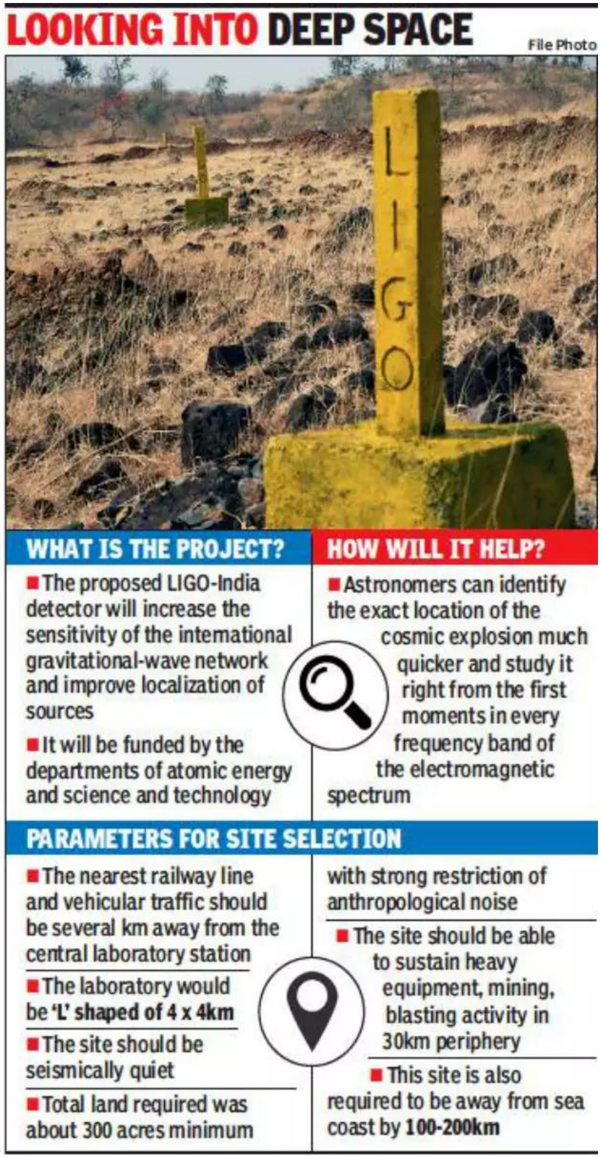
LIGO Livingston, Louisiana

# KAGRA inauguration

Signing of the MOA with LIGO and VIRGO
Toyama, October 4, 2019

# LIGO-India: construction has started (online 2024?)

The 4 km interferometer will be sited at Hingoli in Maharashtra, about 450 km from Pune



**LOOKING INTO DEEP SPACE**

File Photo

**WHAT IS THE PROJECT?**

- The proposed LIGO-India detector will increase the sensitivity of the international gravitational-wave network and improve localization of sources
- It will be funded by the departments of atomic energy and science and technology

**HOW WILL IT HELP?**

- Astronomers can identify the exact location of the cosmic explosion much quicker and study it right from the first moments in every frequency band of the electromagnetic spectrum

**PARAMETERS FOR SITE SELECTION**

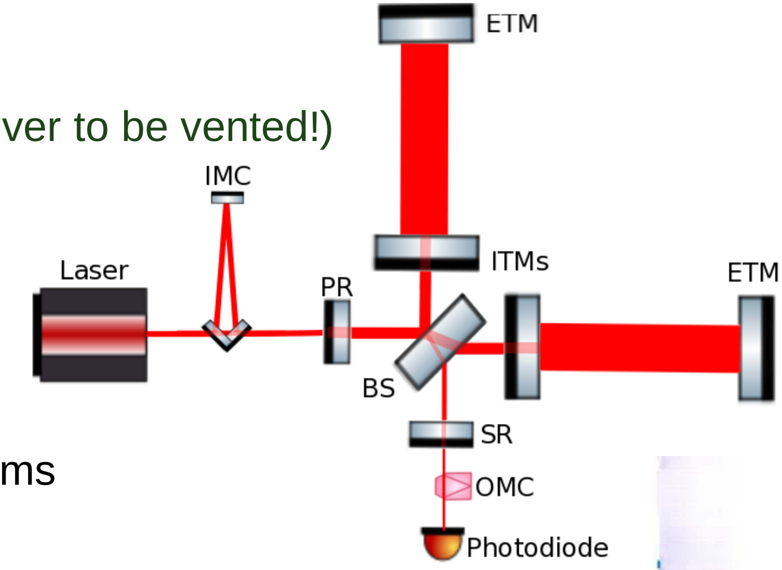
- The nearest railway line and vehicular traffic should be several km away from the central laboratory station
- The laboratory would be **'L' shaped of 4 x 4km**
- The site should be seismically quiet
- Total land required was about 300 acres minimum with strong restriction of anthropological noise
- The site should be able to sustain heavy equipment, mining, blasting activity in 30km periphery
- This site is also required to be away from sea coast by **100-200km**

# Dual recycled Fabry-Perot interferometer

Two separate vacuum systems:

Beam tube vacuum

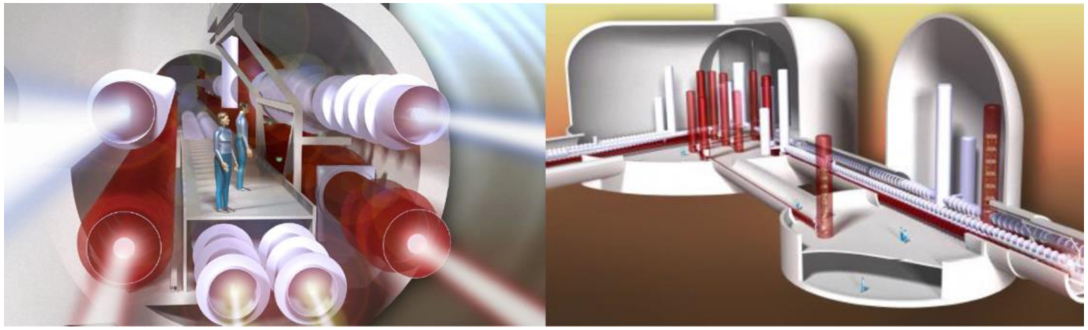
- Essentially a long hole in the air (never to be vented!)
- Highly “unconventional”



Equipment vessels (towers)

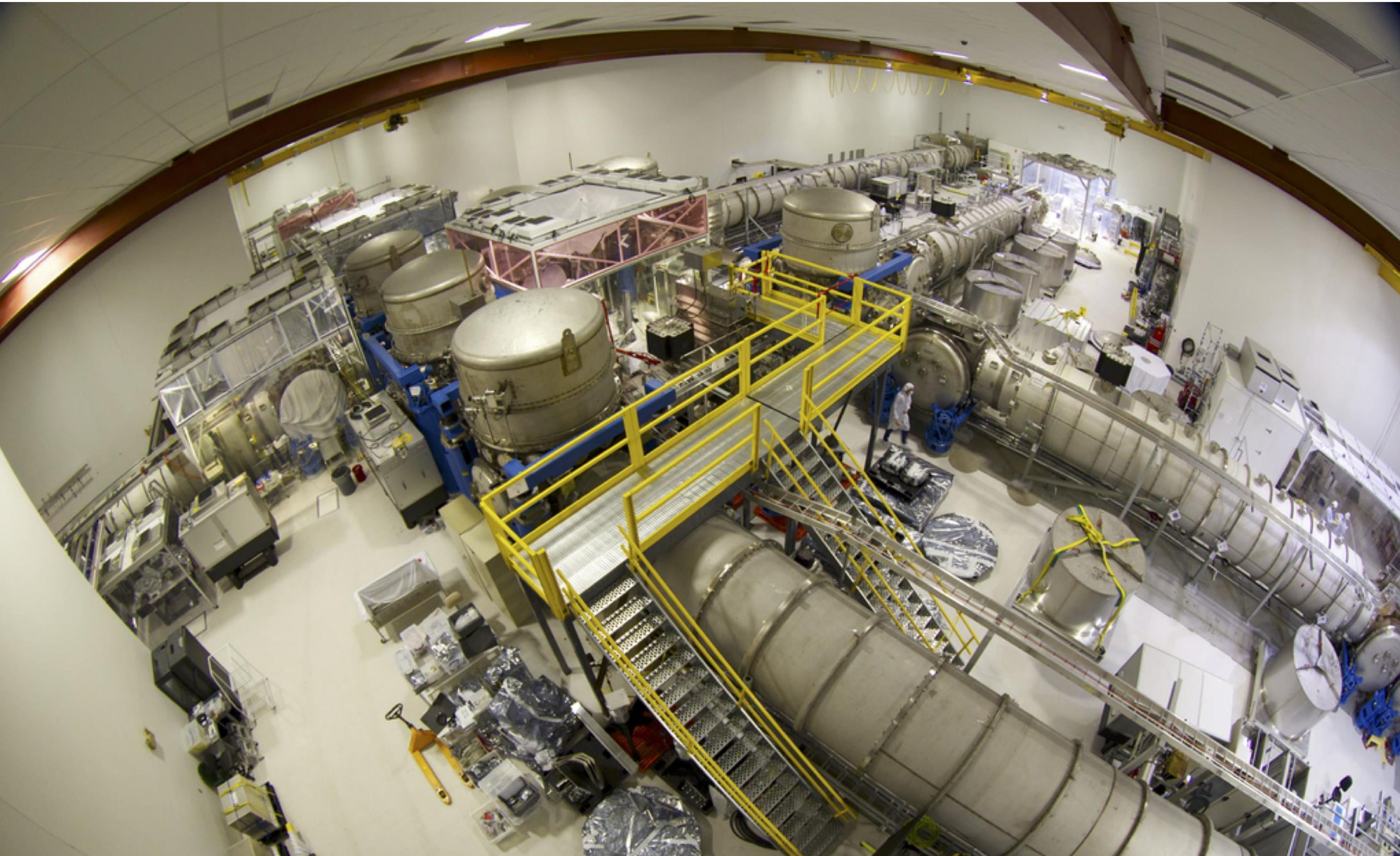
- Houses detector apparatus
- Isolation (valves), access (doors)
- Electrical, mechanical, optical systems
- Pumping & instrumentation

Einstein Telescope has 6 FP ITFs in a triangular topology

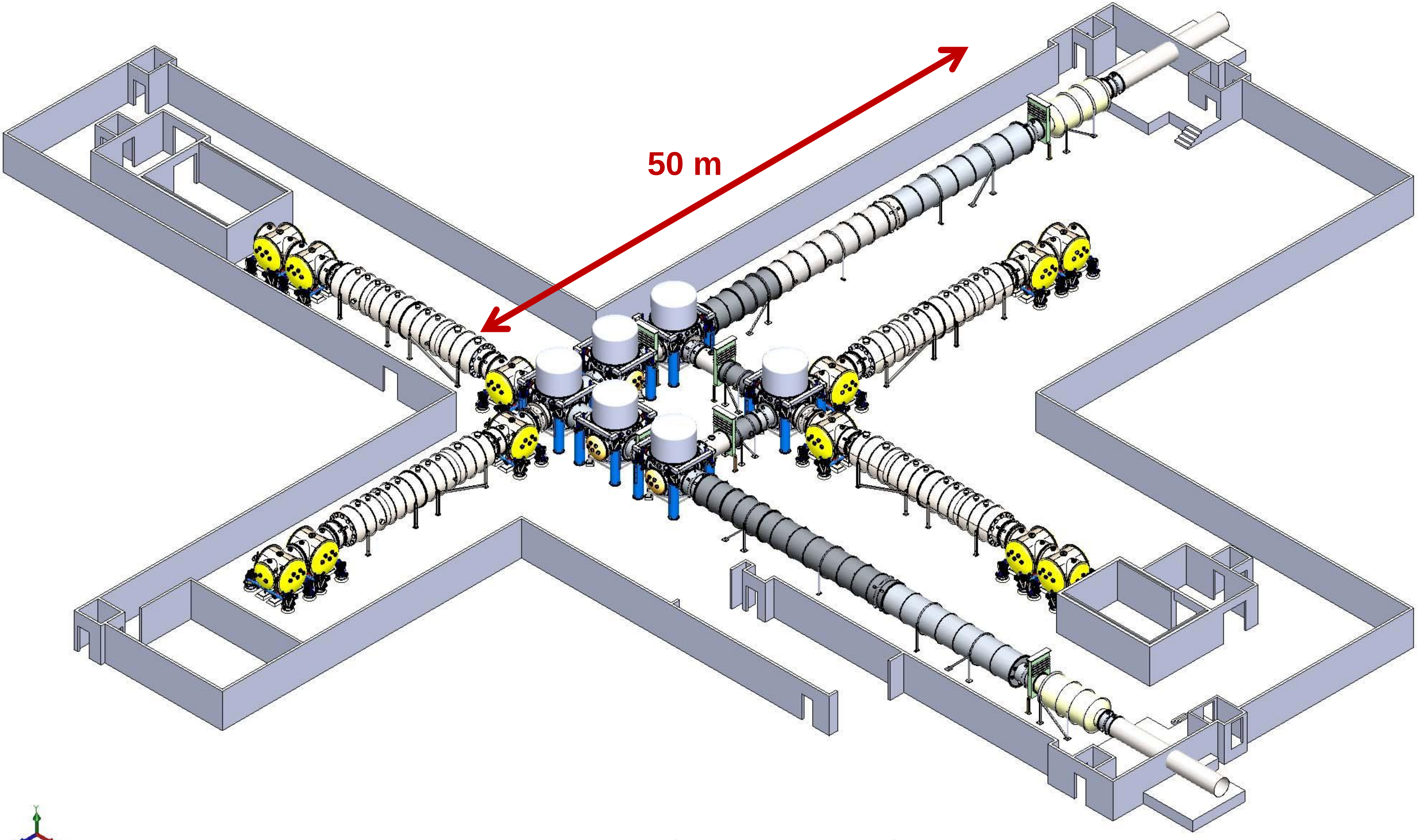


# Vacuum Equipment

# Vacuum Equipment: LIGO Hanford corner station

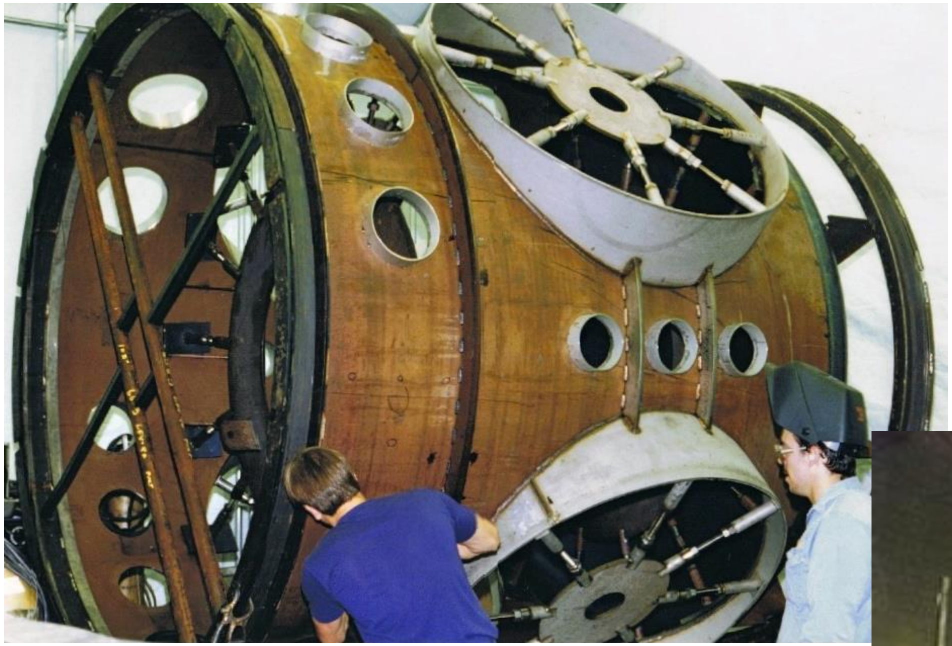


# Modular vacuum equipment design



D0901865 AdvLIGO Vacuum Equipment Layout, LHO Corner Station.SLDASM

# BSC chamber (boring symmetric chamber …)

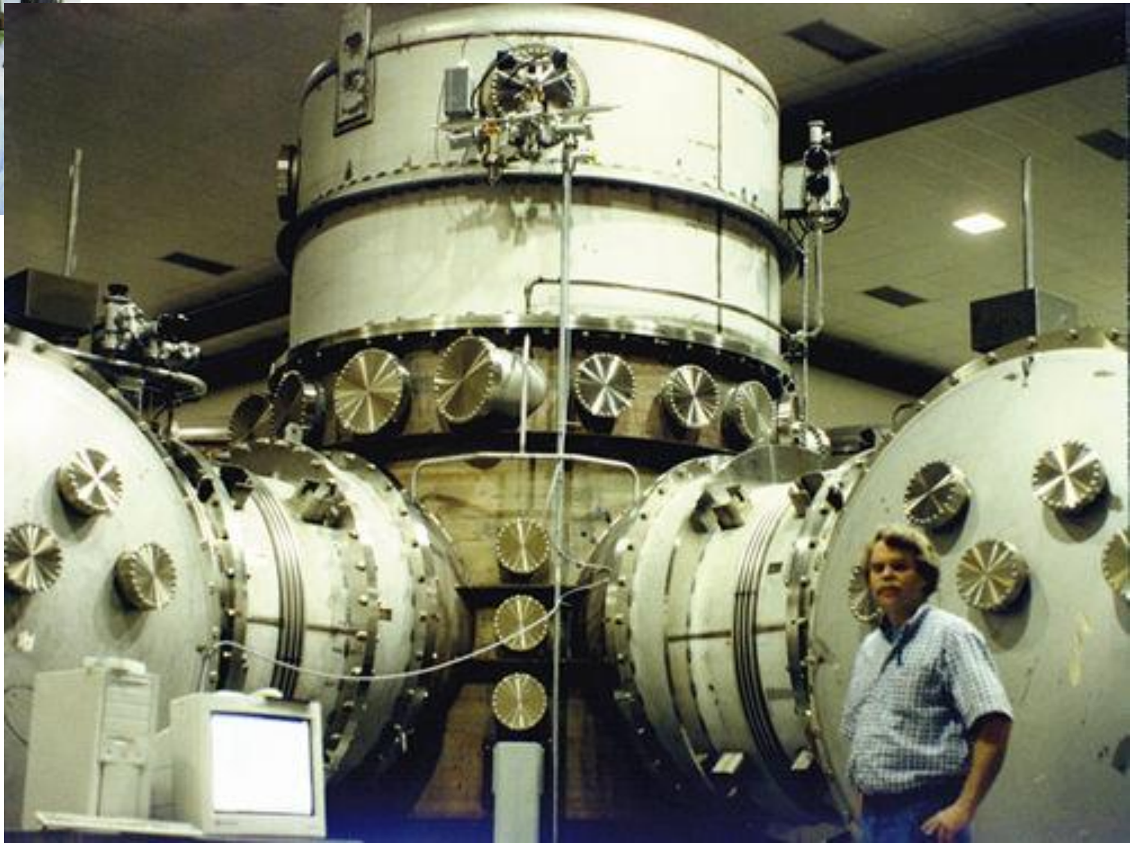


Dimensions: 2.8 m Ø x 5.5 m h

Upper third removable dome

Thin (10-15 mm) 304L SS shell with welded stiffeners, F&D heads

Combination of GTAW and plasma welding

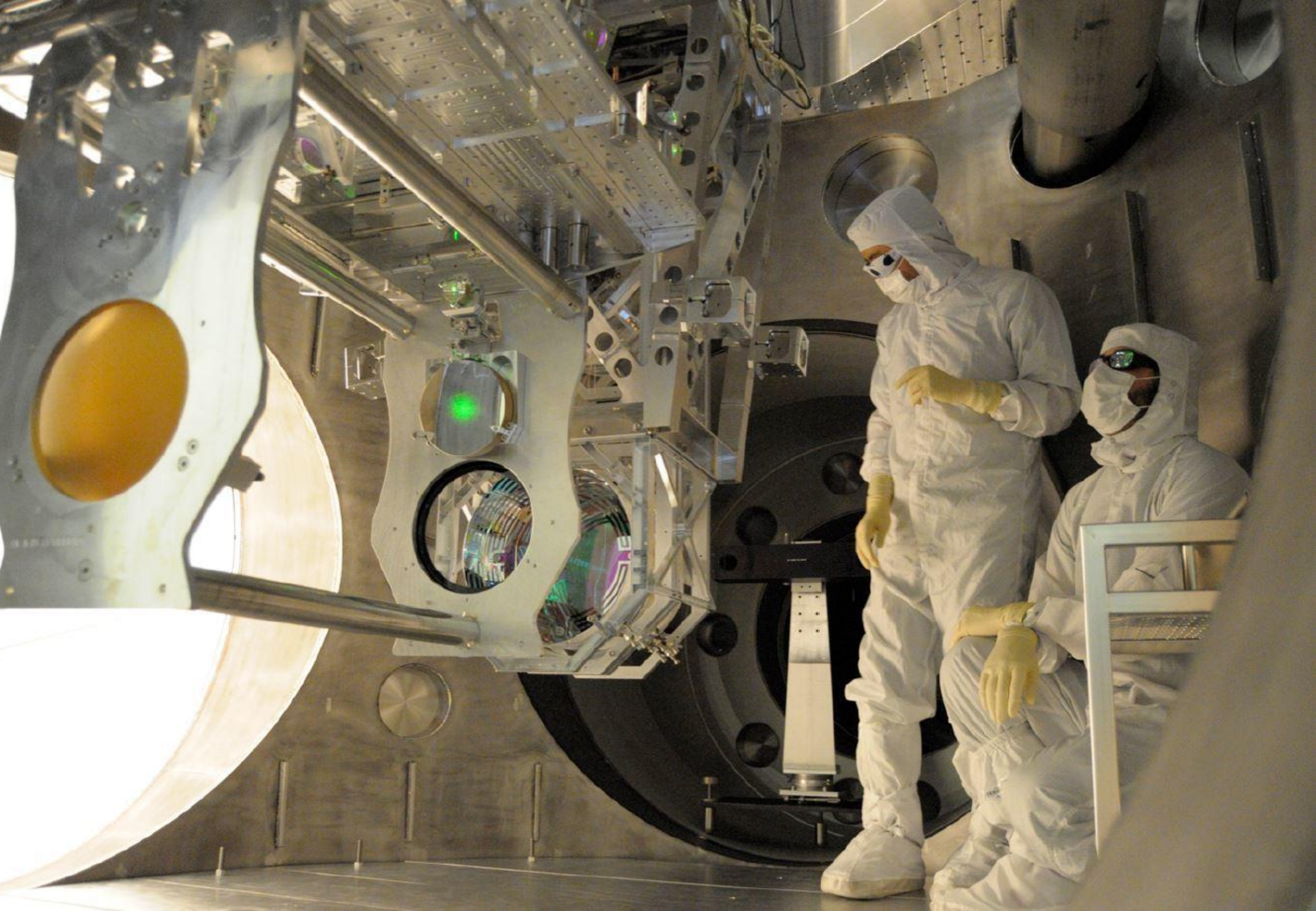


Ports < 35 cm Ø: ConFlat$^{TM}$

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

# BSC equipment installation

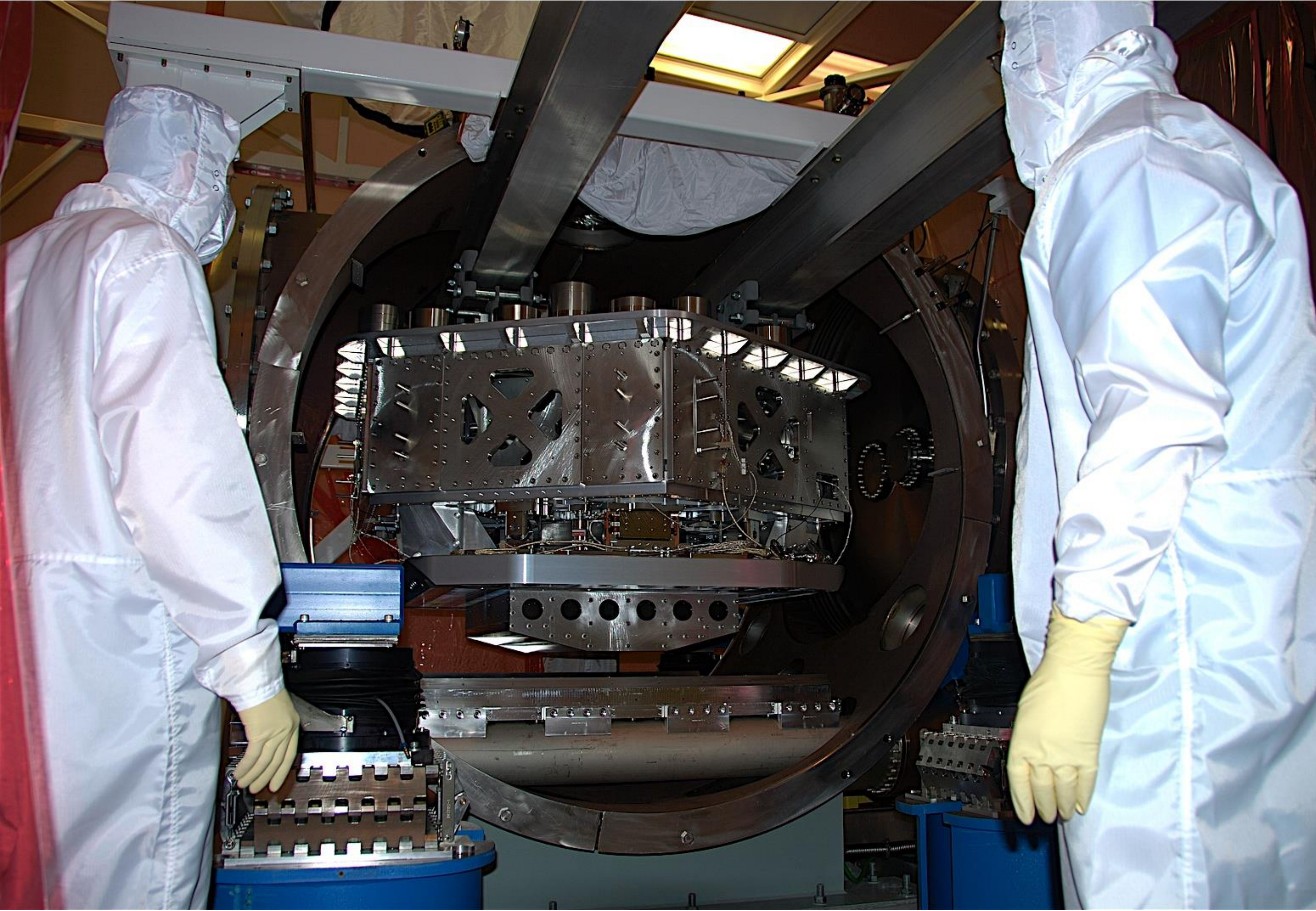
# Livingston ETM Y BSC “Cartridge” Installation; 2-21-2014

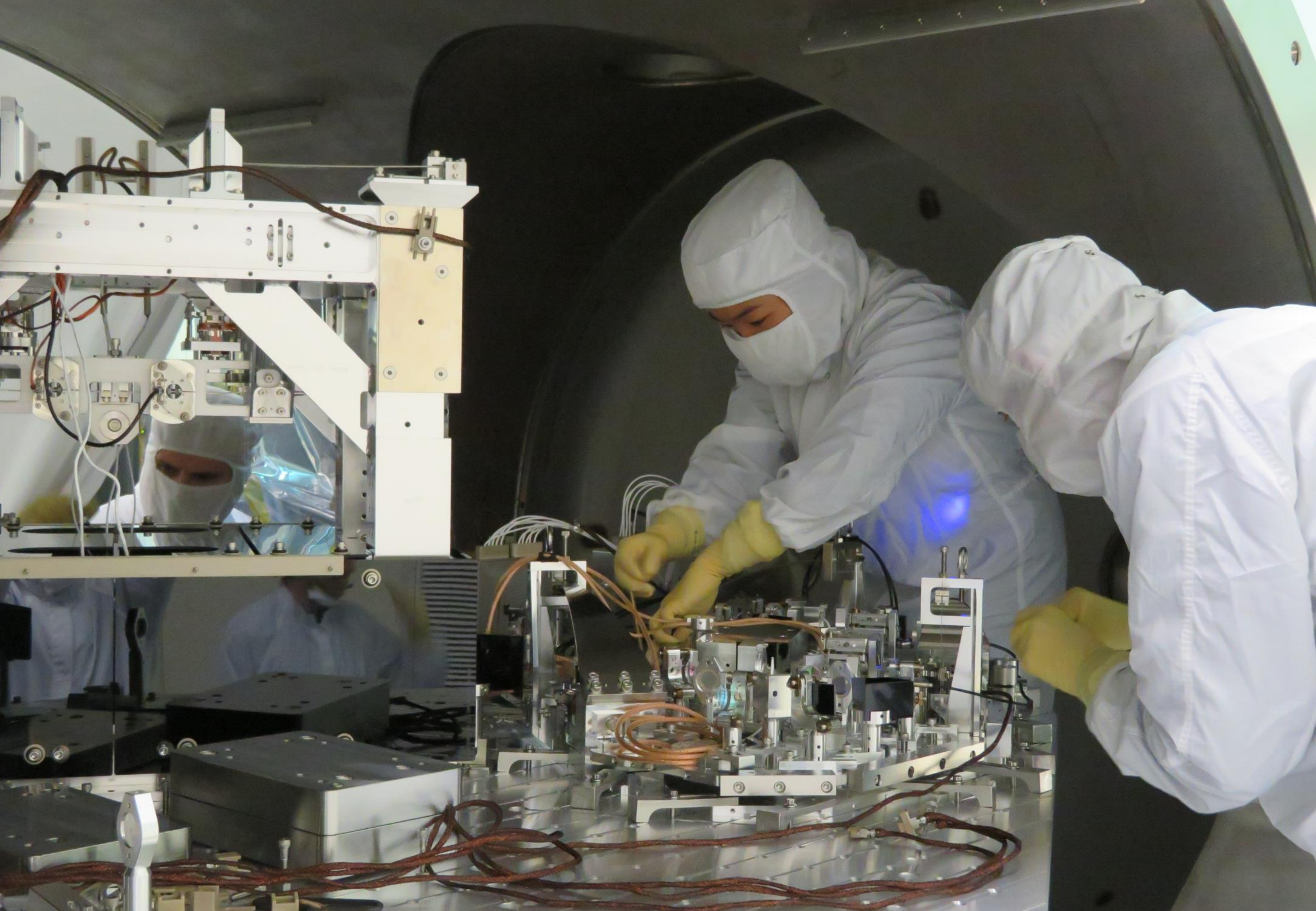


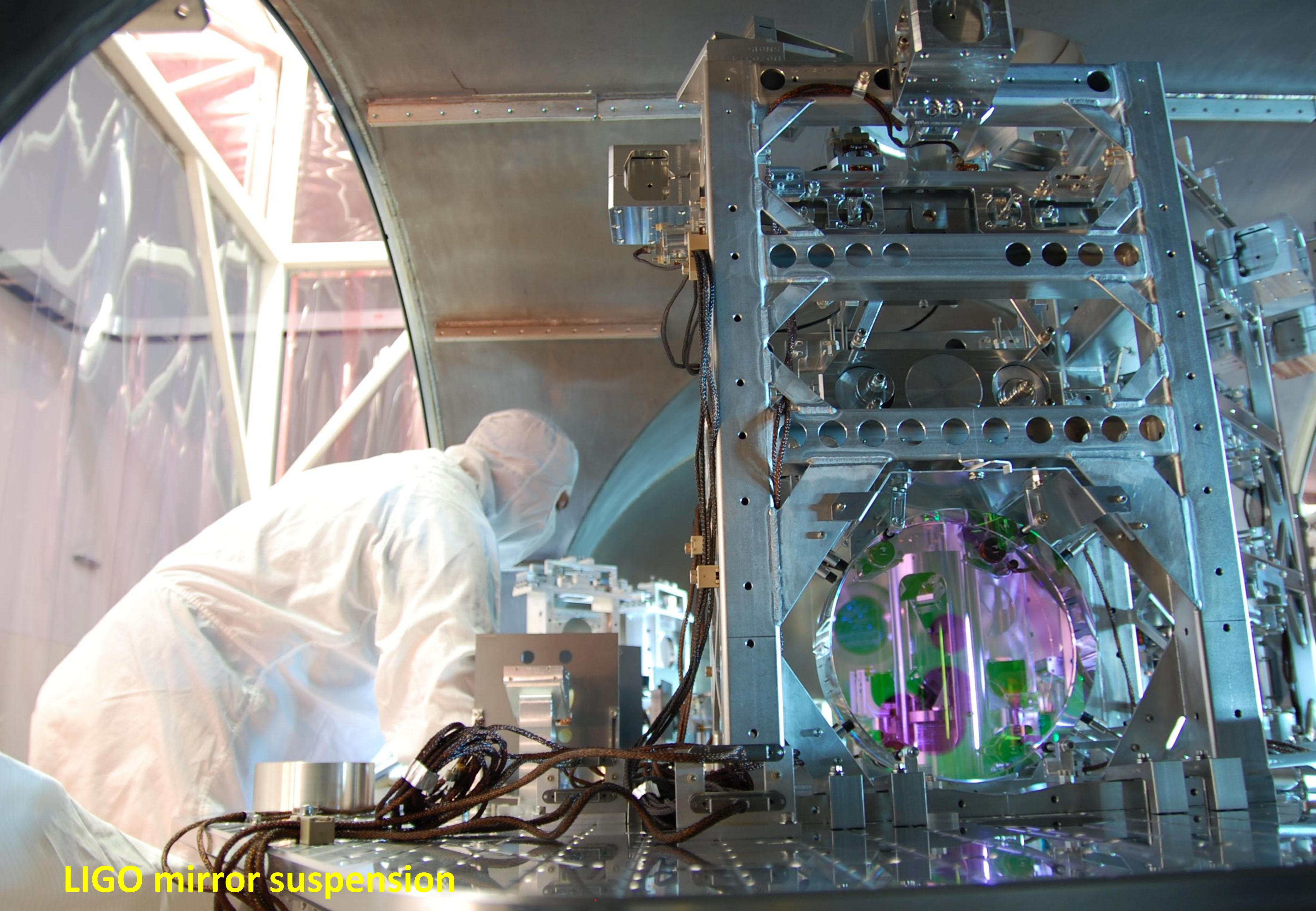
LIGO mirror

# HAM chamber (horizontal-axis module)

- House complex input/output optics
- 2.1m Ø x 2m w
- More than 70% of area is removable access doors







LIGO mirror suspension

# Operational aspects

# Bake-out

# Cryolinks to achieve UHV in the ITF arms of Advanced Virgo

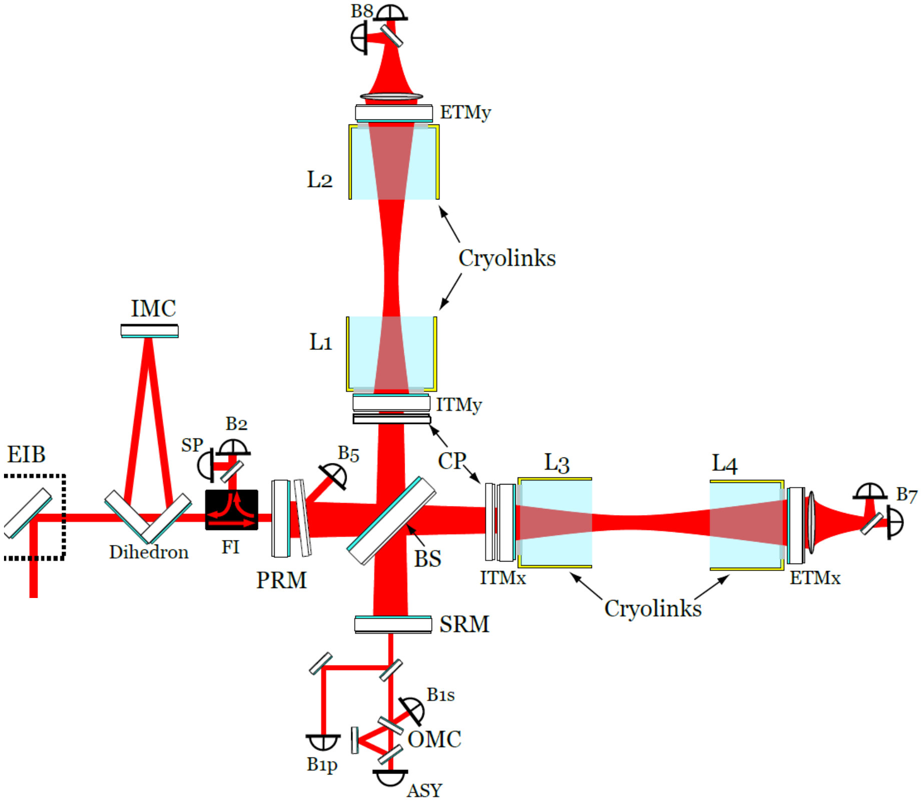
Four cryogenic links installed and commissioned. Advanced Virgo requires an ultra-high vacuum with pressures below $10^{-9}$ mbar

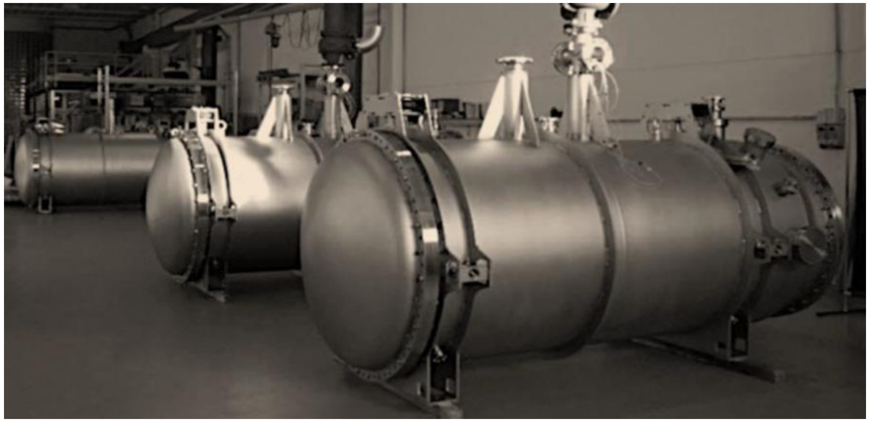
Four LN2 links: $10^{-10}$ mbar region

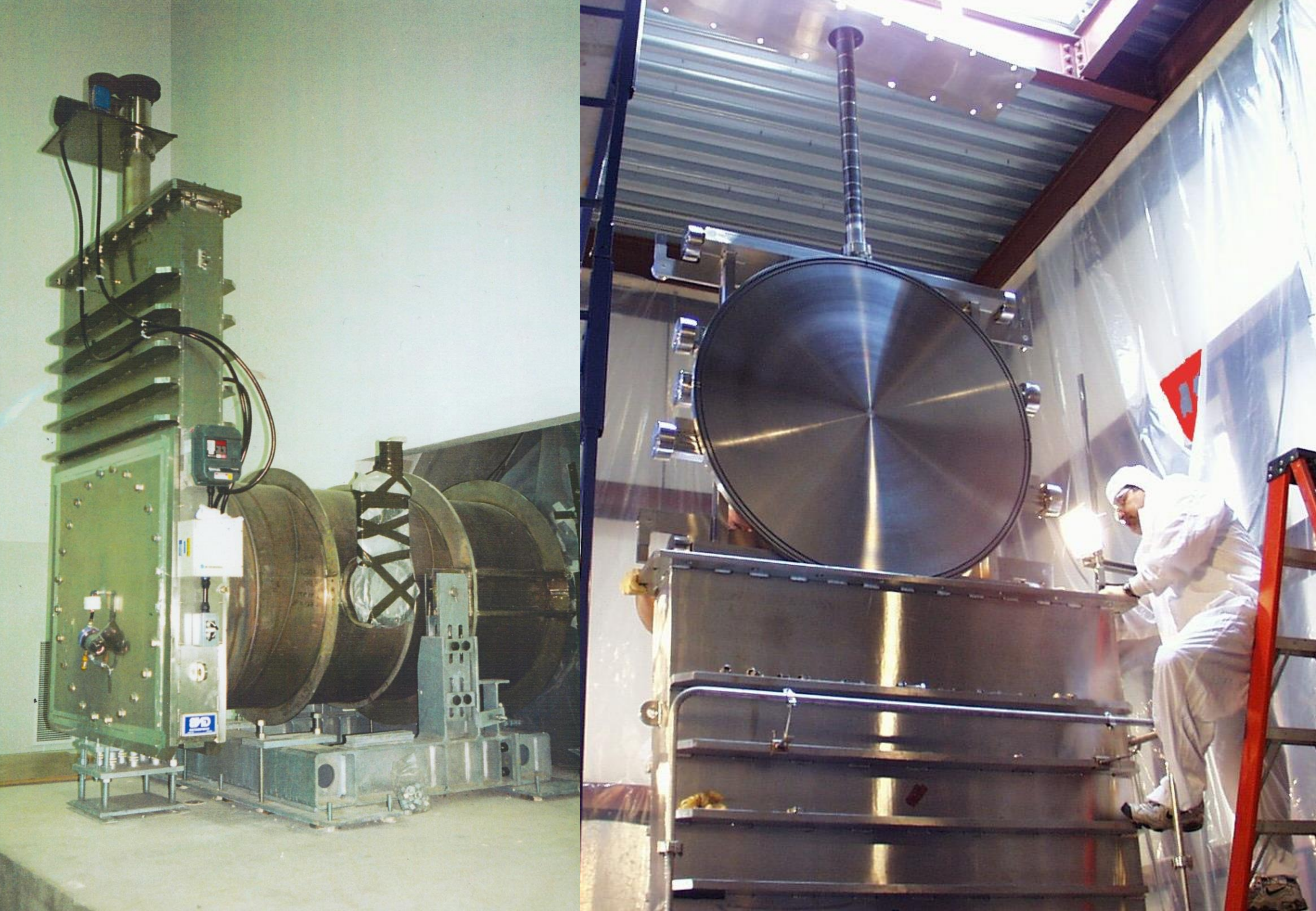
Designed by Nikhef

Involved experts from Demaco

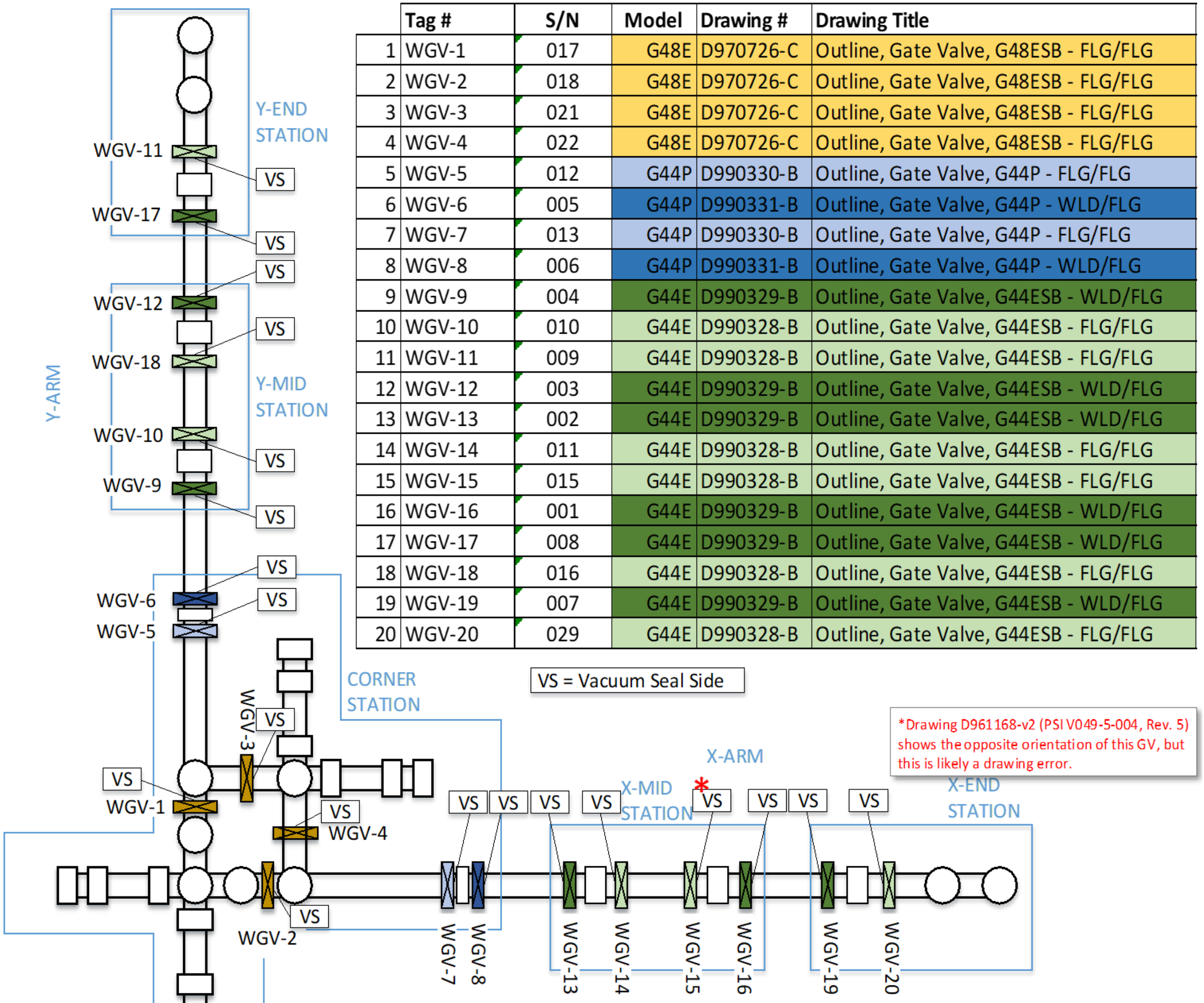
Installed in Virgo and operational







# Layout of vacuum valves



| | Tag # | S/N | Model | Drawing # | Drawing Title |
|---|---|---|---|---|---|
| 1 | WGV-1 | 017 | G48E | D970726-C | Outline, Gate Valve, G48ESB - FLG/FLG |
| 2 | WGV-2 | 018 | G48E | D970726-C | Outline, Gate Valve, G48ESB - FLG/FLG |
| 3 | WGV-3 | 021 | G48E | D970726-C | Outline, Gate Valve, G48ESB - FLG/FLG |
| 4 | WGV-4 | 022 | G48E | D970726-C | Outline, Gate Valve, G48ESB - FLG/FLG |
| 5 | WGV-5 | 012 | G44P | D990330-B | Outline, Gate Valve, G44P - FLG/FLG |
| 6 | WGV-6 | 005 | G44P | D990331-B | Outline, Gate Valve, G44P - WLD/FLG |
| 7 | WGV-7 | 013 | G44P | D990330-B | Outline, Gate Valve, G44P - FLG/FLG |
| 8 | WGV-8 | 006 | G44P | D990331-B | Outline, Gate Valve, G44P - WLD/FLG |
| 9 | WGV-9 | 004 | G44E | D990329-B | Outline, Gate Valve, G44ESB - WLD/FLG |
| 10 | WGV-10 | 010 | G44E | D990328-B | Outline, Gate Valve, G44ESB - FLG/FLG |
| 11 | WGV-11 | 009 | G44E | D990328-B | Outline, Gate Valve, G44ESB - FLG/FLG |
| 12 | WGV-12 | 003 | G44E | D990329-B | Outline, Gate Valve, G44ESB - WLD/FLG |
| 13 | WGV-13 | 002 | G44E | D990329-B | Outline, Gate Valve, G44ESB - WLD/FLG |
| 14 | WGV-14 | 011 | G44E | D990328-B | Outline, Gate Valve, G44ESB - FLG/FLG |
| 15 | WGV-15 | 015 | G44E | D990328-B | Outline, Gate Valve, G44ESB - FLG/FLG |
| 16 | WGV-16 | 001 | G44E | D990329-B | Outline, Gate Valve, G44ESB - WLD/FLG |
| 17 | WGV-17 | 008 | G44E | D990329-B | Outline, Gate Valve, G44ESB - WLD/FLG |
| 18 | WGV-18 | 016 | G44E | D990328-B | Outline, Gate Valve, G44ESB - FLG/FLG |
| 19 | WGV-19 | 007 | G44E | D990329-B | Outline, Gate Valve, G44ESB - WLD/FLG |
| 20 | WGV-20 | 029 | G44E | D990328-B | Outline, Gate Valve, G44ESB - FLG/FLG |

VS = Vacuum Seal Side

*Drawing D961168-v2 (PSI V049-5-004, Rev. 5) shows the opposite orientation of this GV, but this is likely a drawing error.

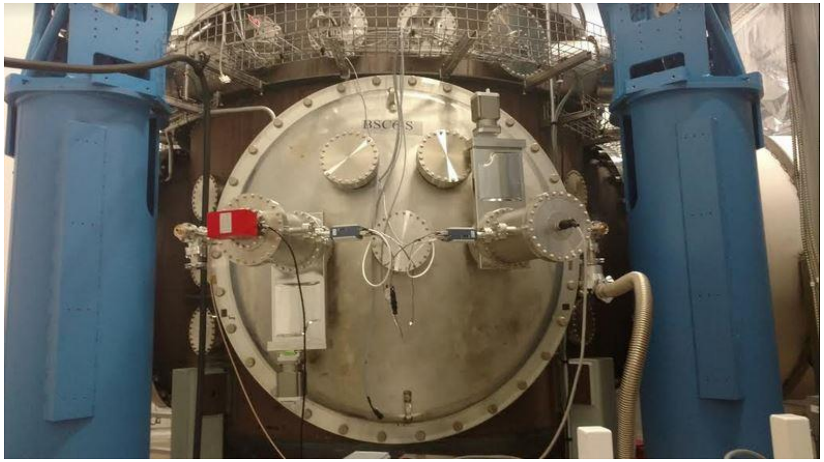
D1600164-v1, Gate Valve Designations, Locations, Orientations and Quantities
Sheet1: LHO

# Pumping of non-condensable gases

Maglev turbos for initial evacuation only

Ion pumps assisted by NEGs in normal operation

**NO rotating or vibrating machinery** allowed during interferometer operation



# Beam tubes

# LIGO beam tube

Volume: 9000 m$^3$

Surface area: 30,000 m$^2$

50 km of spiral welds

Vacuum pressure: ~10$^{-9}$ Torr

Budget

$ 40M (1997)

$ 2500/m

$ 50/lb

# Beam tubes

304L SSt, 3.2 mm thick with external stiffeners

Raw stock air baked 36h @ 455C

**Final $J_{H2}$ < 1e-13 Tl/s/cm$^2$**

Coil spiral-welded into 1.2m tube 16m long

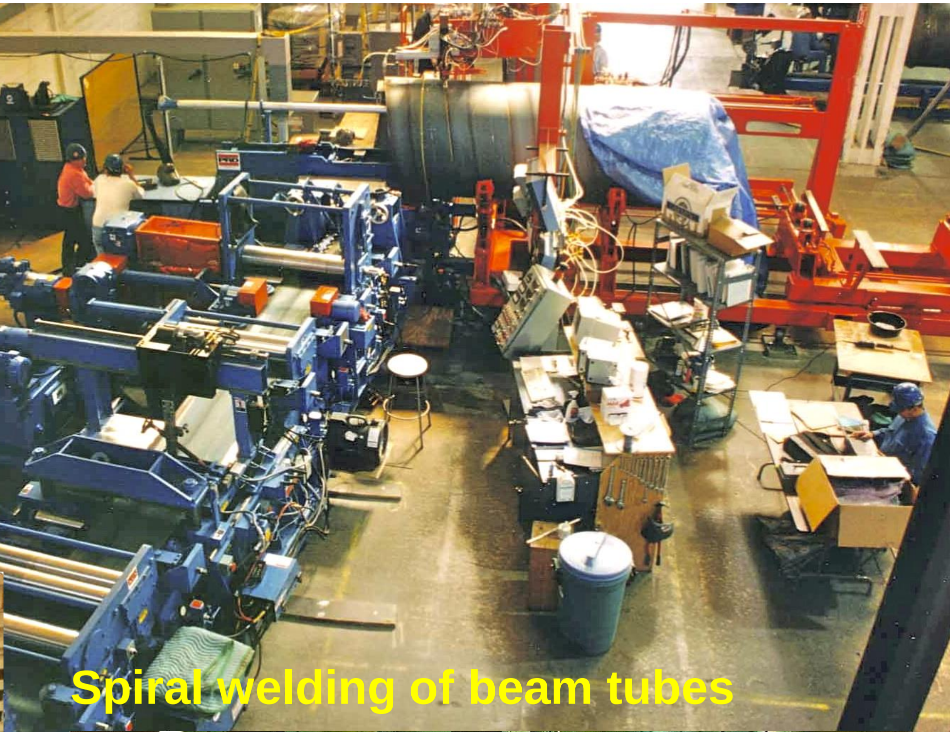
**method adapted from sewer pipe industry**

16 m sections cleaned, leak checked

FTIR analysis to confirm HC-free

Sections field butt-welded together in travelling clean room

Over 50 linear km of weld



**Spiral welding of beam tubes**

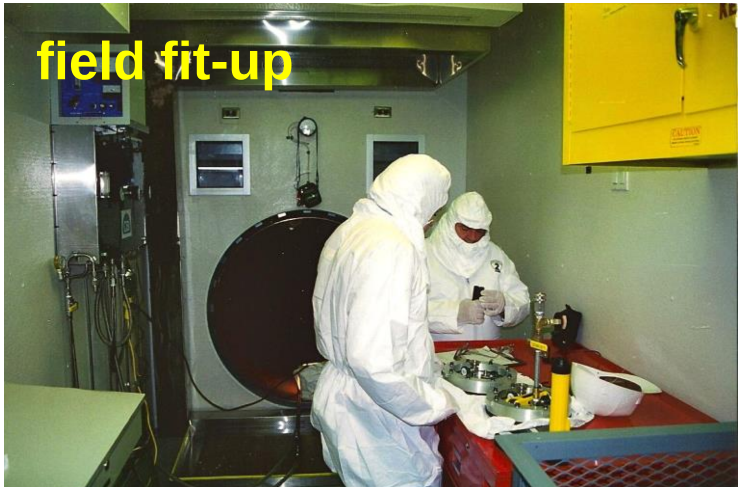
**Reinforcement ribs**

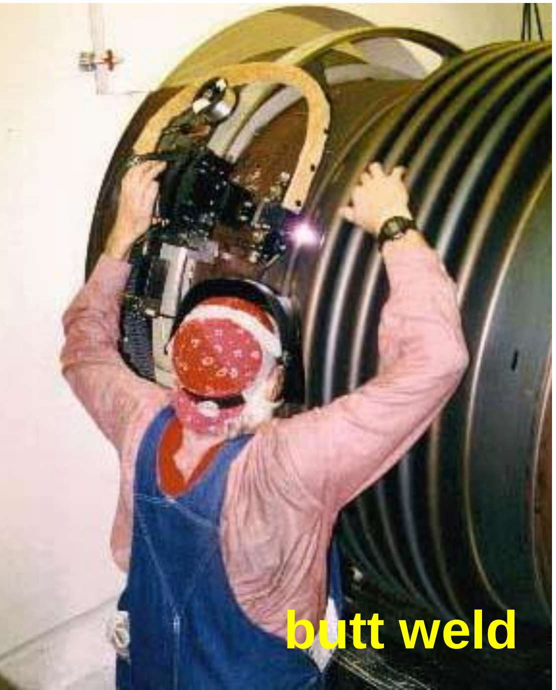
**Leak test “coffin”**

# Beam tube field assembly


transport


position


field fit-up


butt weld


leak check

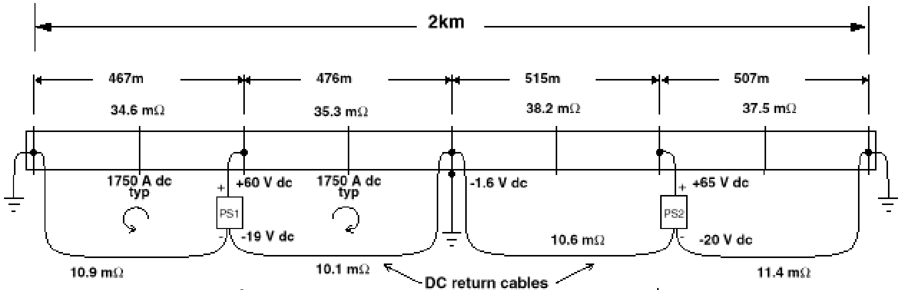

next section

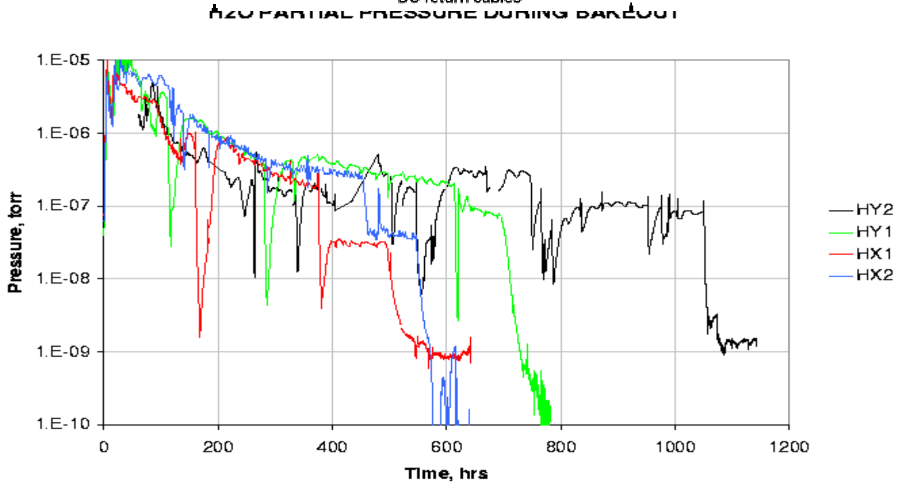
# $I^2R$ bake-out to desorb water

DC current of 2,000 A

3 weeks @ 160ºC

Final outgassing:
$J_{H20} < 2e\text{-}17$ Tl/s/cm$^2$





# Hindsight, and what should be done differently

# Positive experience

Low-hydrogen steel air-bake process

Spiral-welded tube construction (with aggressive QA)

$I^2R$ bake-out heating

Modular chamber

Soft-wall modular cleanrooms for installation

Dual differentially-pumped O-rings on large flanges

Passive $LN_2$ cryo-traps

Ion pumps

Two highly proficient and cooperative subcontractors
- Chicago Bridge and Iron (beam tubes)
- Process Systems International (vacuum equipment)

# Not so positive experience …

Large gate valves

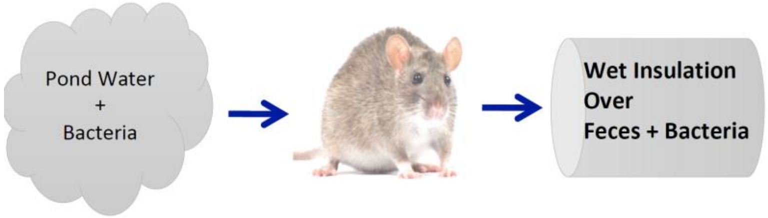
- Have had two develop bizarre leakage through stem
- Serious and increasing concerns about fragility of the mechanism

Microbial-induced corrosion

- Leaks caused by SSt-eating bacteria in Louisiana
- Tube environment was not climate-controlled
- Vermin and moisture "disease vectors"

But LIGO's biggest regret of all is…

Budget constraints left LIGO no standing provision to vent, re-evacuate and re-bake beam tubes in case of future contingency



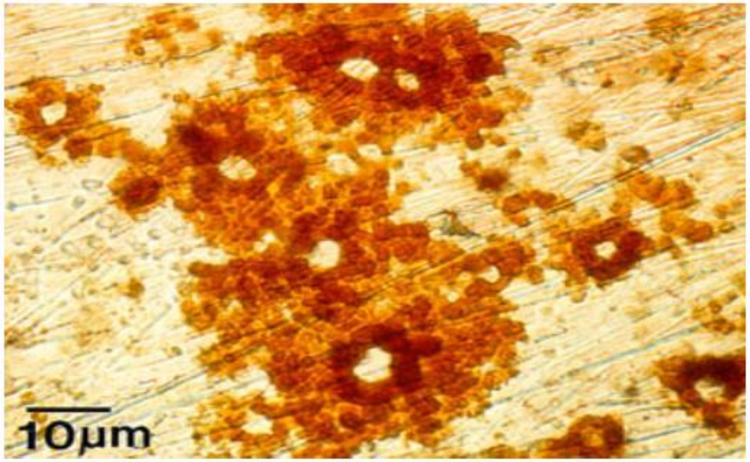
Pond Water
+
Bacteria

→

→

Wet Insulation
Over
Feces + Bacteria

Exterior wall of vacuum beam tube



Interior wall of vacuum beam tube

Credit: D.P. Henkel, RIMKUS – Consulting group

# Overview of possibilities for joint research

Slides to guide discussion

First attempt, so likely incomplete …

# Timeline Einstein Telescope

| | |
|---|---|
| Sites qualification | now – 2023 |
| ESFRI proposal submission | 2020 |
| ESFRI decision | 2021 |
| Site decision | 2023 |
| Research infrastructure operational design | 2023 – 2025 |
| Research infrastructure construction | 2026 – 2032 |
| Detector installation | 2030 – 2034 |
| Operation | 2035 |

# Exploratory topics for lowering the cost

**Options for reducing the cost of conventional vacuum pipe technology**

- Novel surface treatment techniques for conventional and non-conventional materials
- Meeting contaminant and $H_2O$ outgassing requirements

**Nested vacuum systems**

- Gettering options within the UHV sections of vacuum pipe
- Maintaining differential pressures with nested systems

# Conventional vacuum pipe technology

## Geometry for Einstein Telescope

- Configuration - Single-wall metal tube
- Diameter – About 1 m
- Arm length – 10 km per arm (6 interferometers with 2 arms each …)

## Material Choices

- Austenitic stainless steel (304L) well understood and was chosen for LIGO and Virgo
- Carbon Steel referred to as “mild steel” or “plain carbon steel,” proposed as a lower-cost alternative to stainless steel.
  - It could be attractive seen the case of steel produced through Ruhrstahl-Heraeus vacuum process during steel refining, resulting in low hydrogen content and extremely low hydrogen outgassing. Important factors must be considered: deoxidizing, grain size and shape (hot rolled or cold rolled), hardenability, weldability, inclusion content
  - Appropriate surface treatment needs to be developed to avoid rusting and other forms of corrosion and to prevent water adsorption. Both plasma deposition and wet chemistry deposition of various coatings should be investigated to find the optimum type of coating

**Given the large amount of material required, there is an opportunity to go beyond commercially available carbon steels**

# Two concentric tube design

Independent inner and outer vacuum tubes

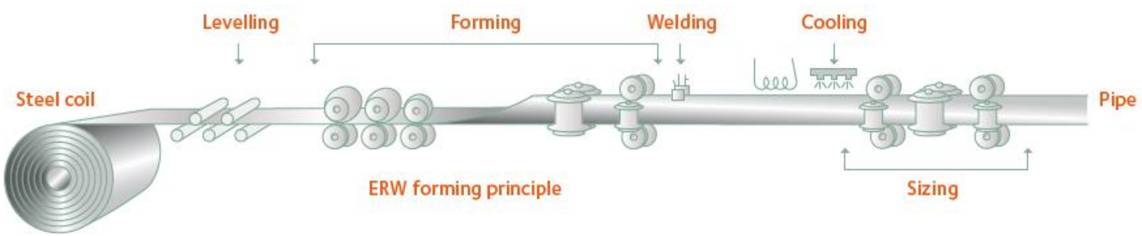
Sealed inner UHV vacuum tube, concentrically disposed inside an independent outer “guard” vacuum tube

Discuss with **coating suppliers and manufacturers.** TiN and DLC coatings seem promising. Use to **reduce corrosion by creating barrier layers** against incoming oxidizing species at the surface. These barriers may reduce the outgassing of lighter molecular gases released from the deeper metal layers

Development of such a process would require a cooperative arrangement between industry, steel-mill and research labs! Potential advantages for Einstein Telescope and for the companies involved in a new technological development

# Production optimization

## Local construction facility at Einstein Telescope site



Courtesy of SCC Nigeria

Courtesy of Corinth Pipeworks

Courtesy of Corinth Pipeworks (Greece)

SAWH API 5L pipes being inspected during the coating operation.

Pickled and oiled coils ready for overseas shipment (Fos-sur-Mer)

Facilities

Bremen, Fos-sur-Mer and Krakow

# Thanks for your attention! Questions?