The quest for Gravitational Waves:

Status of ground based projects

Federico Ferrini
EGO

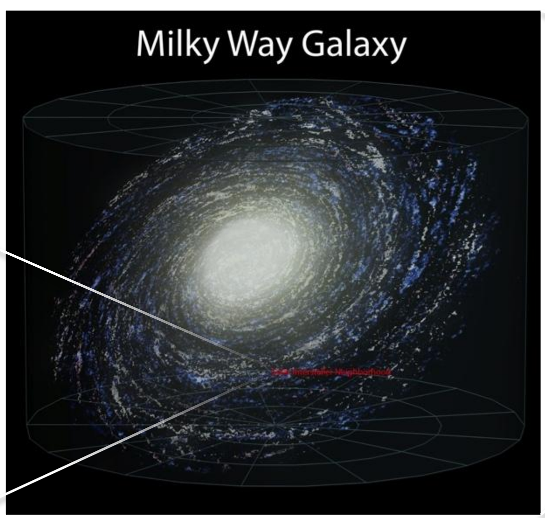
With contributions from

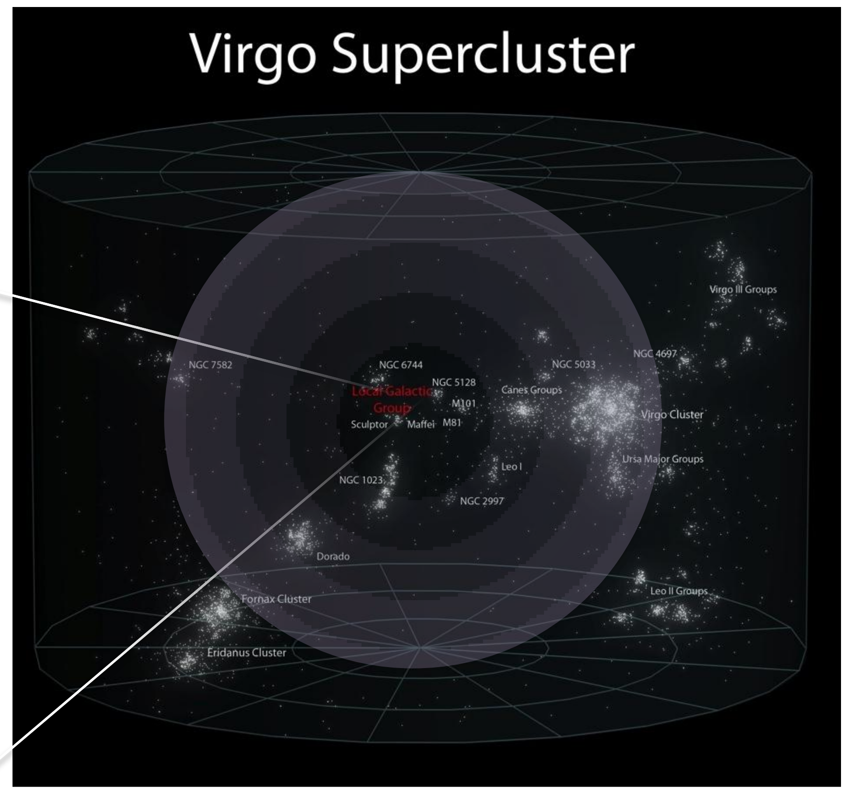
H. Grote – GEO
T. Kajita – KAGRA
B. Iyer – IndIGO
D. Shoemaker – LIGO

No Detections Yet… Why not?

- First generation detectors reached about 100 galaxies
- Events happen once every 10,000 years per galaxy…
- Need to reach more galaxies to see more than one signal per lifetime

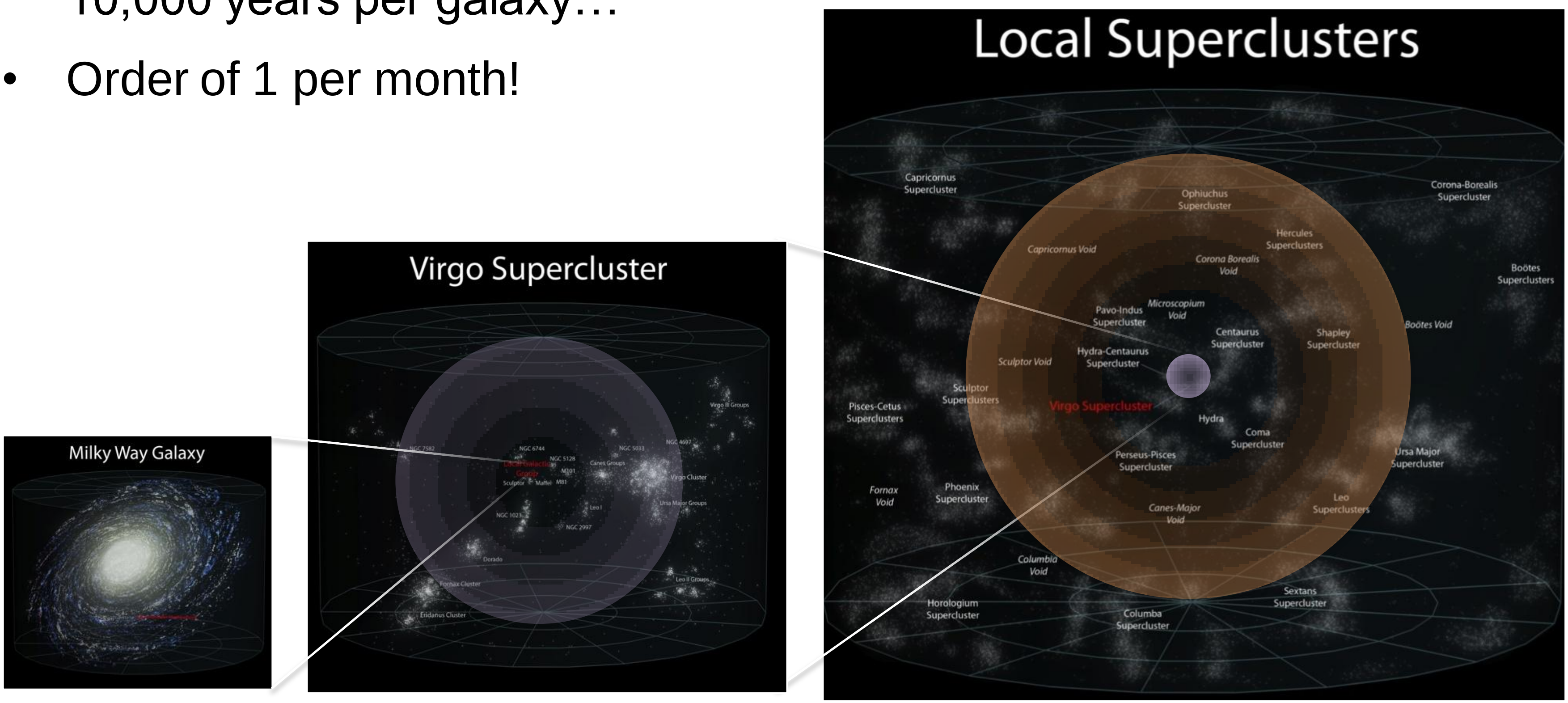
(considering NS-NS mergers)



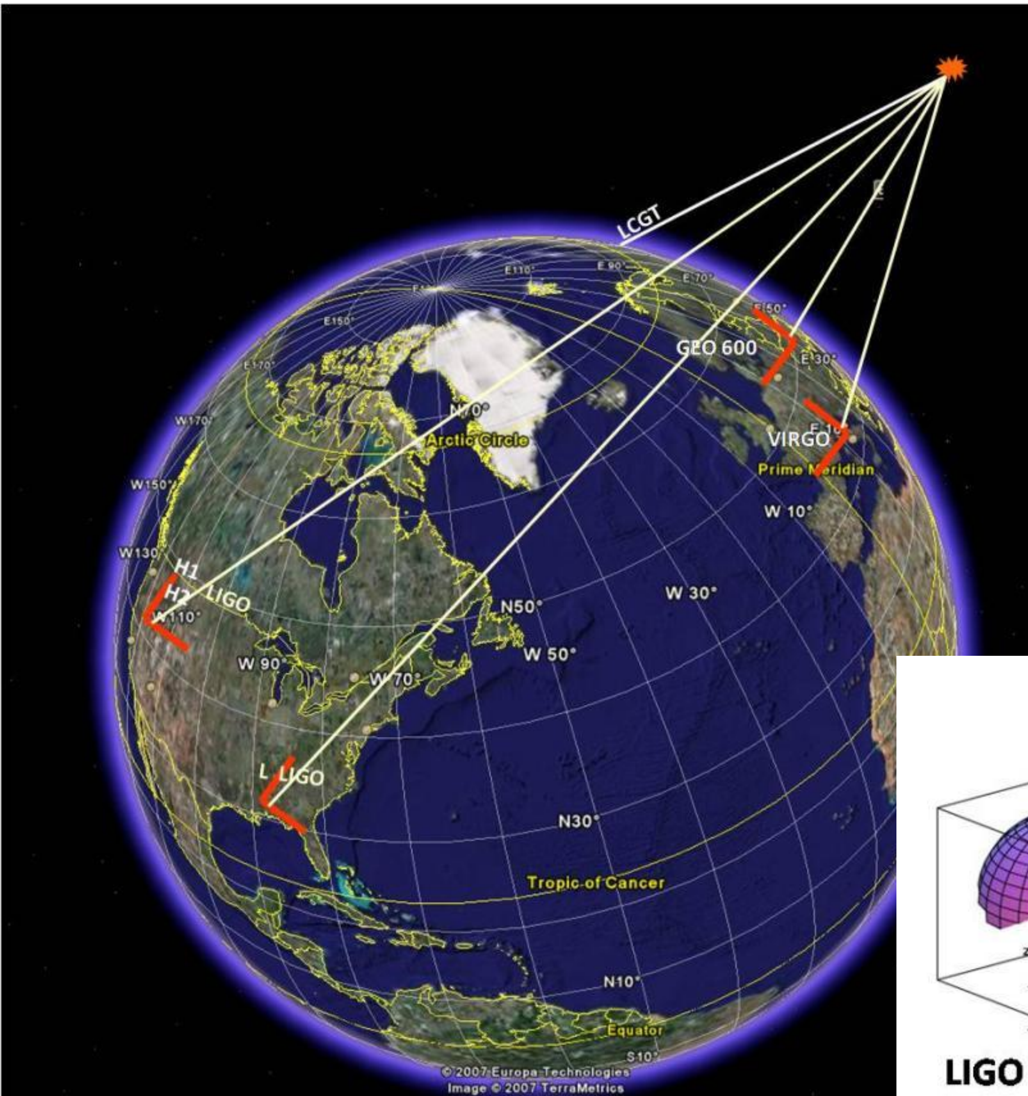


Advanced Sensitivity:
10x More Range makes a qualitative difference

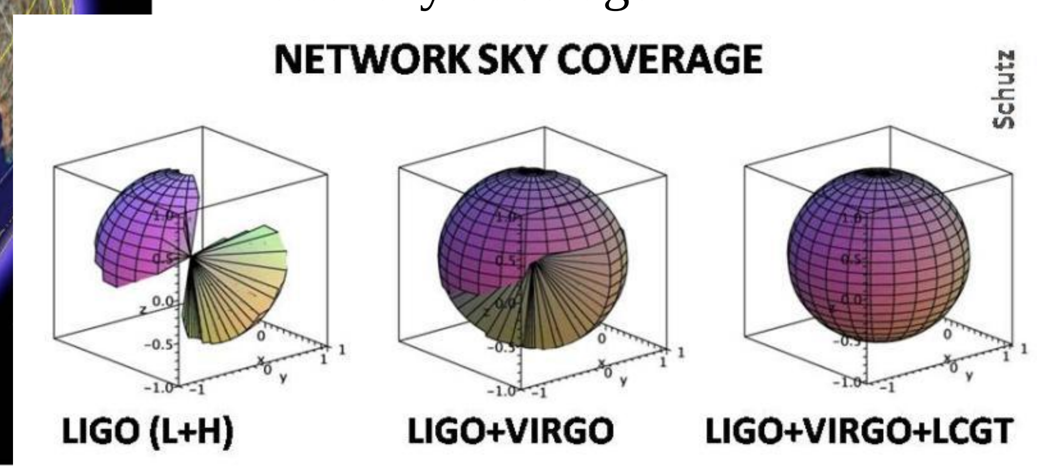
- Advanced detectors will reach about 100,000 galaxies
- Events happen once every 10,000 years per galaxy…
- Order of 1 per month!



The search for GW signal emitted by a binary system (NS-NS) requires a network of (distant) detectors

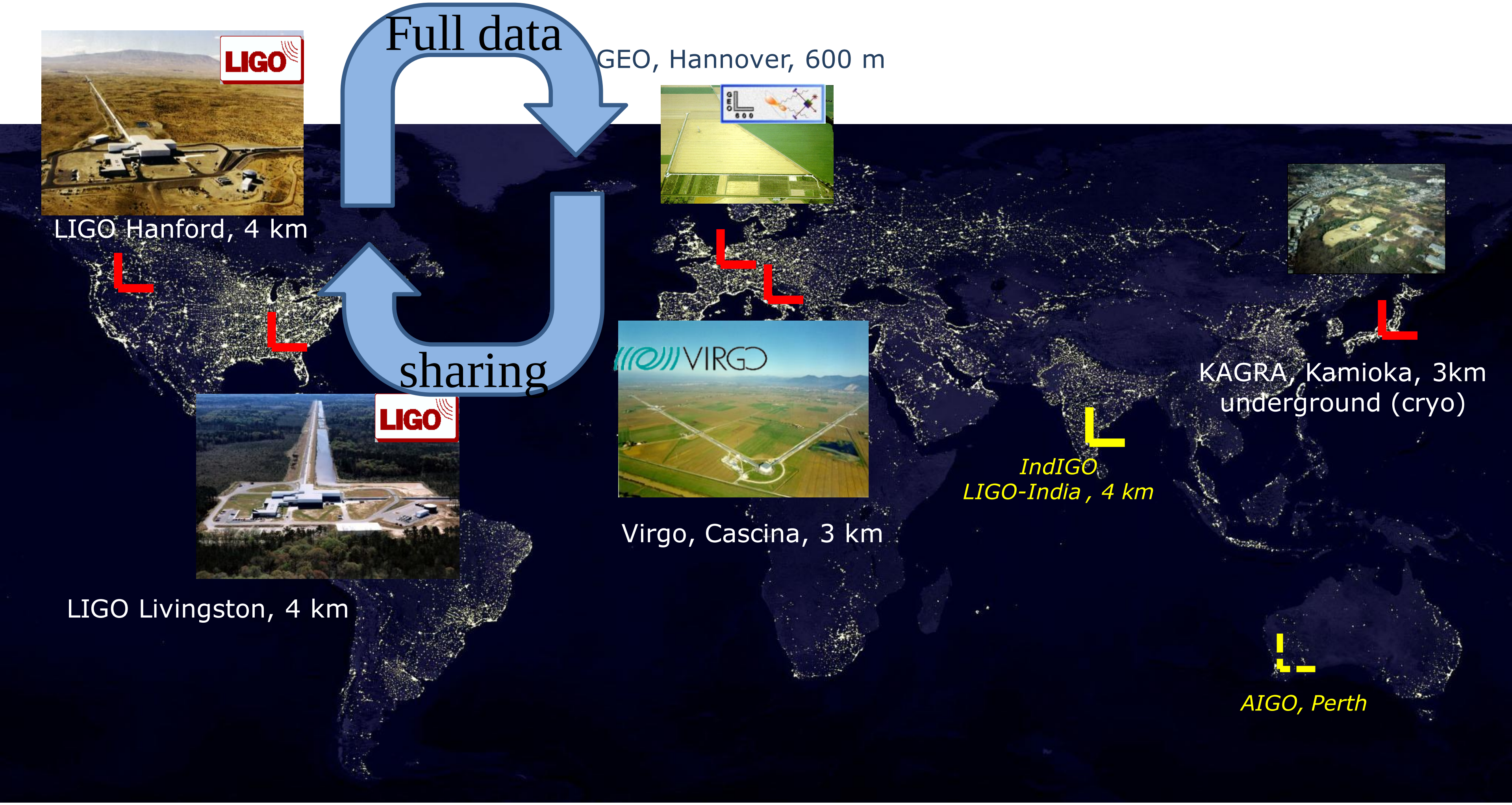


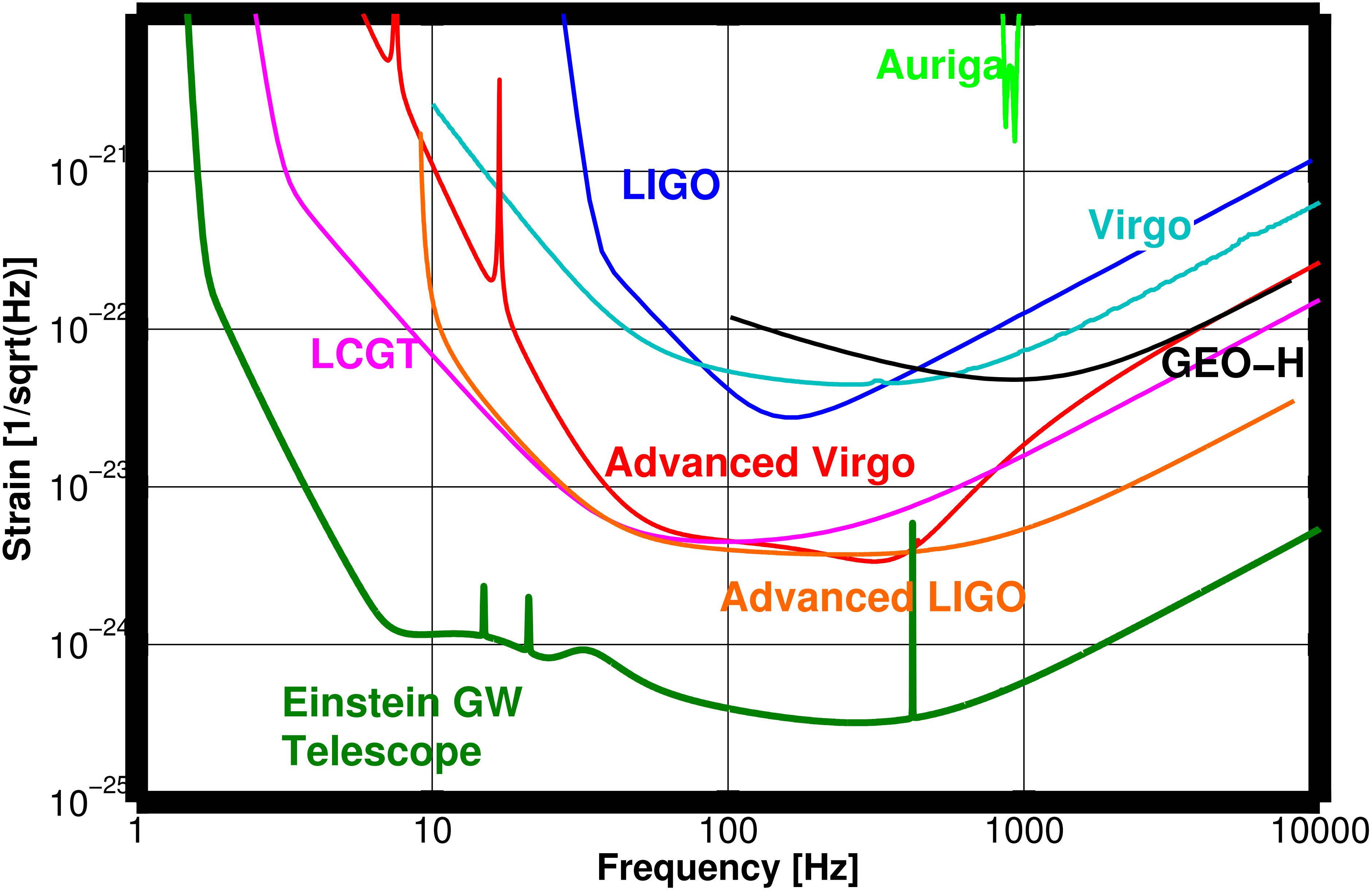
- Event reconstruction
  - Source location in the sky
  - Reconstruction of polarization components
  - Reconstruction of amplitude at source and determination of source distance (BNS)
- Detection probability increase
- Detection confidence increase
- Larger uptime
- Better sky coverage



GW interferometric detectors

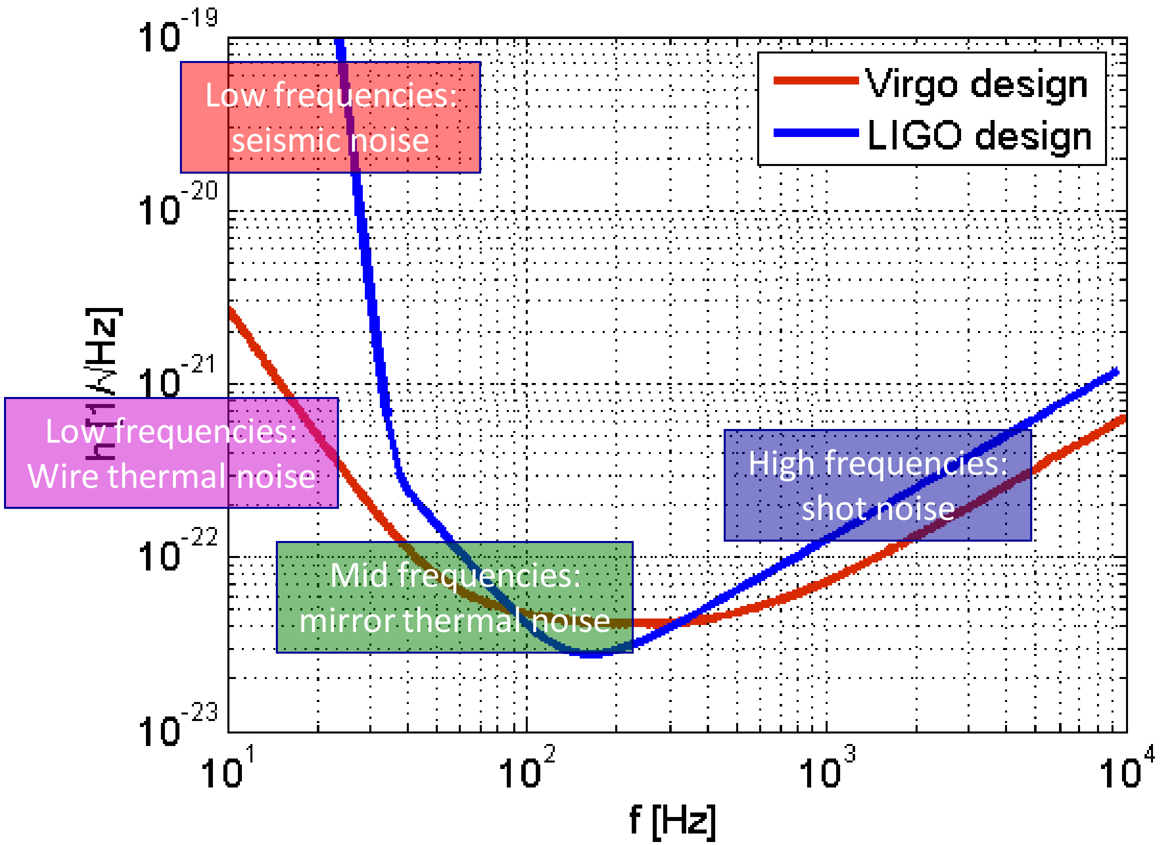
- A network of detectors be active in the World





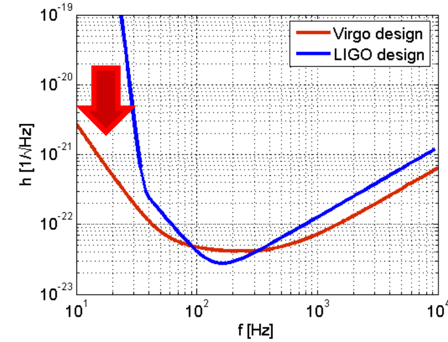
Auriga
LIGO
Virgo
LCGT
GEO−H
Advanced Virgo
Advanced LIGO
Einstein GW Telescope
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Strain [1/sqrt(Hz)]
1
10
100
1000
10000
Frequency [Hz]

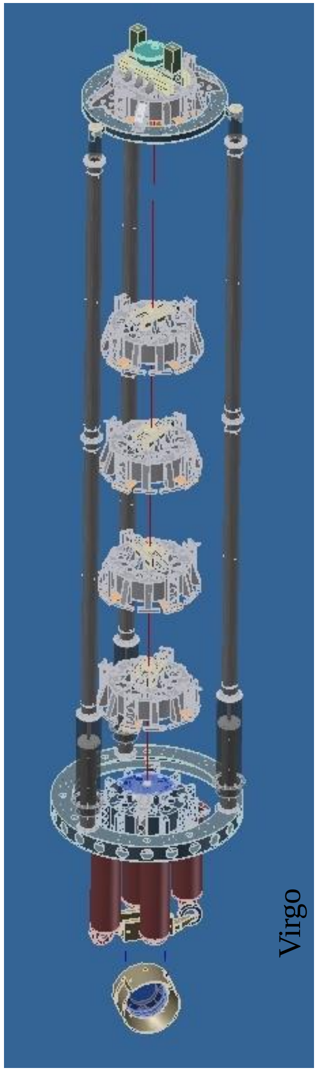
BEYOND THE LIGO/VIRGO SENSITIVITY

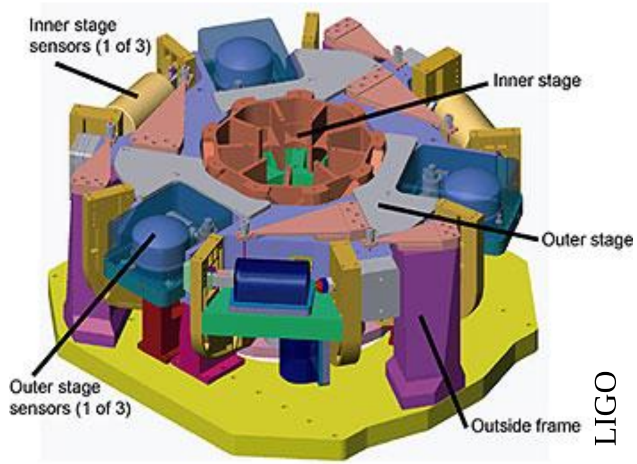


Which ideas/technologies to gain a factor 10 in sensitivity?

FREE TEST MASSES



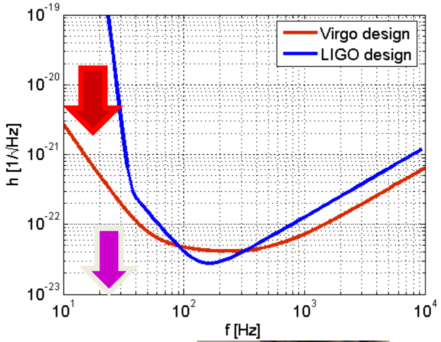




LIGO

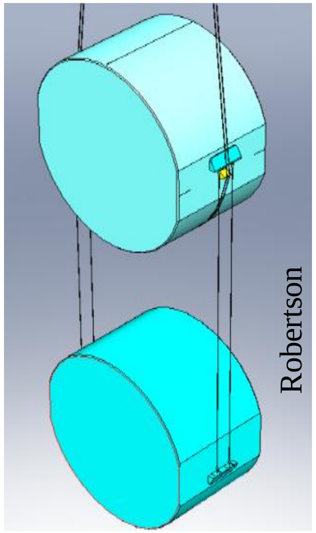
- Virgo test masses are currently suspended from a vibration isolator compliant with 2nd generation
- LIGO has developed a new active system (most of seismic suppression achieved by feedback)
- Both detectors will work with a lower cutoff at ≈10 Hz

LOW FREQUENCY RANGE

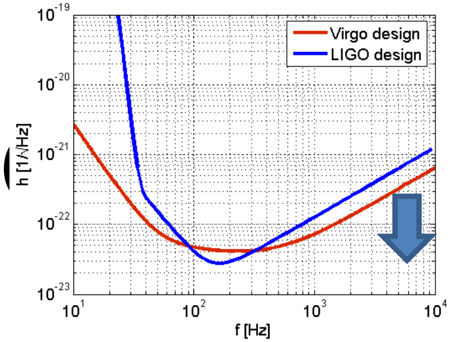


MAIN SCIENCE TARGETS: BH/BH binaries, pulsars

- Sensitivity limited by thermal noise in wires suspending the mirrors (now steel wires)
- SOLUTION: use low dissipation materials (fused silica: 1000x better than steel, 30x improvement in thermal noise)
- Fused silica suspensions pioneered by GEO600
- Long R&D activity in the community to engineer the solution
  - Fiber geometry
  - Welding to mirrors
  - Assembly procedure
  - Robustness issues
- Monolithic payload to be tested on Virgo in 2010 (TBC, risk reduction in view of Advanced Virgo)

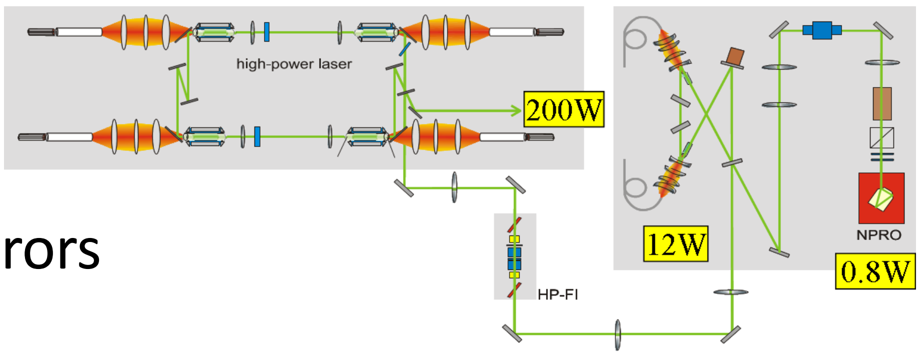


HIGH FREQUENCY RAN



MAIN SCIENCE TARGETS: Supernovae

- Sensitivity limited by laser shot noise
- SOLUTION: increase laser power
- Available technology: solid state laser providing up to 200 W developed at Laser Zentrum Hannover (GEO600)
- High power drawbacks:
  - Radiation pressure noise
  - Thermal effects in the mirrors
- Drawbacks mitigation
  - Heavier mirrors
  - Thermal Compensation System (TCS)



GEO600

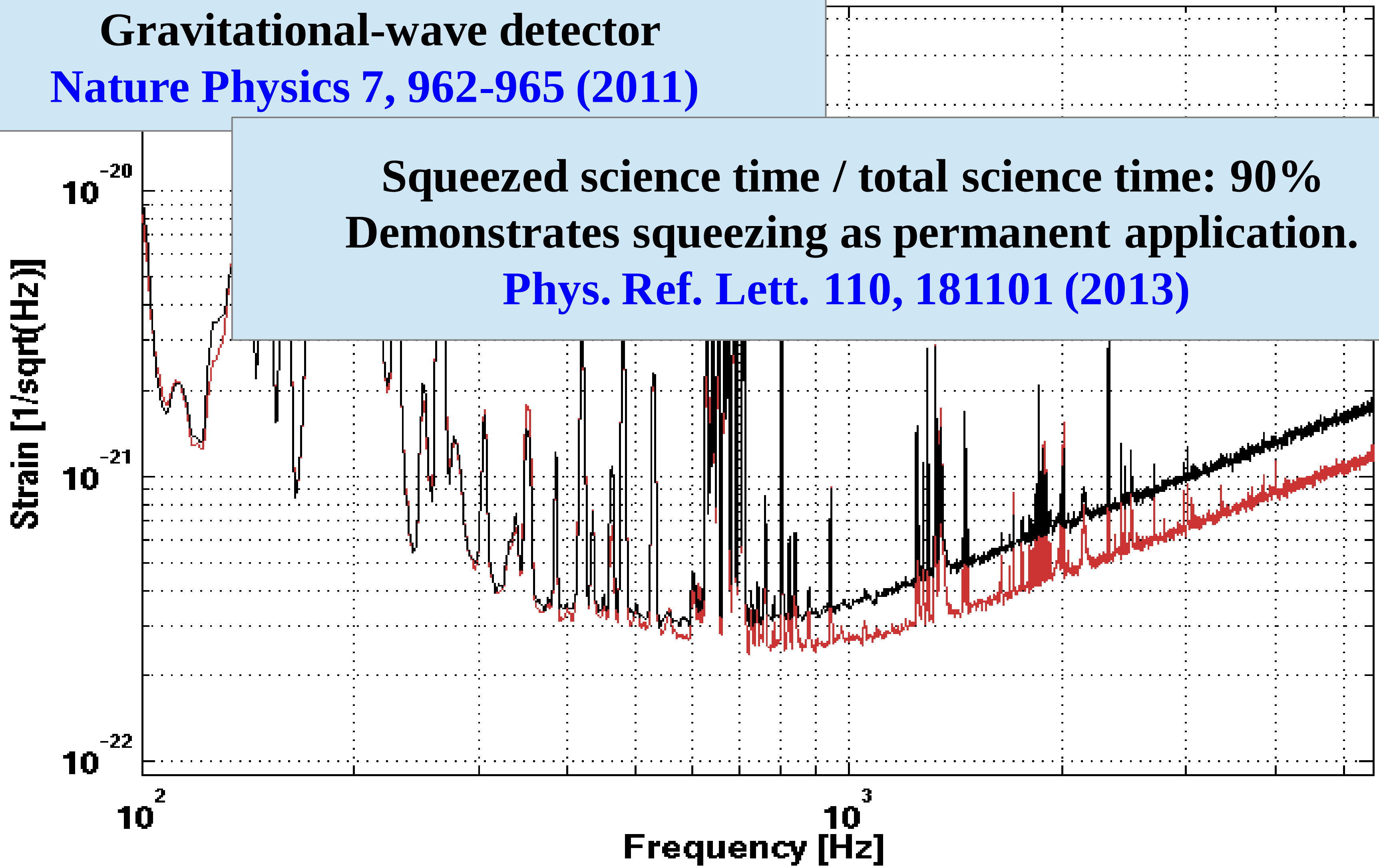
- German-British (+ Spain) collaboration, location Hannover / Germany

GEO600: The First Gravitational Wave Detector using Squeezed Light!

Squeezing: up to 3.5dB yet

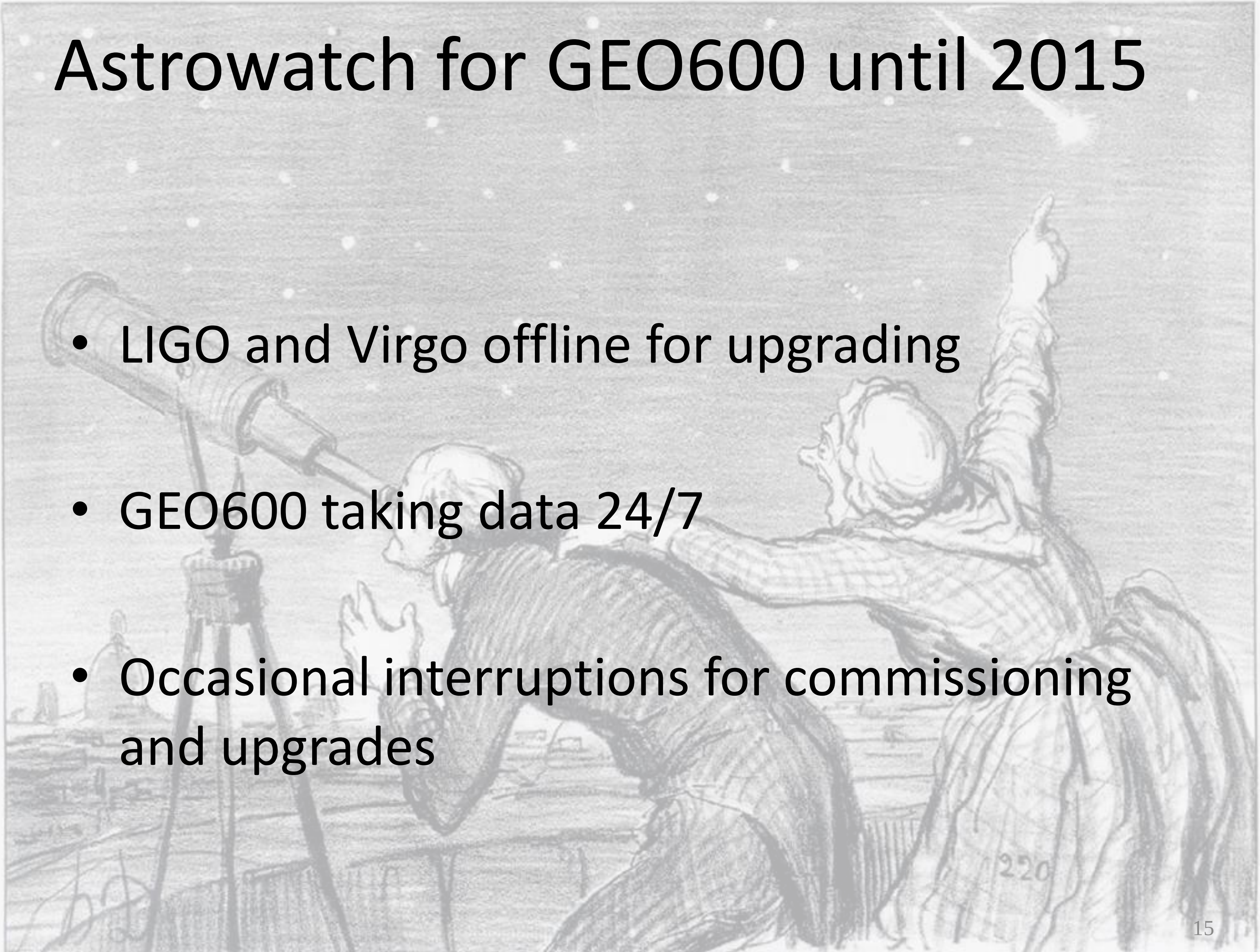
First demonstration of squeezing at a Gravitational-wave detector
Nature Physics 7, 962-965 (2011)

Squeezed science time / total science time: 90%
Demonstrates squeezing as permanent application.
Phys. Ref. Lett. 110, 181101 (2013)



Largest Dedicated Computer Cluster in the World for GW Data Analysis at AEI

Astrowatch for GEO600 until 2015

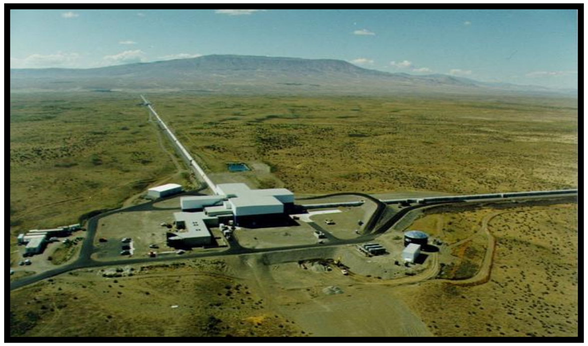


- LIGO and Virgo offline for upgrading
- GEO600 taking data 24/7
- Occasional interruptions for commissioning and upgrades

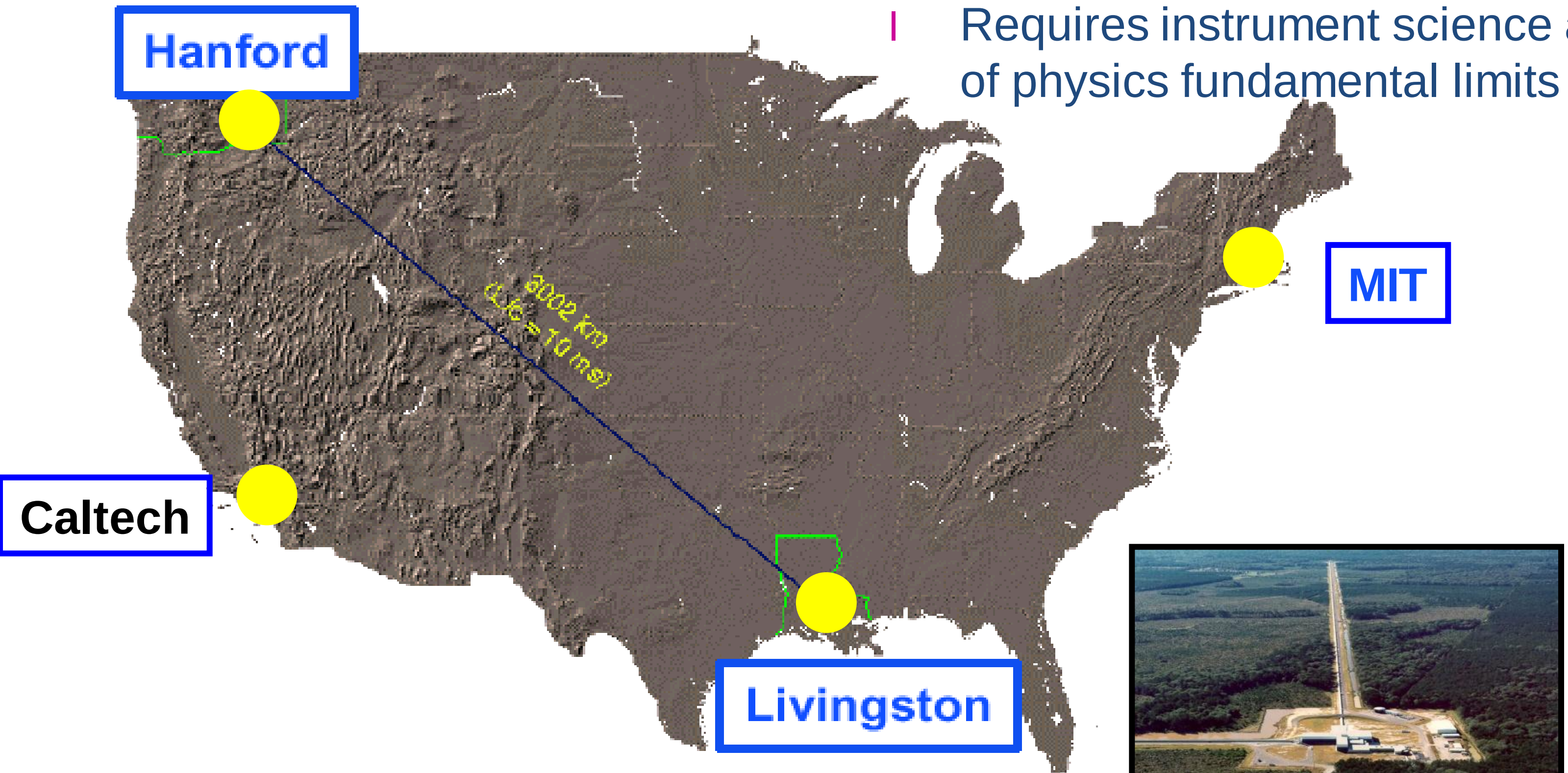
LIGO Scientific Collaboration

LIGO
LSC
Massachusetts Institute of Technology
California Institute of Technology
Leland Stanford Junior University
PennState
University of Glasgow
GEO 600
University of Washington
ACIGA
University of Rochester
Southeastern Louisiana University
Università degli Studi del Sannio
University of Wisconsin Milwaukee
ANU The Australian National University
University of Maryland
UTB TSC
The University of Western Australia
Trinity University
The University of Texas at Austin
Loyola University New Orleans
Andrews University
University of Massachusetts Amherst
UIB Universitat de les Illes Balears
Northwestern University
Syracuse University
NASA Goddard Space Flight Center
PAH
R·I·T
Moscow State University
The University of Adelaide Australia
Cardiff University
Montana State University
Michigan
San José State University
Washington State University
University of Southampton
Tsinghua University
NAOJ
LSU
Embry-Riddle Aeronautical University
The University of Mississippi
Carleton College
California State University Fullerton
University of Minnesota
UF University of Florida
Science & Technology Facilities Council Rutherford Appleton Laboratory
Universität Hannover
University of Strathclyde
Southern University Agricultural & Mechanical College
Hobart and William Smith Colleges
Charles Sturt University
PAN

LIGO Laboratory: two Observatories and Caltech, MIT campuses



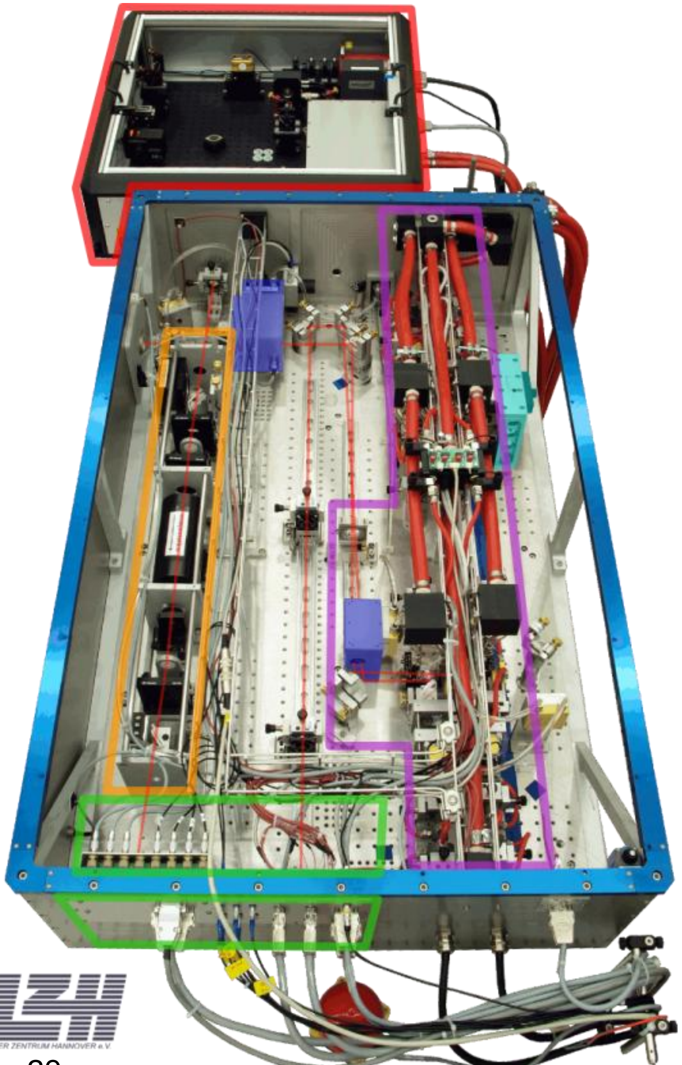
- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits

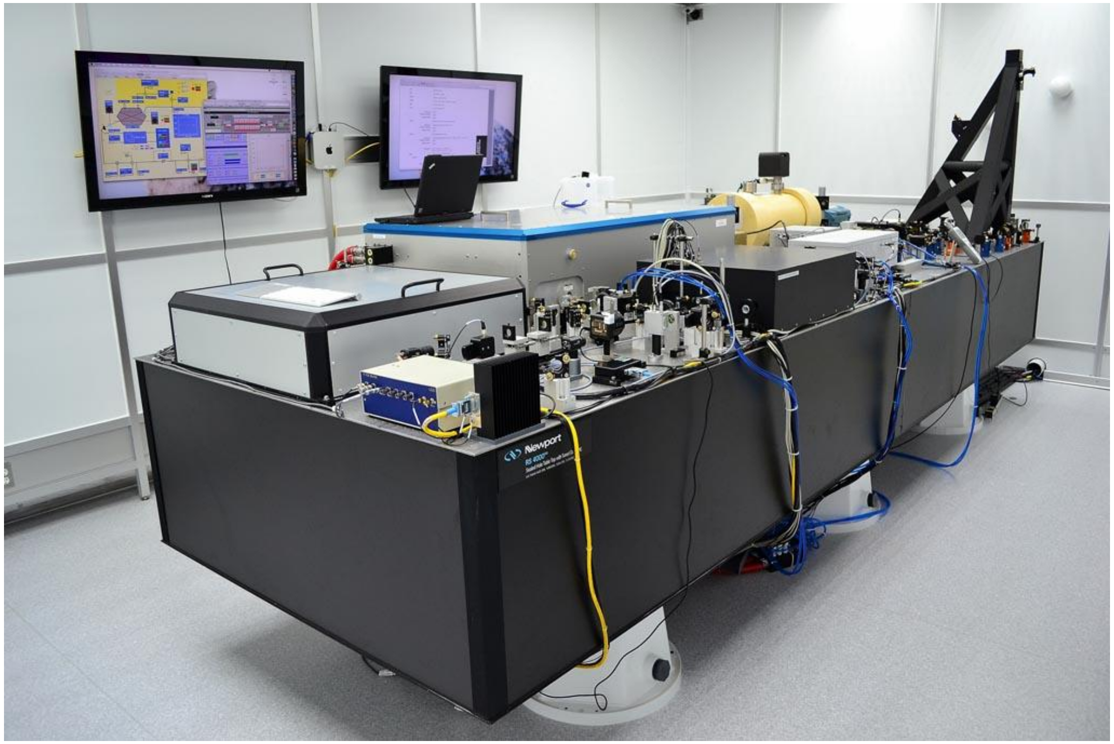


LIGO in Washington state…

…LIGO in Louisiana

200W Nd:YAG laser, stabilized in power and frequency



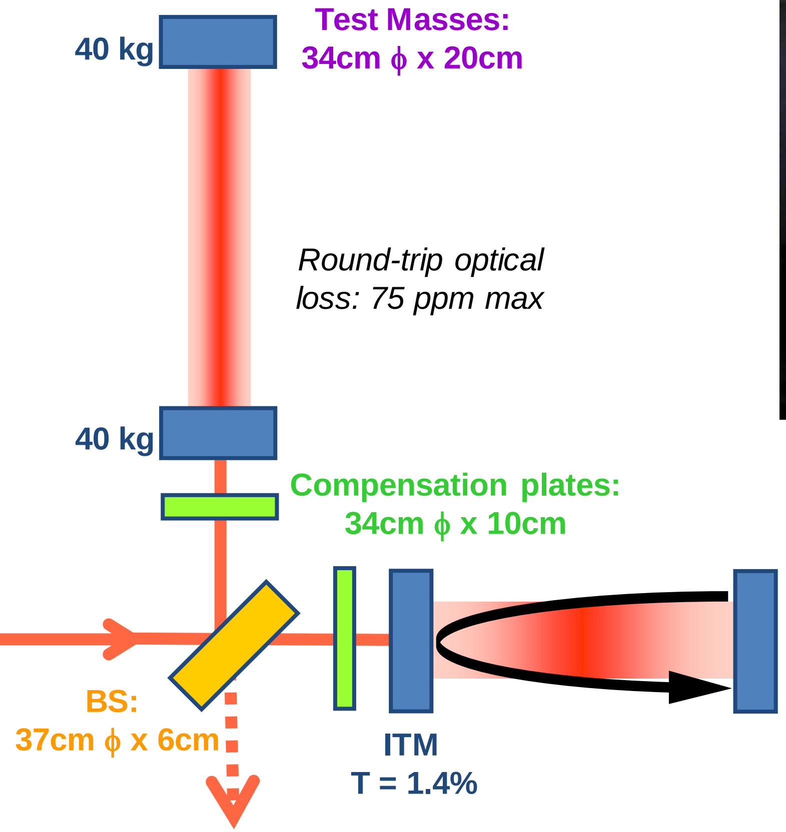


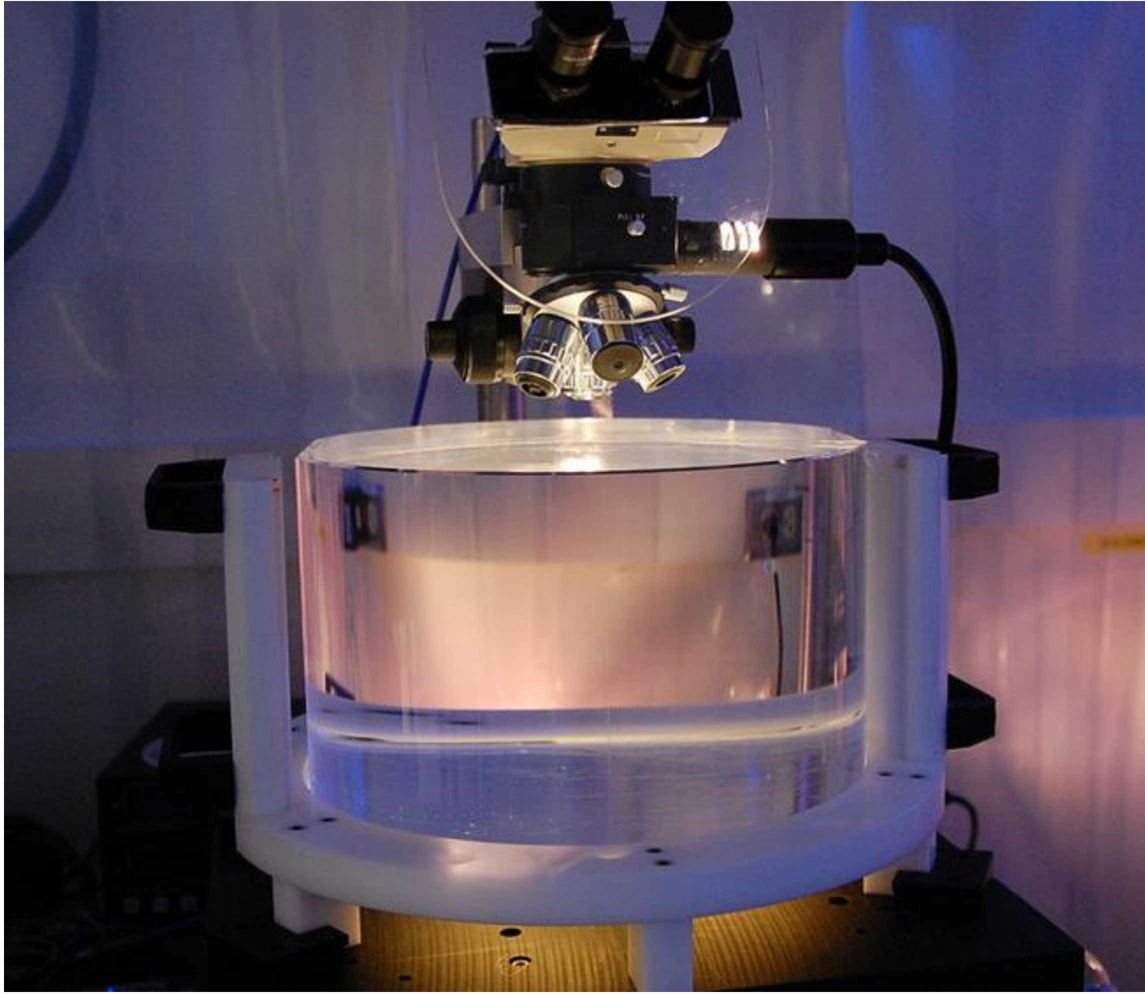
- Designed and contributed by Max Planck Albert Einstein Institute
- Uses a monolithic master oscillator followed by injection-locked rod amplifier

LASER ZENTRUM HANNOVER e.V.

Test Masses

- Requires the state of the art in substrates and polishing
- Pushes the art for coating!

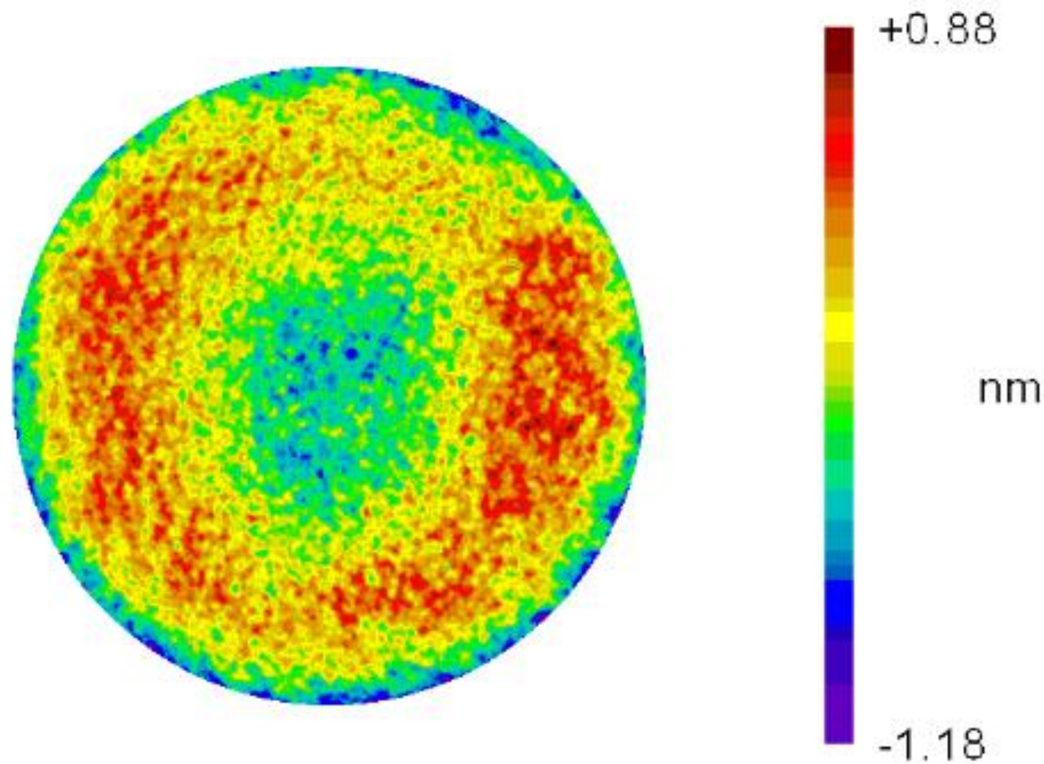




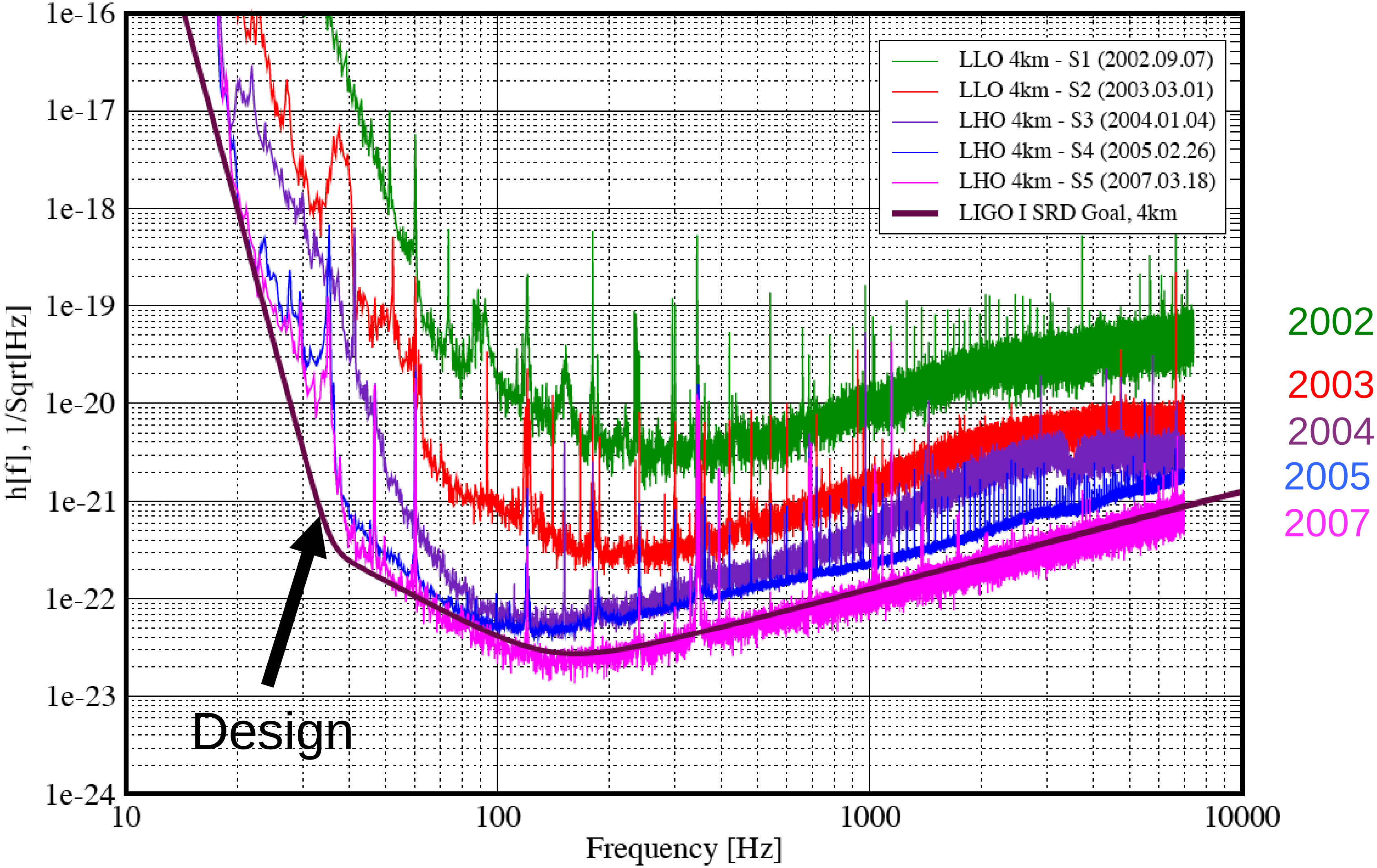
- Both the physical test mass, a free point in space-time, and a crucial optical element
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency
- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

Test Mass Polishing, Coating

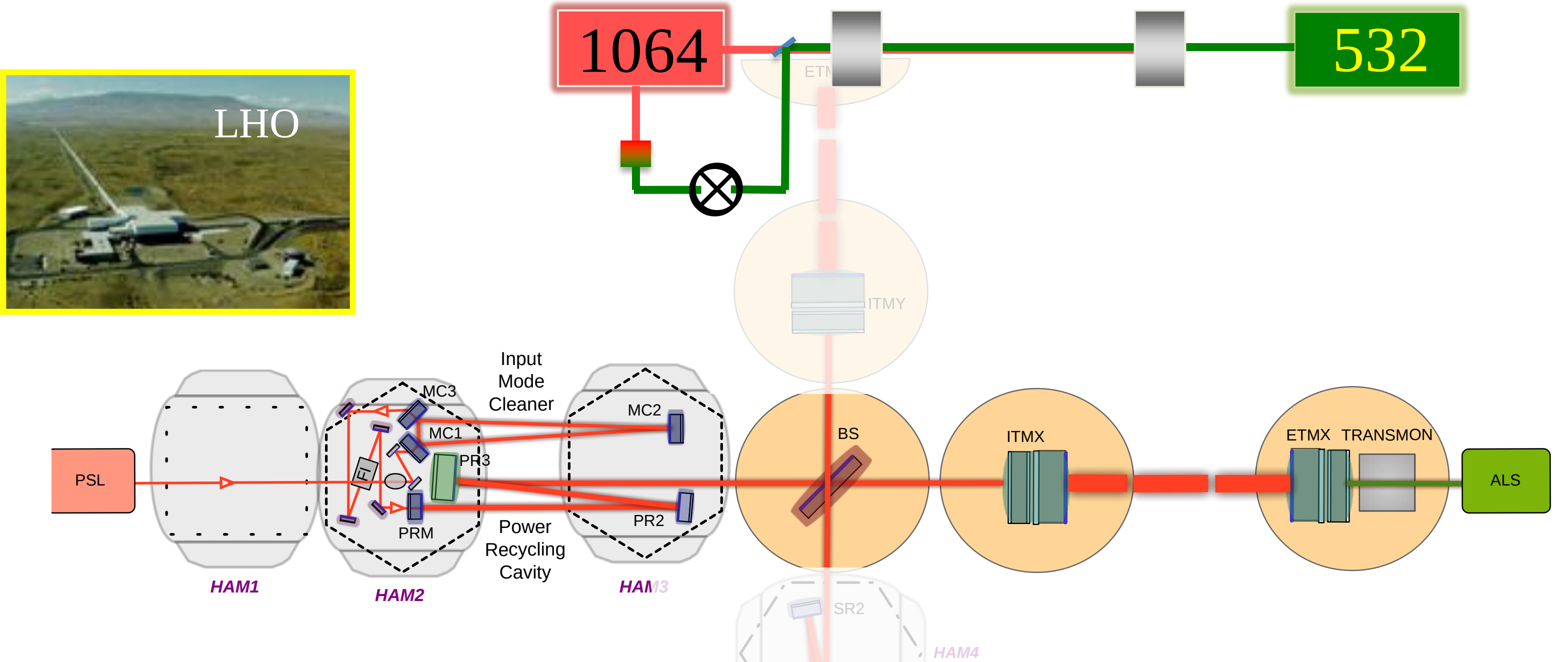
- Heraeus substrates
- Superpolished
- Ion-beam assisted sputtered coatings (LMA Lyon)



Initial LIGO: first lock in 2000 – **7 years to reach goal**



"Half Interferometer" in progress @ Hanford (now one arm, in the fall the other)

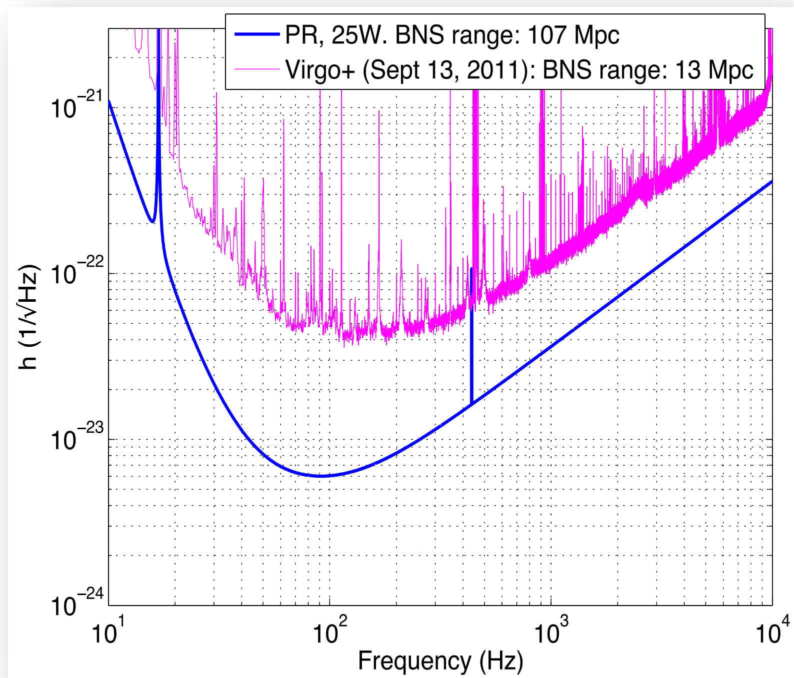


✓Auxiliary green laser to initially stabilize the arm cavity length
✓1.06 micron detection light held precisely on, or off resonance
✓First measurement of arm cavity motion


VIRGO
LAPP – Annecy
NIKHEF – Amsterdam
Radboud Univ. - Nijmegen
RMKI - Budapest
INFN – Firenze-Urbino
INFN – Genova
LMA – Lyon
INFN – Napoli
OCA – Nice
LAL – Orsay
APC – Paris
LKB - Paris
INFN – Padova-Trento
INFN – Perugia
INFN - Pisa
INFN – Roma 1
INFN – Roma 2
POLGRAV - Warsaw
EGO
CNRS, INFN & NIKHEF

2015 CHALLENGE

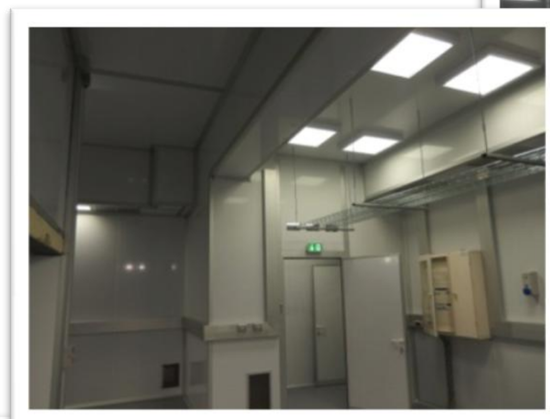
- Start in 2015 with a simplified configuration, similar to Virgo+: likely to reduce commissioning time
  - No signal recycling (reduce locking complexity)
  - Virgo+ laser (up to 60W)
- Target BNS inspiral range: >100 Mpc



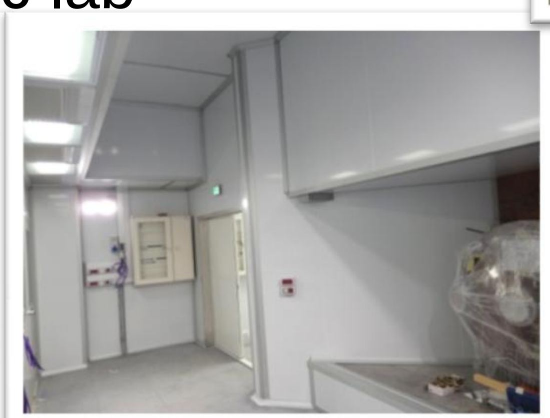
INFRASTRUCTURE

- INJ/DET clean labs
  - civil works completed
  - final details being worked out
  - start-up/tests in 1-2 weeks

DET lab

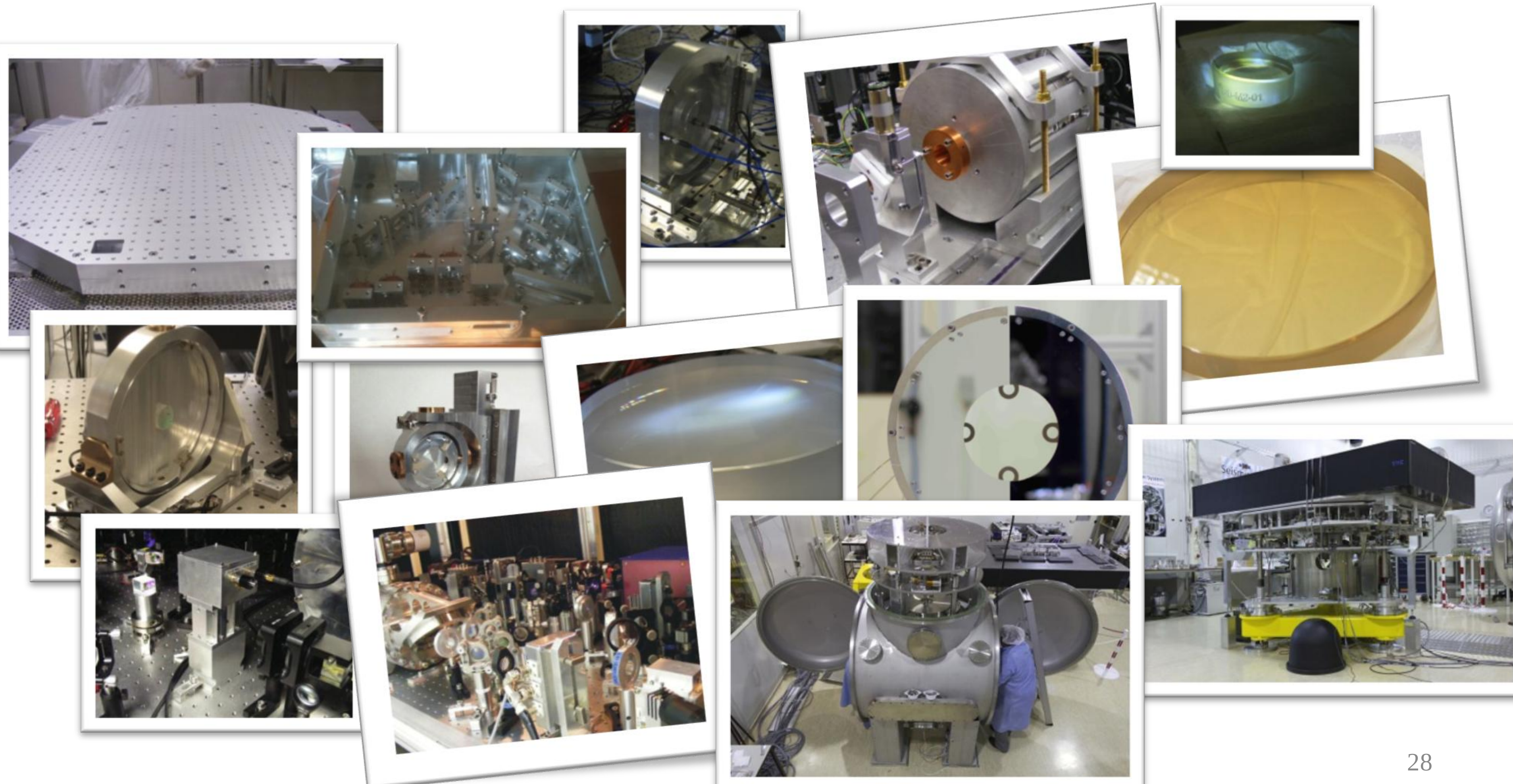


INJ lab

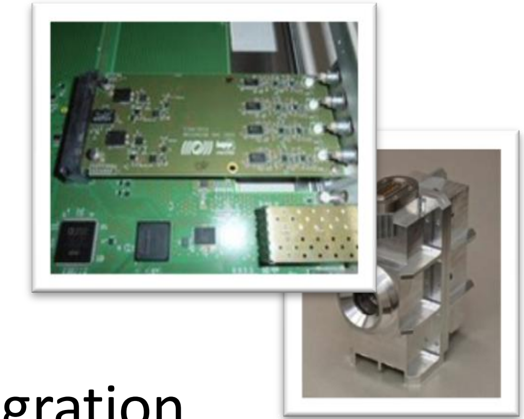


INSTALLING INJ (and more…)

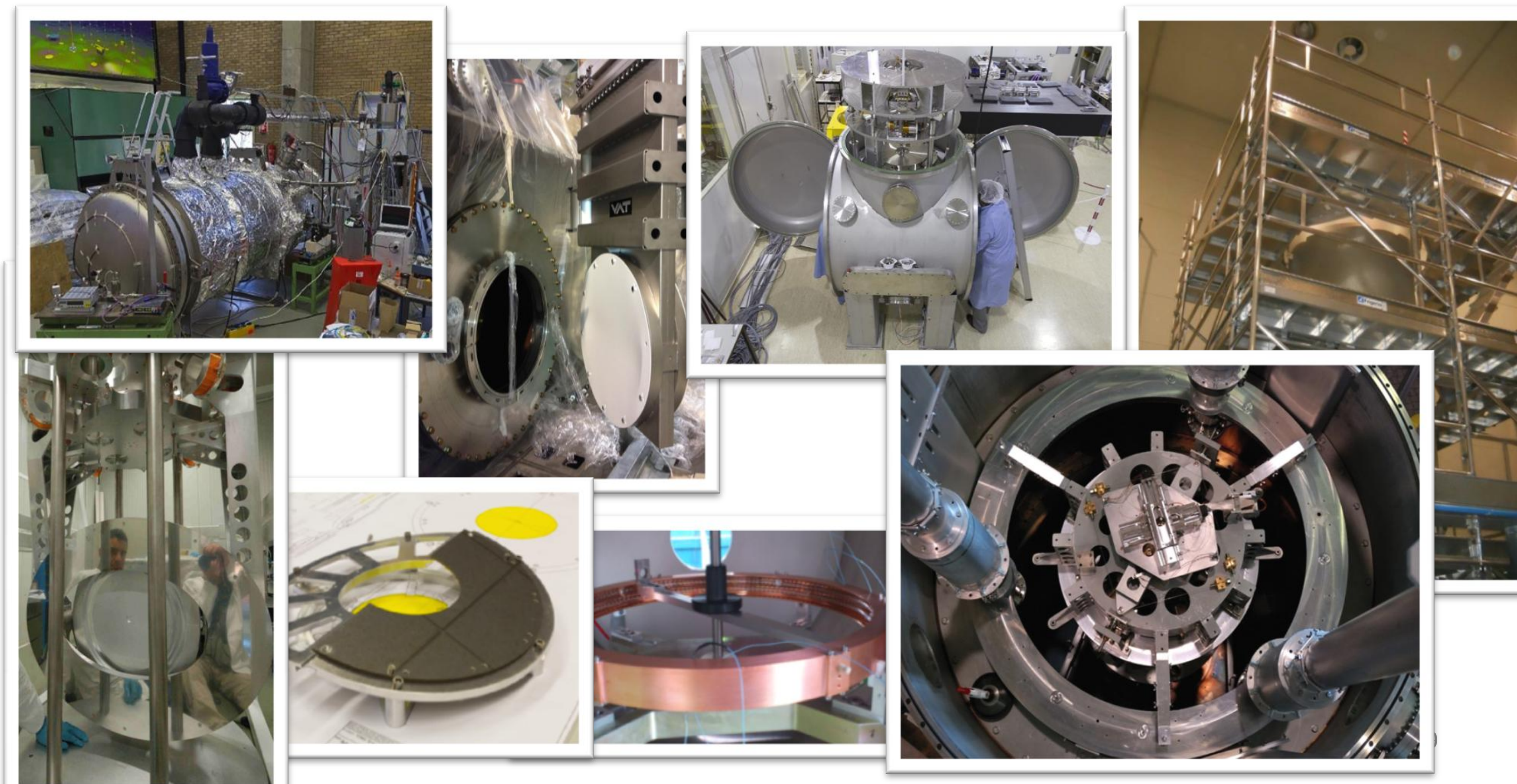
- Ready to start the installation of the injection system and all is needed to operate it



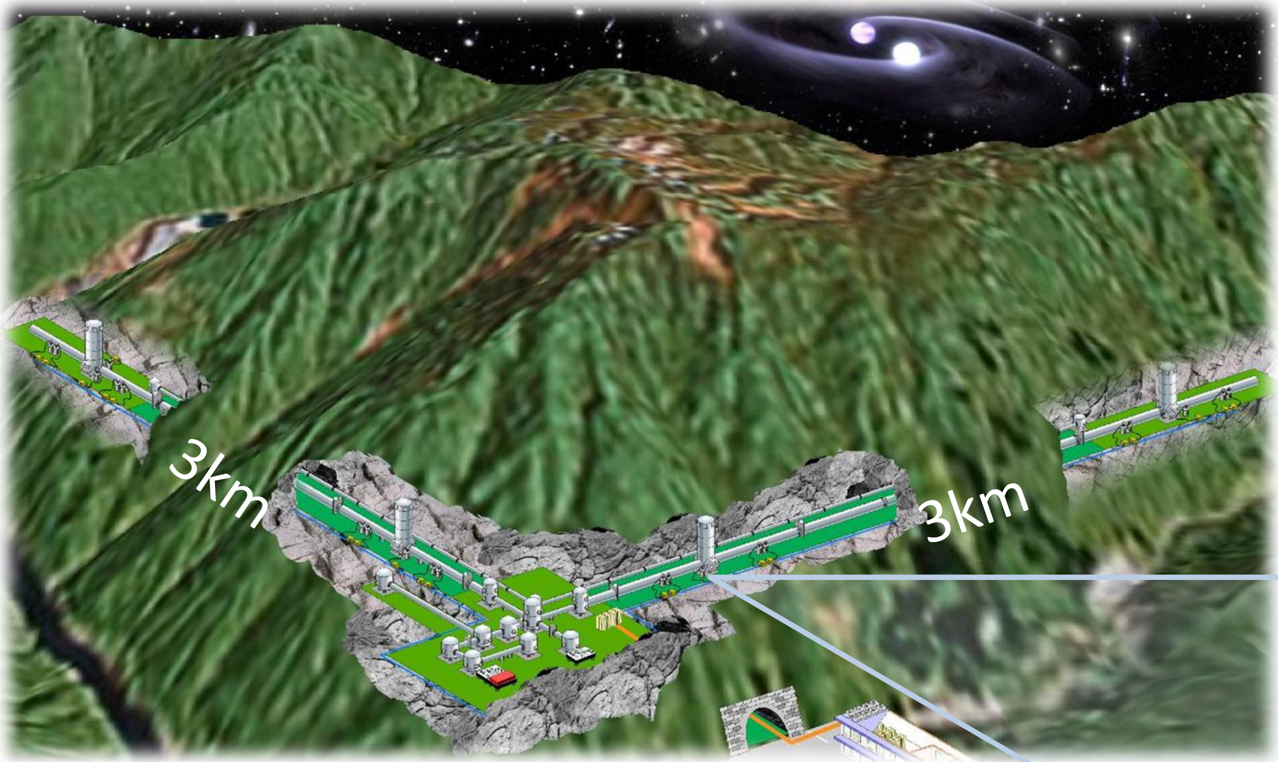
MUCH MORE IS COMING

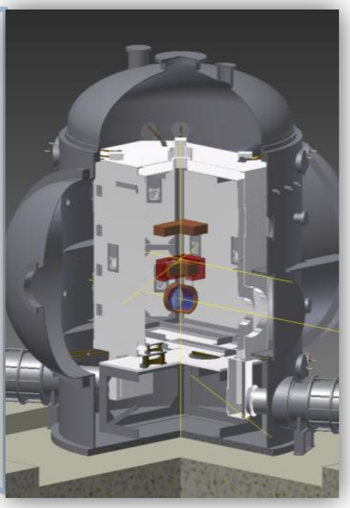


- Many parts are ready (or will soon be ready) to be installed
- 2014 will be a crucial year for the assembly & integration



Key features of KAGRA

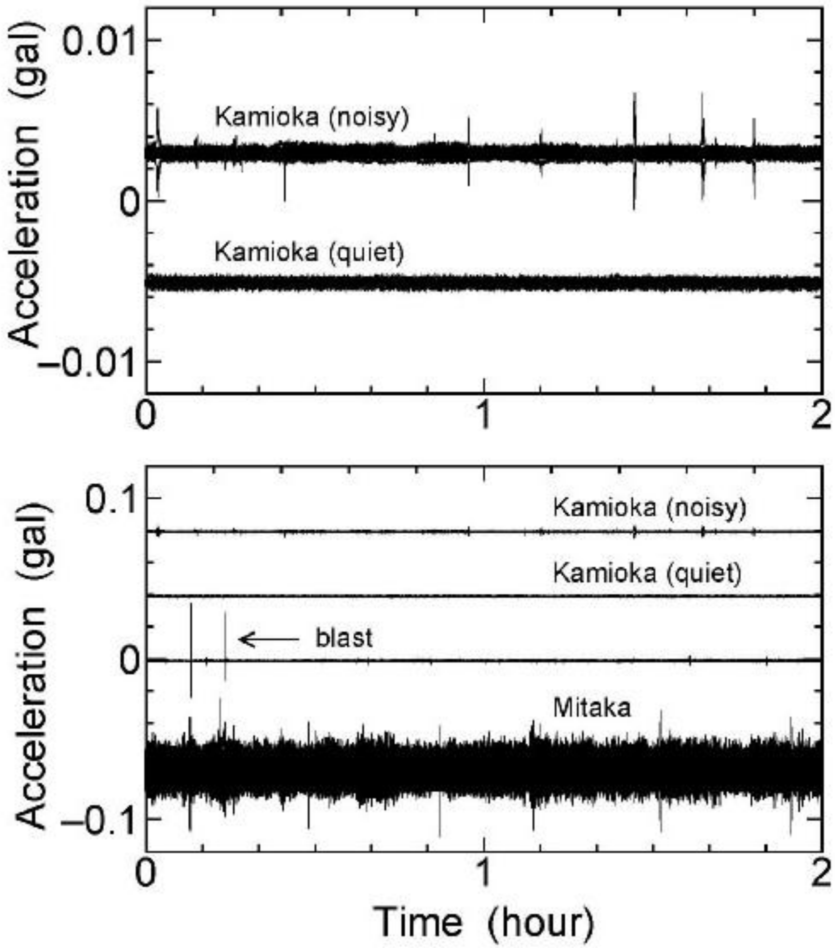


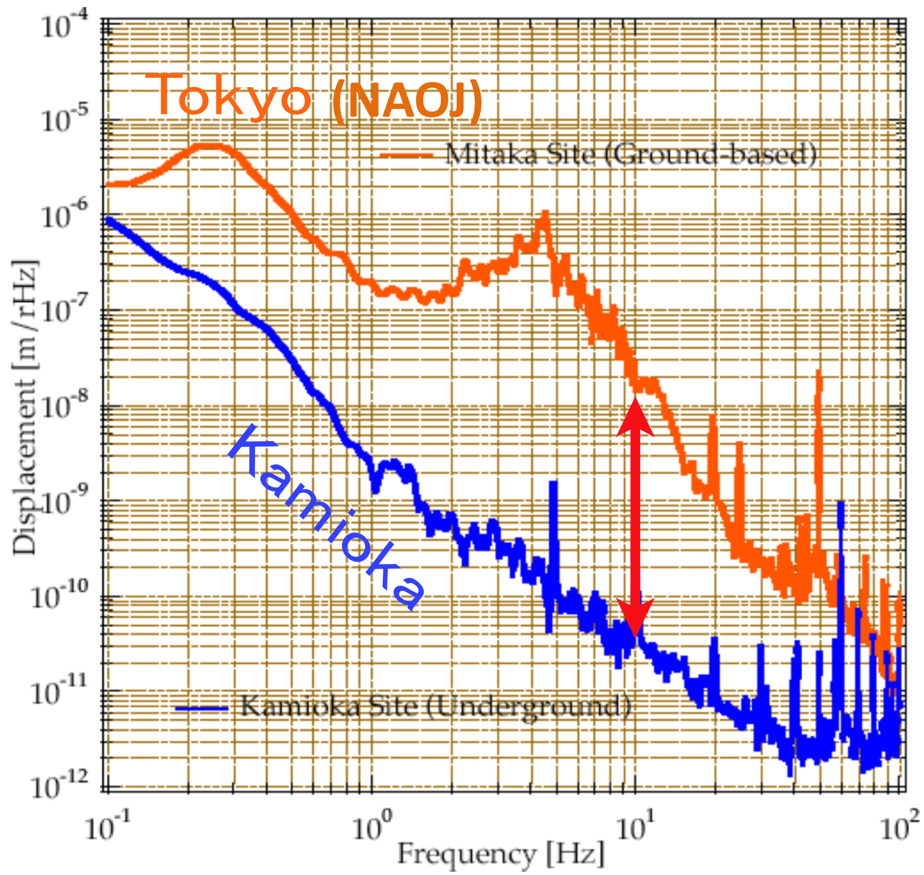


The detector will be constructed underground Kamioka.
➔ Reduction of seismic noise (to approximately 1/100).

Cryogenic mirrors will be used to reduce the thermal noise (in the 2nd phase).

Key features of KAGRA: Underground

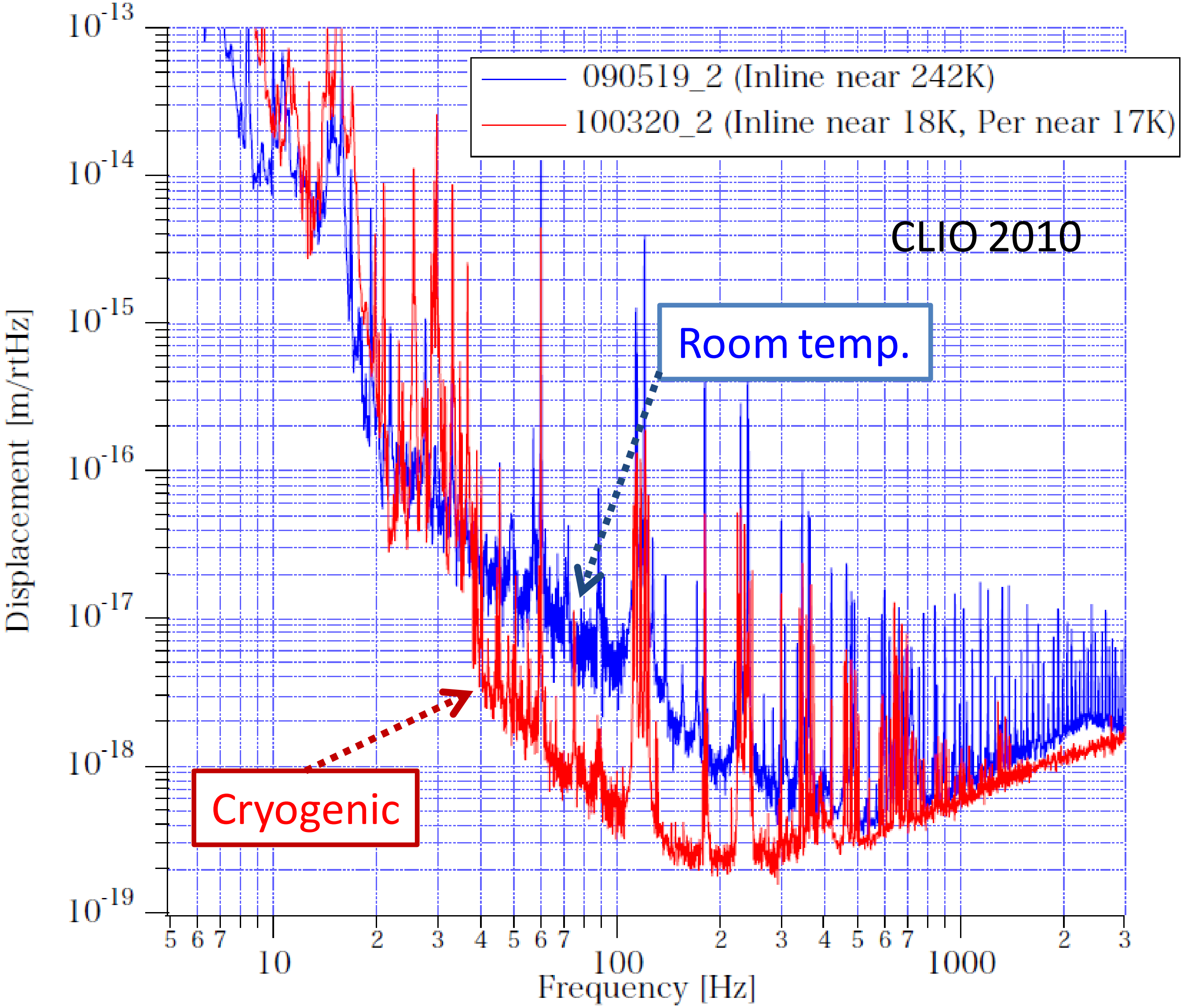




Amplitude of seismic motion

Key features of KAGRA: Cryogenic mirrors

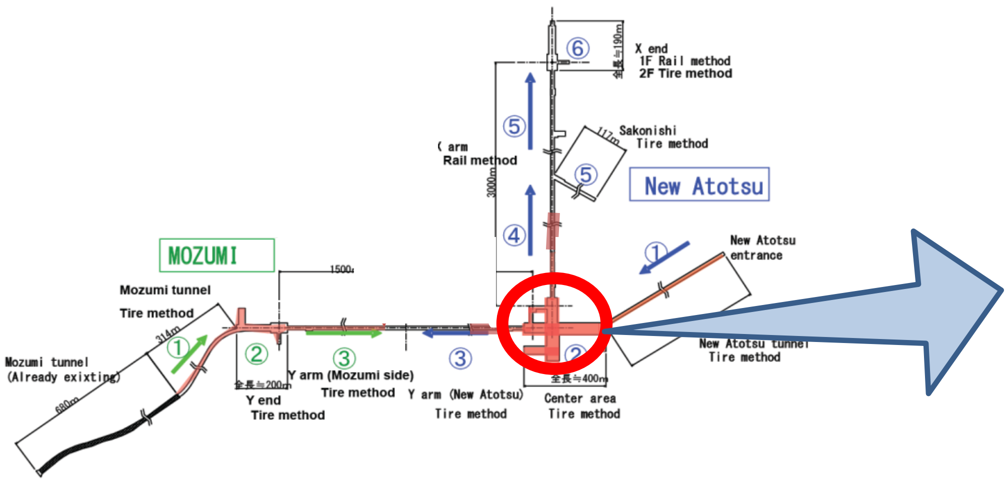
CLIO @Kamioka

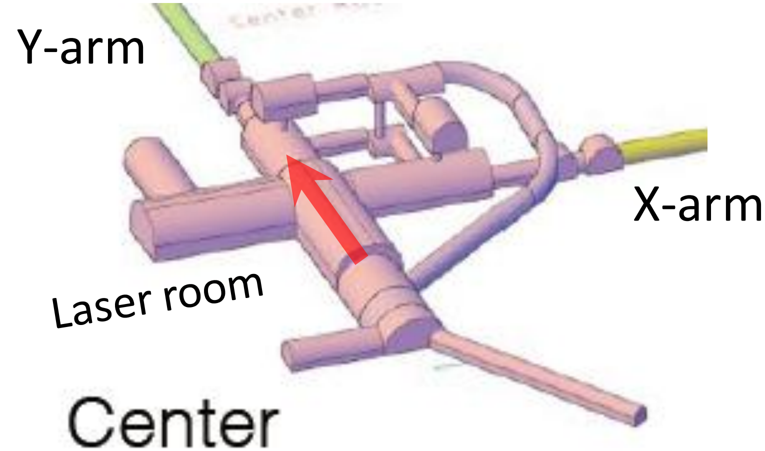


Excavation status (Center room)

To laser room   To Y-arm   To X-arm

(Dec. 2012)





Status of preparation: Vacuum

- All the pipes (total 6km) were produced and delivered to Kamioka.

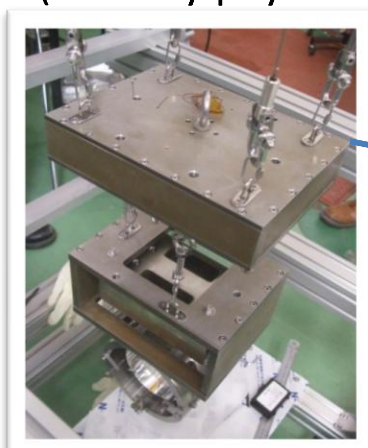
- A mockup tunnel has been prepared at a factory near Kashiwa.

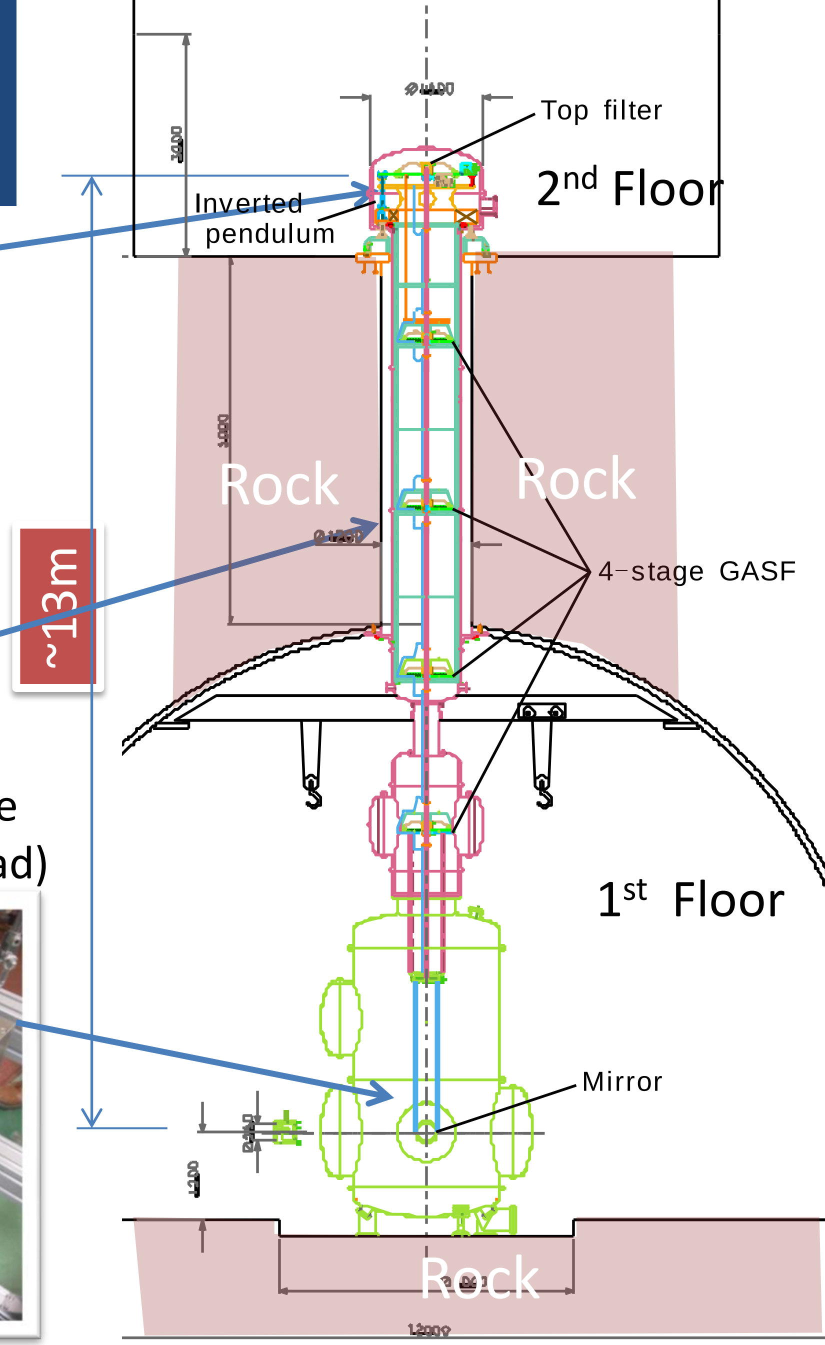
Status of construction: Seismic Attenuation

Prototype pre-isolator with the digital control system at ICRR

Standard Filter

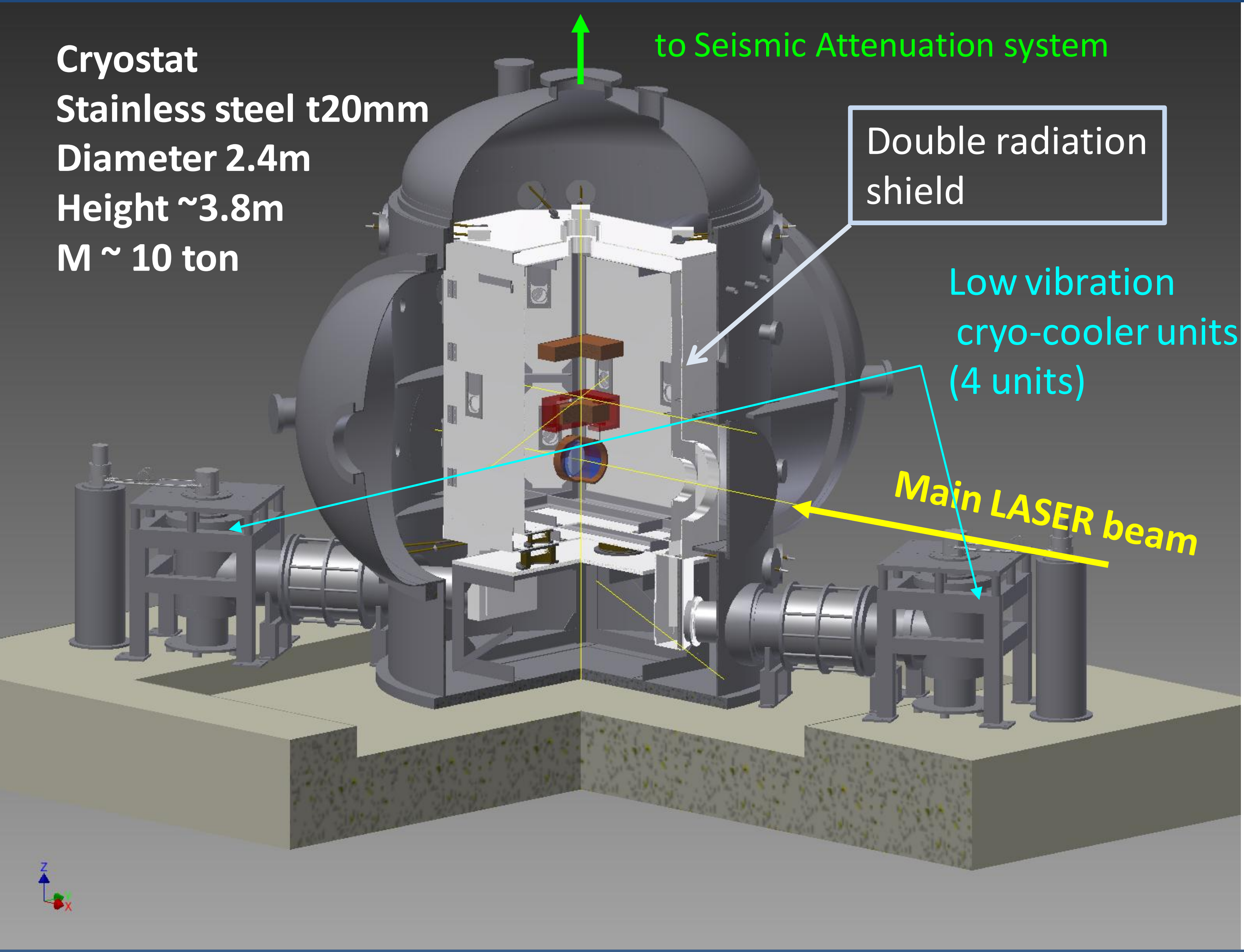
Proto-prototype (Dummy payload)

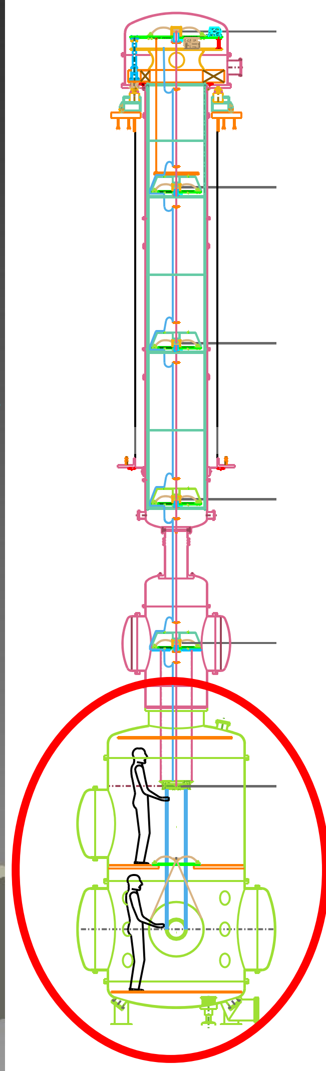




(Takahashi et al)

Status of construction: Cryogenic system





Status of construction: Cryogenic system (Real)

Feb. 2013

LIGO-India Project

- Construction and Operation of a **Advanced LIGO** Detector in India in collaboration with the LIGO Lab. Set up a **three node global Advanced LIGO detector network** by 2020 and operate it for 10 years.

- **The entire hardware components of the aLIGO detector along with designs and software to be provided by LIGO-USA and its UK, German and Australian partners ($120 M including R&D).**

- **The entire infrastructure including the 8 km beam tubes, UHV system, Corner and End stations, Related Labs and Clean rooms as well as the team to build and operate the Observatory will be the Indian responsibility ($250 M, 15 yrs) .**

LIGO-India proposal update

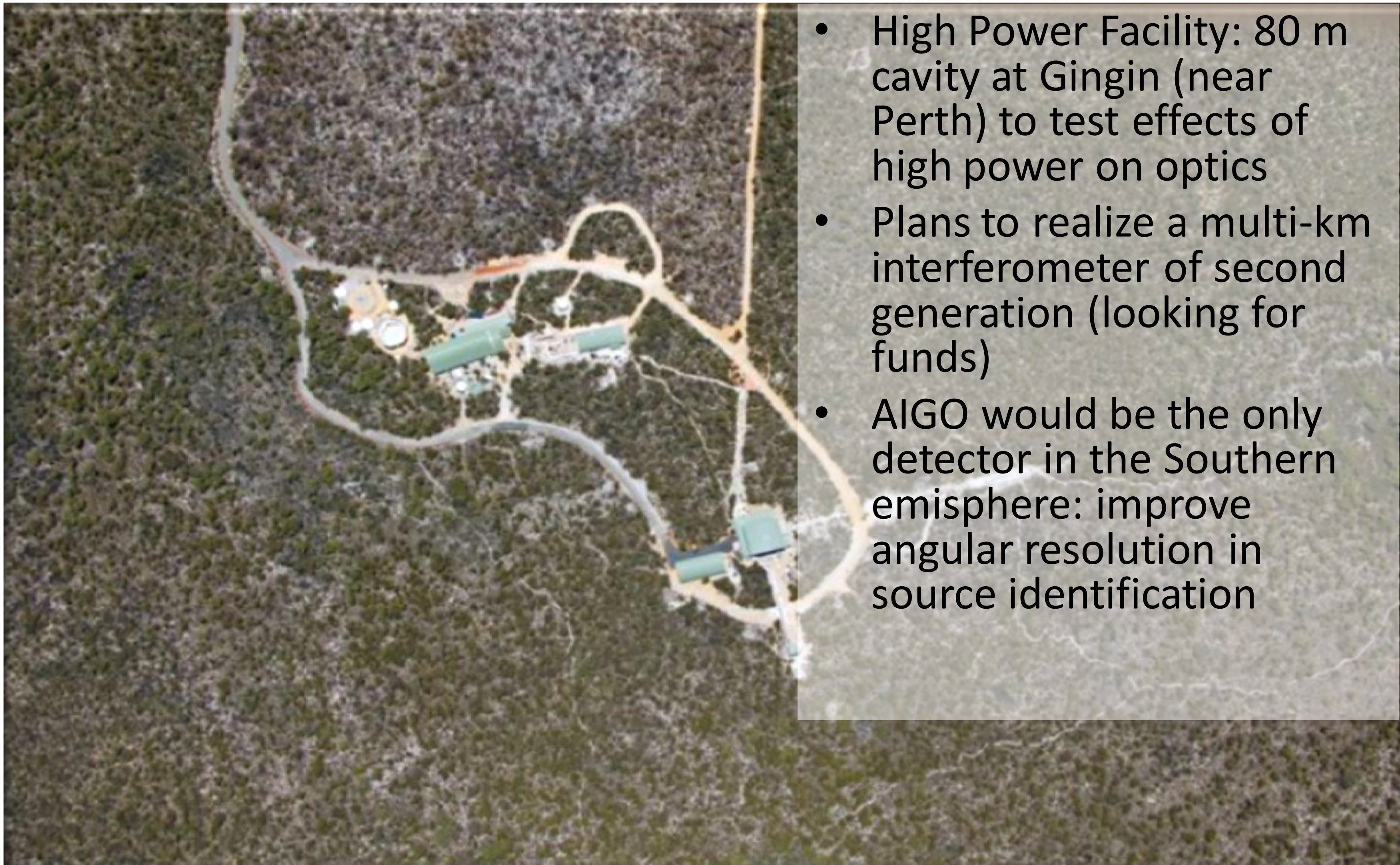
- **October 2011: LIGO-India included in the list of *Mega Projects* under consideration by the Planning Commission**
- **Dec 2011: IPR, RRCAT, IUCAA commit to DAE-DST to take on Lead Complementary Nodal Institutional responsibilities.**
- **Oct 2011, Apr, June 2012 : NSF Reviews on LIGO-India**
- **August 2012: National Science Board *approved the proposed Advanced LIGO Project change in scope, enabling plans for the relocation of an advanced detector to India.***
- **April 2012 – LIGO-India discussed at Atomic Energy Commission (AEC) meeting as a DAE Mega Project**
- **Dec 2012 – National Development Council Meeting to approve the Twelfth Five year Plan. LIGO-India included and figures *first* in the list of Mega-Projects in its report.**
- **Feb - Sept 2013 – LIGO-Lab visits, Meetings on UHV costing, Site selection, Infrastructure, Resolution of Technical issues on Seismic Data handling,..**
- **Dec 2013: Expected submission of note from DAE for Cabinet approval of the LIGO-India Project**

Meanwhile….

- Membership of IndIGO Consortium and IndIGO-LSC is growing
- Project Coordinators appointed at 3 lead institutes
- Project Teams set up for LIGO-India at 3 lead institutes consisting of scientists and engineers ..

  IPR (8), RRCAT (5), IUCAA (14)
- IUCAA: First phase of Tier-2 data & compute centre for archival of GW data and analysis (30 Tflop , 600 Tb storage ..)
- Site pre-selection, Visits of Indian team to LIGO Labs and Observatories, Visits by LIGO-Lab scientists to India, Student internships, Workshops, Post-doc appointments,…
- Laboratory at RRCAT designed to house all the Interferometer Detector related activities for the LIGO-India project
- Building planned by IPR for vacuum and infrastructure team
- Nov, Dec 2013 – LIGO-Lab, LIGO-India meetings scheduled in India to finalize DPR , MoU and Management structures
- GWPAW, IUCAA , Pune , Dec 17-20, 2013
- School on GW - Experimental Aspects, RRCAT Dec 23 -28, 2013

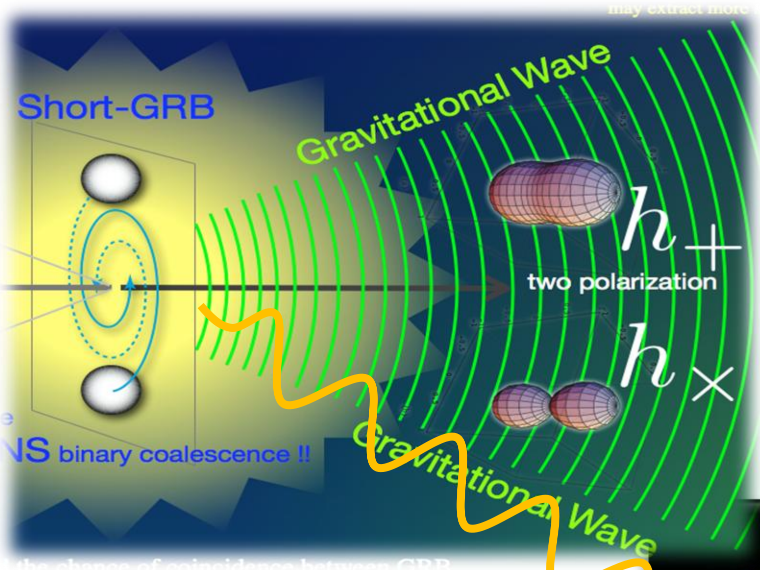
AIGO

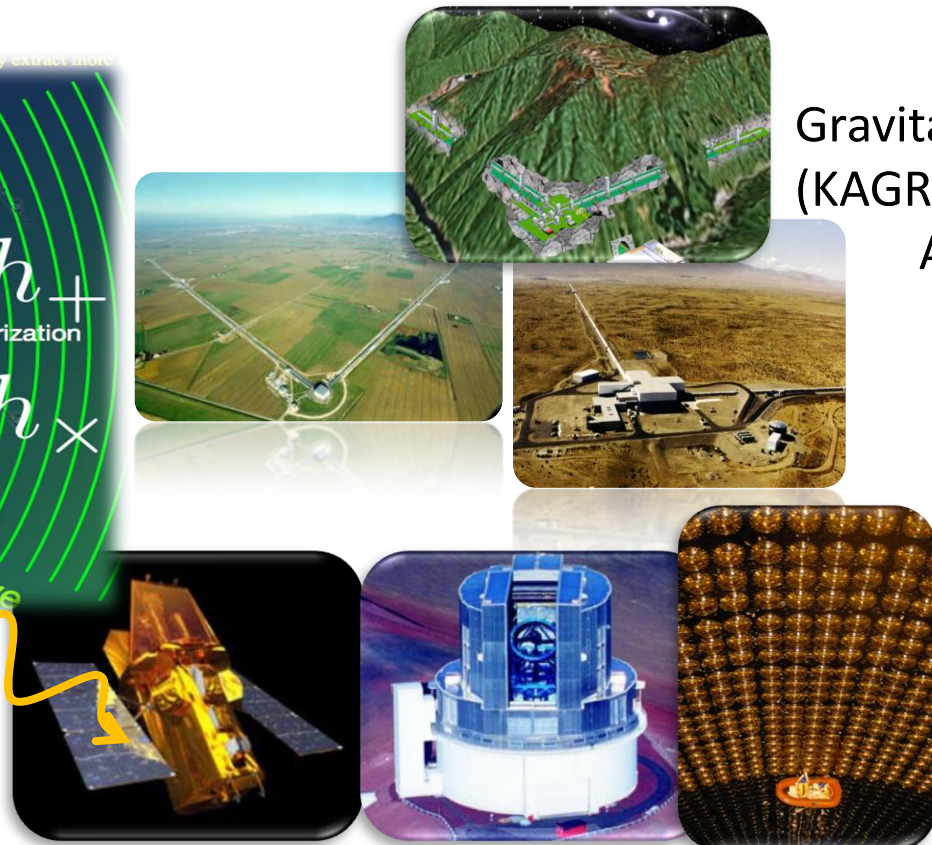


- High Power Facility: 80 m cavity at Gingin (near Perth) to test effects of high power on optics
- Plans to realize a multi-km interferometer of second generation (looking for funds)
- AIGO would be the only detector in the Southern emisphere: improve angular resolution in source identification

Multi-messenger astronomy:
Example: Short Gamma Ray Burst

✓ NS-NS binary might be a progenitor of Short-GRB ?



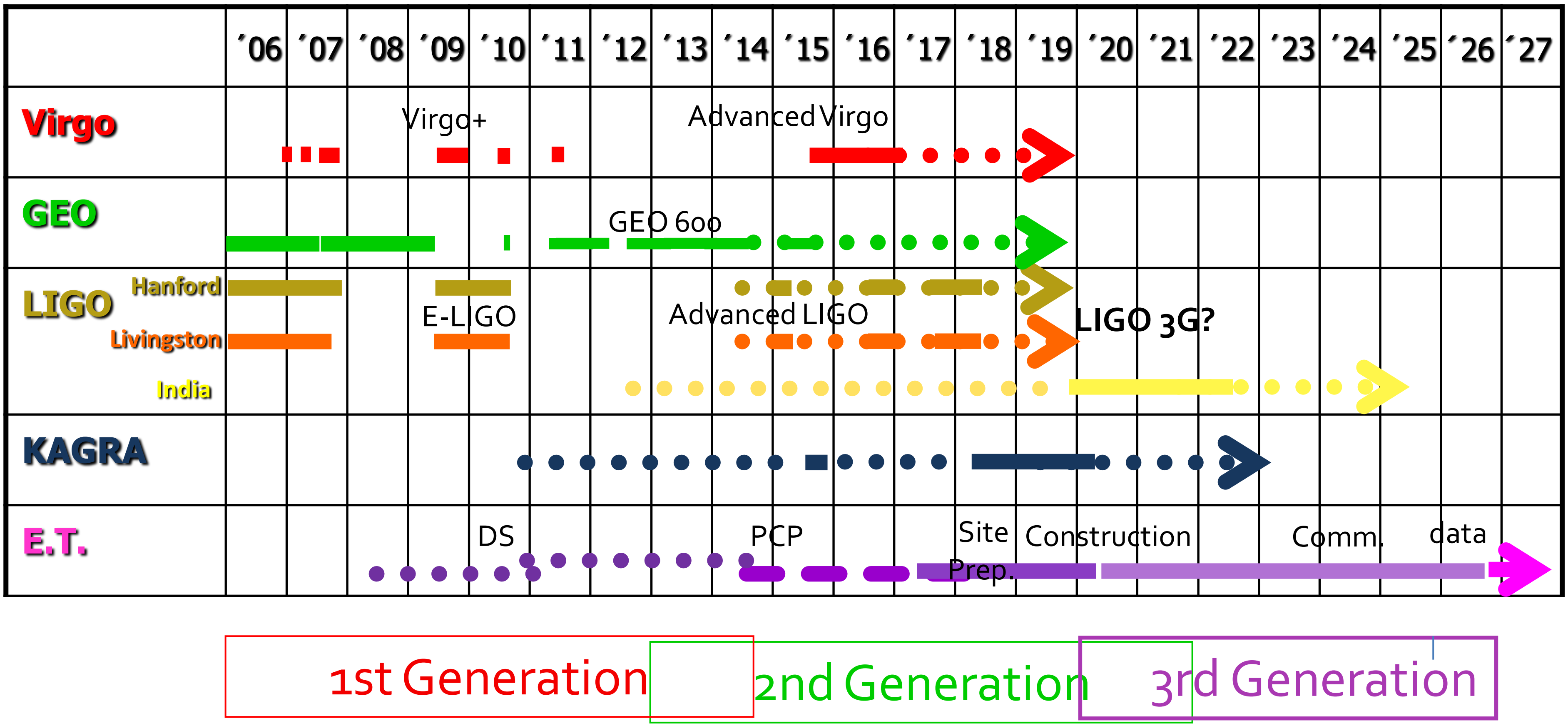


Gravitational wave
(KAGRA, Adv.LIGO,
Adv.Virgo, …)

Gamma ray,
neutrino and
optical
observations

Grants-in-Aid for Scientific Research “New developments in astrophysics through multi-messenger observations of gravitational wave sources”, PI: T. Nakamura

GW Timelines



Networking

- Networking in GW research is crucial:
  - Know-how and Data exchange
  - Interactions with Astrophysics and Numerical Relativity communities
  - Common R&D
  - Commissioning
  - Planning
- EGO strategy in EU towards a full integration of GW research in the World
  - Main tool: European Projects

European Projects

- European projects are a good opportunity to join together the German and British GEO groups with the Virgo collaboration
- In the past: 2004-2008
  - FP6-ILIAS integration activities (under the ASPERA hat)
    - EGO coordinated the networking in GW - FR, DE, GB, IT (0.1M€)
- Recently: 2008-2012
  - Einstein Telescope Design Study - FR, DE, GB, NL + HU, PL, ES (3 M€)
- Now: 2012-2016
  - ELiTES (FP7-IRSES) - DE, GB, IT, NL + JP (0.3 M€)
  - GraWIToN (FP7-ITN) - FR, DE, GB, IT (3.6 M€)
  - ASPERA R&D - DE, GB, NL, PL, RU + FR, HU, IT (1.3 M€)

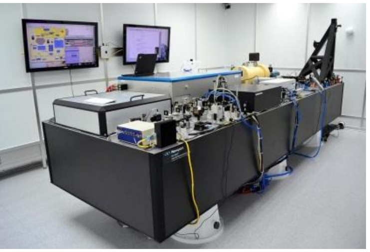
Why a global strategy

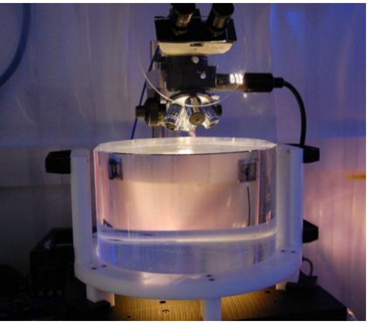
- ~100 yrs from Einstein's "prediction", only indirect evidence ➔ "Complexity"
- Requirements ➔ high tech and "ad hoc" research infrastructures
- Ambiguity of sources (local noise vs outer signal) ➔ coincidences
- Identification of sources ➔ vision by multiple eyes

The same nature of the physical problem determines the strategy of research.

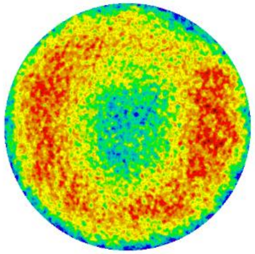
Hence, Cooperation more than Competition

The Last Page





- The next generation of gravitational-wave detectors will have the sensitivity to make frequent detections
- The Advanced detectors are coming along well, planned to complete in 2015
- The world-wide community is growing, and is working together toward the goal of gravitational-wave astronomy



Goal: Direct Detection 100 years after Einstein's paper on GWs