

Gravitational Wave Detection History

Lecture 1

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IV José Plínio Baptista School on Cosmology

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“Speed” of the gravitational force propagation

- Newton's Principia (1687),
- after the experimental confirmation of the existence of electromagnetic waves by H. Hertz, in 1887, speculation was made about the possible existence of gravitational waves (GWs).
- Heaviside (1893),
- Lorentz (1900),
- Poincaré (1905),
- Einstein (1916), first mathematical derivation,
- Einstein (1918), a more exact and detailed study.

It took about 100 years for the first gravitational wave be finally detected in 2015.

The history of this effort in the detection of gravitational waves will be presented here.

The pioneering work of Joseph Weber and many others

By the end of the 50s, after four decades of debate, it became possible “for a number of physicists to conclude that general relativity really does predict the existence of gravitational waves.”

Joseph Weber played a major role as pioneer in the search for gravitational wave detection. He was a daring experimentalist and a competent theorist on general relativity. He almost invented the maser earlier in the 50s. On the other hand, he spent the 1955–1956 academic year as a fellow of the Institute for Advanced Study in Princeton, New Jersey, where he dipped himself in general relativity. This rare union between experiment and theory made him the only one with “vision to see that there were technological possibilities of ultimate success” (Thorne 1987).

His major contribution to science was to start this experimental and exciting field of gravitational wave detection, by constructing the first resonant-mass antenna with electromechanical transducers.

On the other hand, the idea of a laser-interferometer gravitational-wave detector was independently proposed by Felix Pirani (1956), Gertsenshtein & Pustovoid (1962), Weber (1964), and Rainer Weiss (Thorne 1987).

The pioneering work of Joseph Weber and many others

Weber's first large suspended bar antenna of high Q aluminum was constructed in the early 60's. It started operating with good sensitivity and isolation around January 1965.

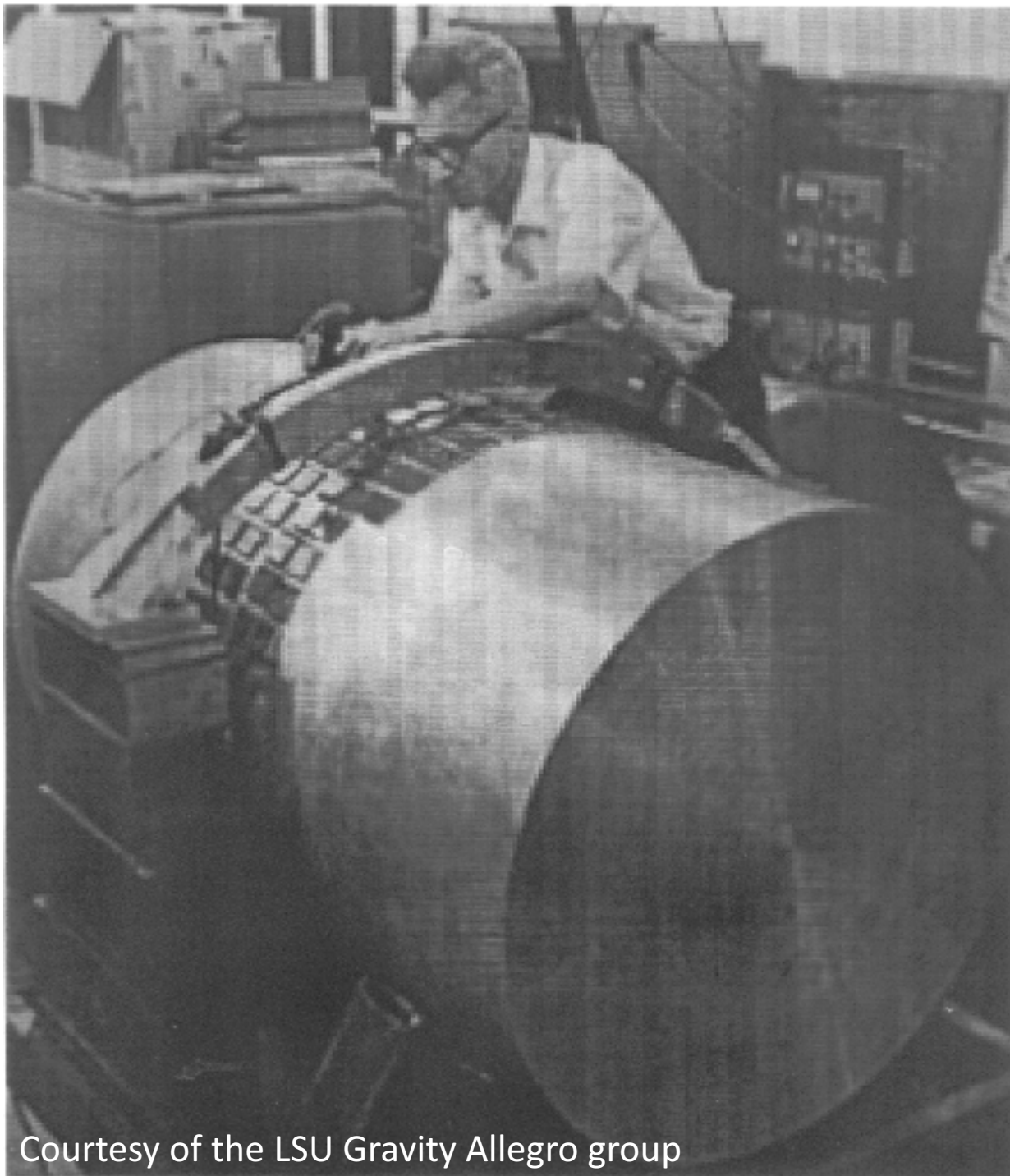
Two years later, Weber reported the first possible gravitational wave signals (Weber 1967).

In 1968, he again reported possible events.

Finally, in 1969, Weber stated that coincidences had been observed on gravitational-radiation detectors over a base line of about 1000km from the Argonne National Laboratory and to the University of Maryland, and that the probability that all of these coincidences were accidental was incredibly small.

By 1973, he had claimed an excess of coincidences from the statistical average of about seven events per day, showing a peak in the direction of the galactic center.

These and subsequent observations by Weber were greeted with great excitement in the early 1970s; however, the strength implied by his signals was very much in excess of what was expected.



Courtesy of the LSU Gravity Allegro group

The pioneering work of Joseph Weber and many others

In the following years, various experimenters built more sensitive bars, including low temperature bars, and looked for signals, but none of them confirmed Weber's findings.

The first ones to find null results were:

- Tyson at Bell Labs Murray Hill, NJ,
- Levine and Garwin at the IBM Thomas J. Watson Research Center, in Yorktown Heights, NY, both in 1973.

Both these experiments disagreed with Weber's results and suggested that the events he found were not gravitational wave events.

The pioneering work of Joseph Weber and many others

However, Weber's pioneering work was decisive for the initial growth of the gravitational wave community.

The following **12 groups**, which operated room temperature resonant-mass GW detectors in the 60s, 70s and 80s, were motivated by Weber's pioneering effort:

- **Moscow, in Russia:** two detectors 20 km apart composed of two 1.2 ton aluminum alloy bars, 150cm long and ~60cm in diameter, resonant at 1640Hz, and equipped with capacitive transducers (Braginski'i et al. 1974);
- **BTL (Bell Labs), New Jersey, USA:** one 3.7 ton aluminum alloy bar, 357cm long, ~70 cm in diameter, resonant at 710Hz, equipped with PZT-8 transducers (Tyson 1973);
- **Rochester, in Rochester (NY), USA:** another 3.7 ton aluminum alloy bar 420 km apart from the one above, 357cm long, ~70 cm in diameter, resonant at 710Hz, equipped with PZT-8 transducers (Douglass et al. 1975);
- **IBM, Yorktown Heights (NY), USA:** one 118 kg aluminum alloy bar, 150 cm long and 19 cm in diameter, resonant at 1695Hz, equipped with PZT-4 transducers (Levine & Garwin 1973; Garwin & Levine 1973);

The pioneering work of Joseph Weber and many others

- **Bristol group, England:** two parallel split-bars in the same vacuum chamber composed of two aluminum half-bars. Each split-bar had its own transducer (made of lithium niobate piezoelectric material) and amplifier detector, but they shared a common vacuum chamber and vibration isolation system. The signals from the two split-bars were monitored separately and were also cross-correlated (Aplin 1972);
- **Glasgow, Scotland:** two split-bar detectors 50m apart composed of two aluminum half-bars of 300 kg total mass and 155cm total length, ~30cm in diameter, cemented together via PZT transducers, resonant at 1020 and 1100Hz (Drever et al. 1973);
- **Reading-Rutherford Lab, England:** two split-bar detectors 30 km apart composed of two aluminum alloy half-bars of 625 kg total mass and 150cm total length, 46 cm in diameter, cemented together via PZT transducers, resonant at 1200Hz (Allen & Christodoulides 1975);
- **Univ. Tokyo, Tokyo, Japan:** two square antennae made of an aluminum alloy, resonant at 145Hz (Hirakawa & Narihara 1975) (later, one of these antennae was mechanically tuned to 60.2Hz in order to become CRAB II (Oide et al. 1979)), square antenna made of an aluminum alloy, resonant at 60.2Hz (CRAB I) (Hirakawa et al. 1978), and some other small antennae ($M < 40$ kg) (Iso et al. 1984, 1985);

The pioneering work of Joseph Weber and many others

– **Munich-Frascati group:** two detectors ~700km apart (later only 10 km, when the Frascati detector was moved to Garching) composed of two 1.2 ton 6061-O aluminum alloy bars, 154 cm long by 62.5 cm in diameter, resonant at 1654Hz, equipped with piezoelectric transducers, and intended to reproduce the precision of the Weber experiment, with some sensitivity improvements (Billing et al. 1975; Billing & Winkler 1976; Bramanti & Maischberger 1972), set the lowest upper limits to the rates of gravitational wave pulses in the 70s (Kafka & Schnupp 1978). They took a piezoelectric material with better mechanical and electrical properties, and arranged the piezos differently (arranging strain and polarization parallel) thereby providing a better coupling. Because of the new topological arrangement of the piezos, they were able to manage an impedance matching between the “source” of the signal, the piezos, and the input of the amplifier. Thus, the detector was noticeably improved in comparison with Weber’s setup. In addition, the signal processing was performed with the two degrees of freedom in phase space, equivalent to amplitude and phase or the two independent quadrants, whereas in most cases Weber just used the energy of the bar (Winkler 2007, private communication);

The pioneering work of Joseph Weber and many others

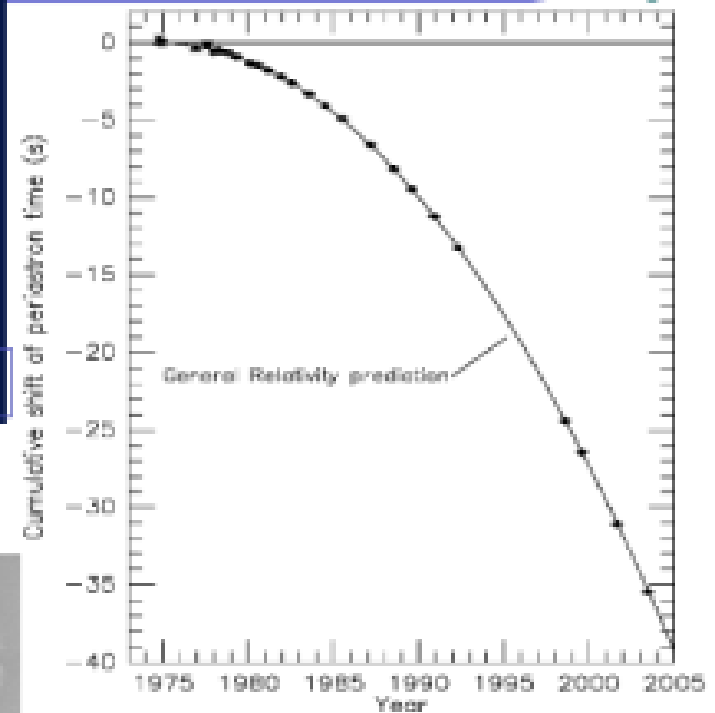
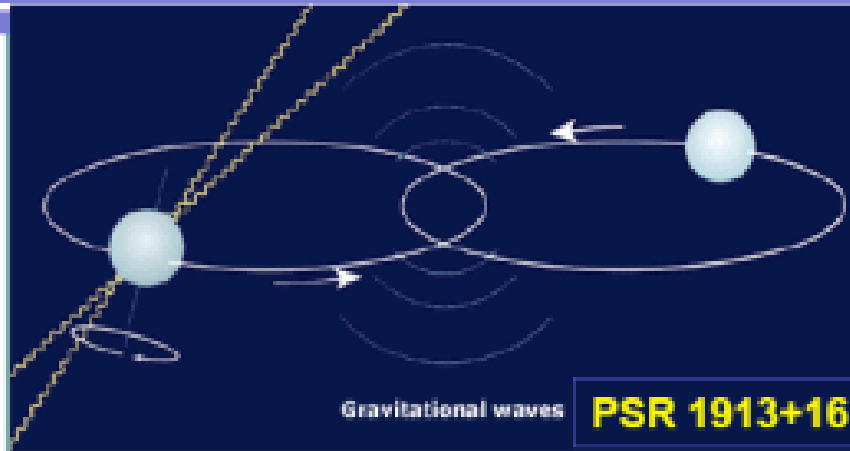
- **Zhongshan Univ., Guangzhou, China:** one~2 ton (1963 kg) aluminum alloy bar, 178cm long, 71.4 cm in diameter, resonant at ~1.5 kHz, using PZT-4 transducers, and one 498 kg 200cm² square antenna, resonant at 47.3Hz, equipped with dc-capacitive transducers (Hu et al. 1986; Zhu et al. 1988);
- **Beijing Univ., Beijing, China:** one 1.3 ton aluminum alloy bar, 153cm long, 62.5 cm in diameter, resonant at 1687 kHz, equipped with PZT transducers (Pizzella 1988b; Feng et al. 1983);
- **Meudon group, in France:** a conical antenna equipped with capacitive transducers (Bonazzola & Chevreton 1973).

Also in the 70s:

PSR 1913+16 (Taylor & Hulse 1974)

(a system with two neutron stars with
an orbital period of 7h45min, in
which one of them was a Pulsar)

First verification of GWs



Nobel 1993

Hulse & Taylor



$$\frac{\dot{P}_{b,corrected}}{\dot{P}_{b,GR}} = 1.0013 \pm 0.0021$$

Also six groups, **Stanford** and **LSU** in the USA, **University of Rome**, **University of Western Australia** (UWA) (Blair 1980), **University of Regina** (Canada) (Papini 1974; Barton et al. 1977), and the **Legnaro group**, were formed in the 60s, 70s and 80s.

They decided to construct cryogenic resonant-mass (RM) GW detectors, instead of room temperature ones, starting a second and a third generation of RM detectors.

At the same time, some other existing groups, such as the ones in **Tokyo** (in collaboration with KEK), **Moscow** (Rudenko et al. 1994), **Rochester** (Bocko et al. 1984), and **Maryland** (Davis & Richard 1980) were switching to cryogenics.

“These groups made a number of significant improvements over Weber’s original design. One improvement was to lower the temperature of the bar to liquid helium temperatures (4K). The second was a better suspension of the bar with increased vibration isolation. The third was the use of a resonant transducer and low noise amplifiers to observe the motion of the bar.”



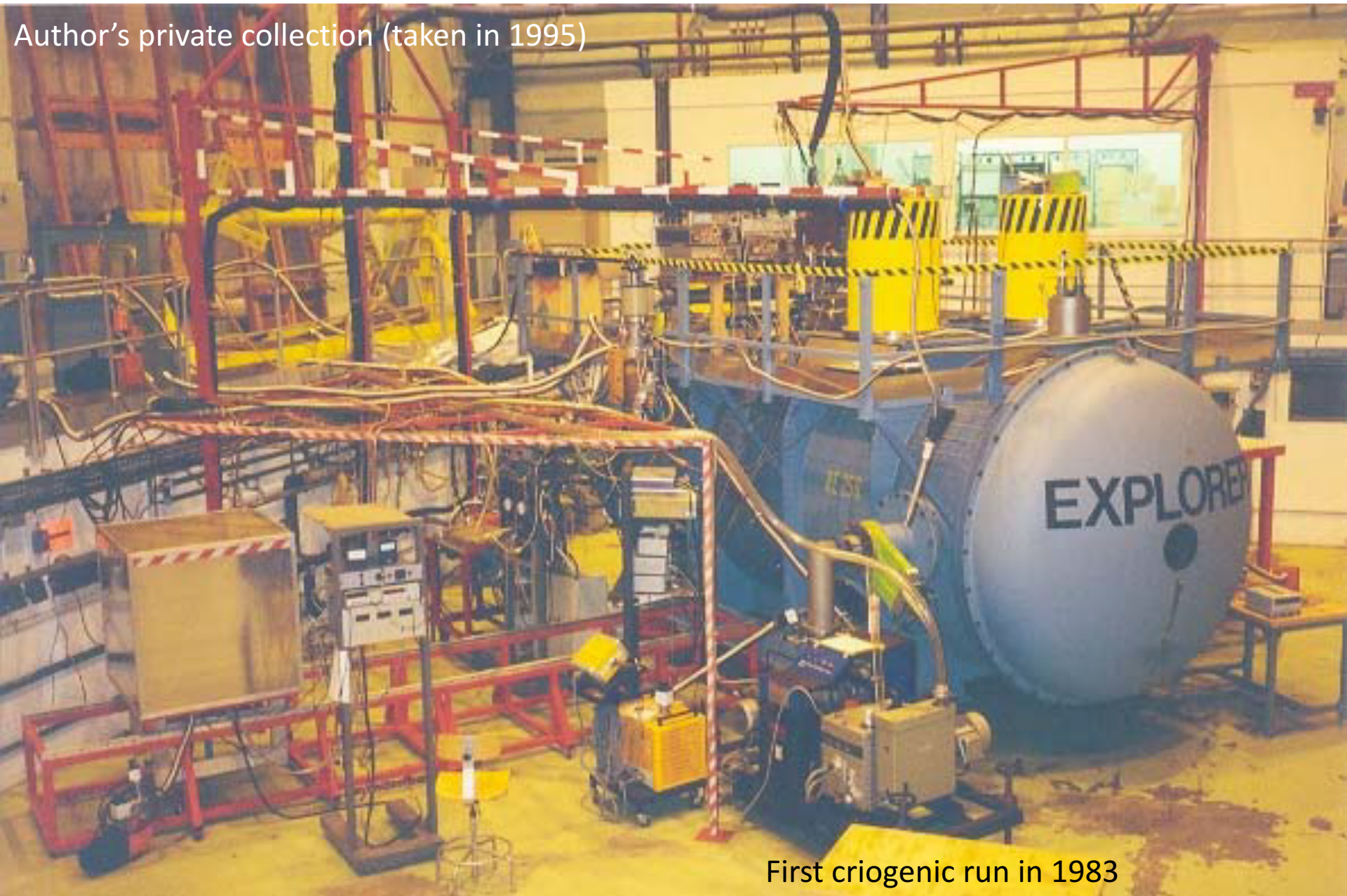
Top left: Weber and one of his room temperature bars (60s); top middle left: the LSU detector dewar arriving at the old lab (early 70s); bottom left: the Explorer detector at CERN; right: the earthquake damaged Stanford bar detector (authors' priv. collection; picture taken in 1994) with the large 4.8 ton 6061 aluminum alloy antenna inside.(Courtesy of the LSU Gravity Allegro group)

Author's private collection (taken in 1994)



First cryogenic run with high sensitivity in 1982

Author's private collection (taken in 1995)



First criogenic run in 1983

(Courtesy of the LSU Gravity Allegro group)



First cryogenic run for
scientific search in 1986

1990

30 authors from 9 institutions

First gravity wave coincidence experiment between resonant cryogenic detectors: Louisiana-Rome-Stanford

E. Amaldi^{1,3}, O. Aguiar⁹, M. Bassan^{2,8}, P. Bonifazi^{3,4}, P. Carelli^{1,5}, M.G. Castellano^{3,4}, G. Cavallari⁷, E. Coccia^{2,3}, C. Cosmelli^{1,3}, W.M. Fairbank⁸, S. Frasca^{1,3}, V. Foglietti^{3,5}, R. Habel^{1,6}, W.O. Hamilton⁹, J. Henderson⁸, W. Johnson⁹, K.R. Lane⁸, A.G. Mann⁹, M.S. McAshan⁸, P.F. Michelson⁸, I. Modena^{2,3}, G.V. Pallottino^{1,3}, G. Pizzella^{1,3}, J.C. Price⁸, R. Rapagnani^{1,3}, F. Ricci^{1,3}, N. Solomonson⁹, T.R. Stevenson⁸, R.C. Taber⁸, and B.-X. Xu⁹

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⁶ ENEA, Centro Ricerche Energia, Frascati (Roma), Italy

⁷ CERN, European Organization for Nuclear Research, Geneva, Switzerland

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Received August 8, accepted November 23, 1988

Summary. The results of a coincidence search for short bursts of gravitational radiation with cryogenic resonant-mass detectors are reported. No significant excess of coincidences at zero time delay were found. The data have been used to set an improved observational upper limit on the flux of impulsive gravitational waves that may be impinging on the Earth.

Key words: gravitational waves – detectors, gravitational waves – coincidence experiment

employs a resonant capacitive transducer (Rapagnani, 1982) matched to a d.c. SQUID amplifier (Carelli, 1985).

The performance of the three detectors during this coincidence experiment did not reach the design goals or previously achieved levels by the Stanford detector in either sensitivity or in non-Gaussian disturbance level (Boughn, 1982). Despite this situation, the limit that we are able to set on the rate of gravity wave pulses impinging on the Earth is better than that set by any previous observations.

First cryogenic run in 1989



Courtesy of the ROG collaboration

Auriga:

The lab was completed in 1992;

First room temperature run 1995;

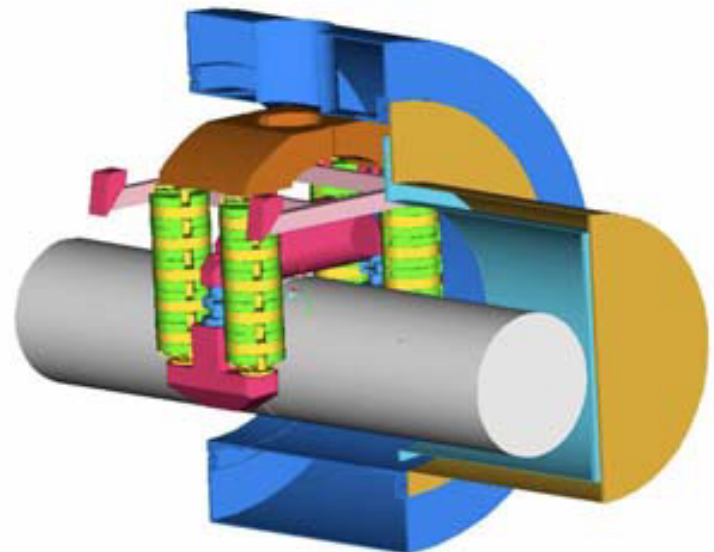
First cryogenic run (using FET amplifier instead SQUID) 1995-96;

First Ultracryogenic run beginning February 1997;

data taking since May 1997;

End of the first Auriga ultracryogenic scientific run 1999.

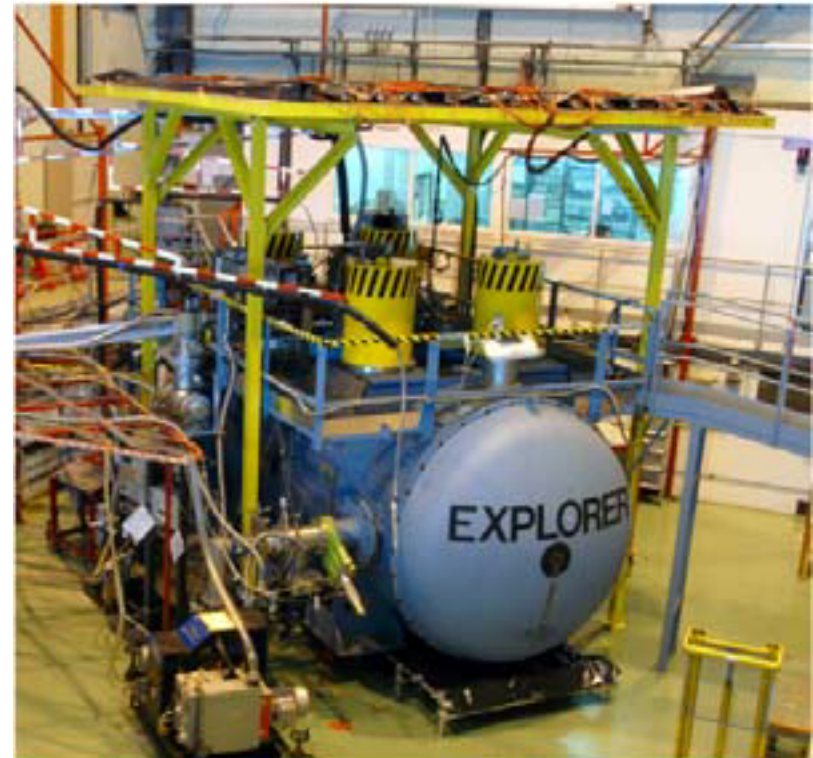
(credit: Jean-Pierre Zendri)



Courtesy of the ROG collaboration

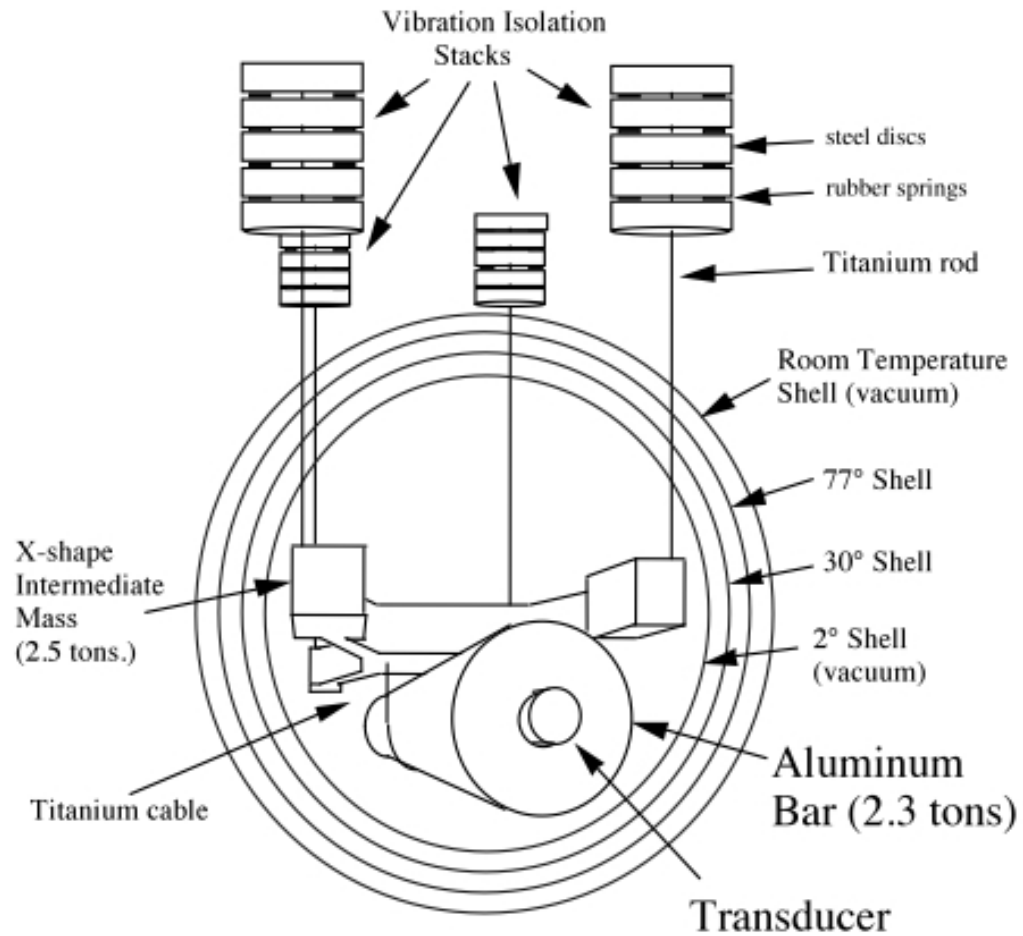


First cryogenic run in 1989



First cryogenic run in 1983

Allegro at its new position at the LSU site



Courtesy of the LSU Gravity Allegro group

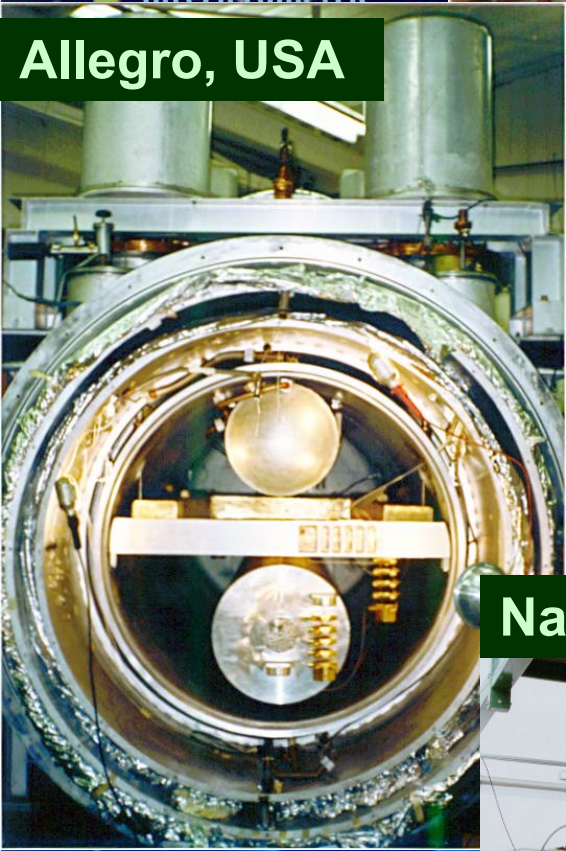
by Arlette de Waard



Explorer
Switzerland



Auriga, Italy



Allegro, USA



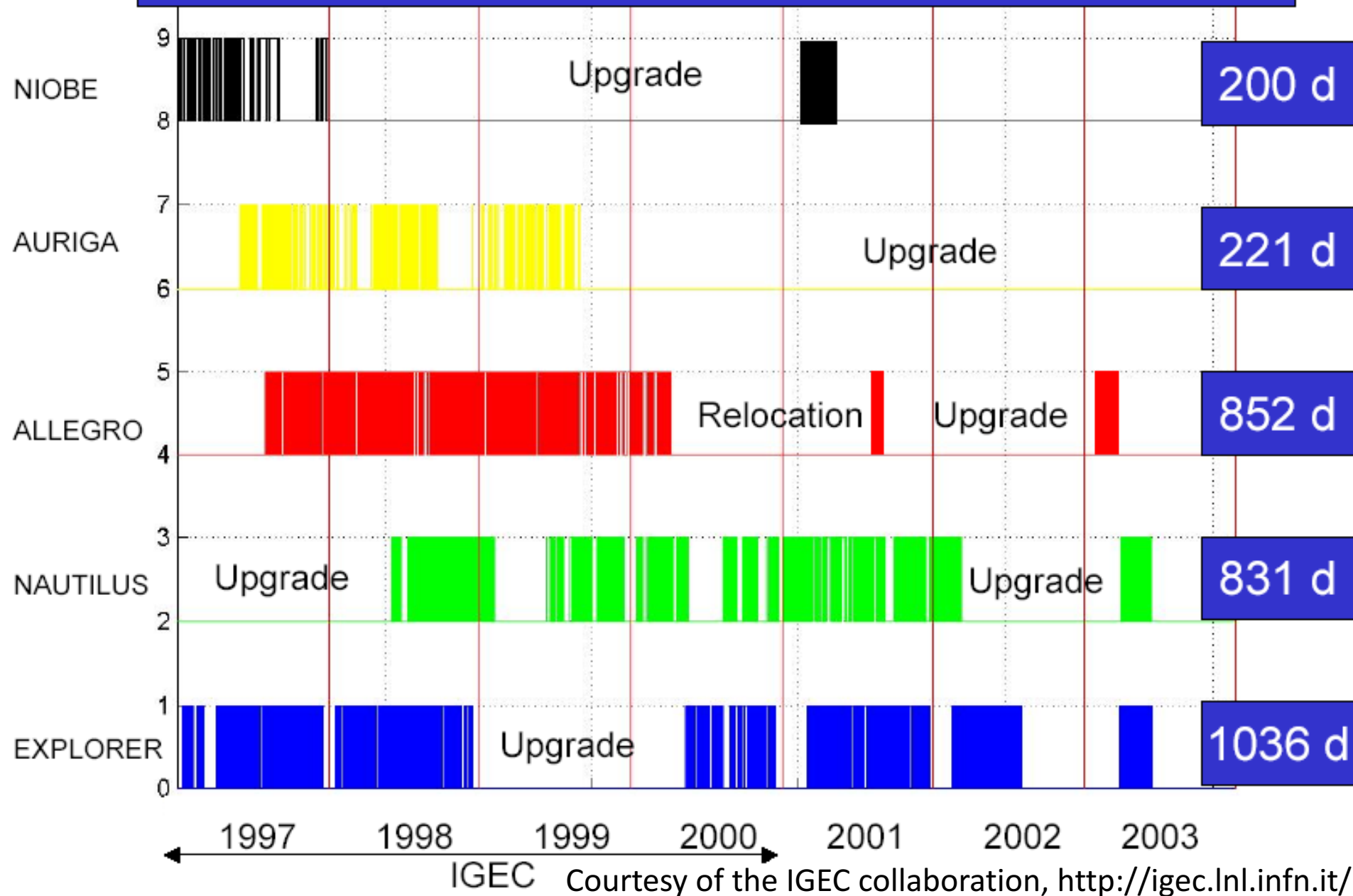
Nautilus, Italy



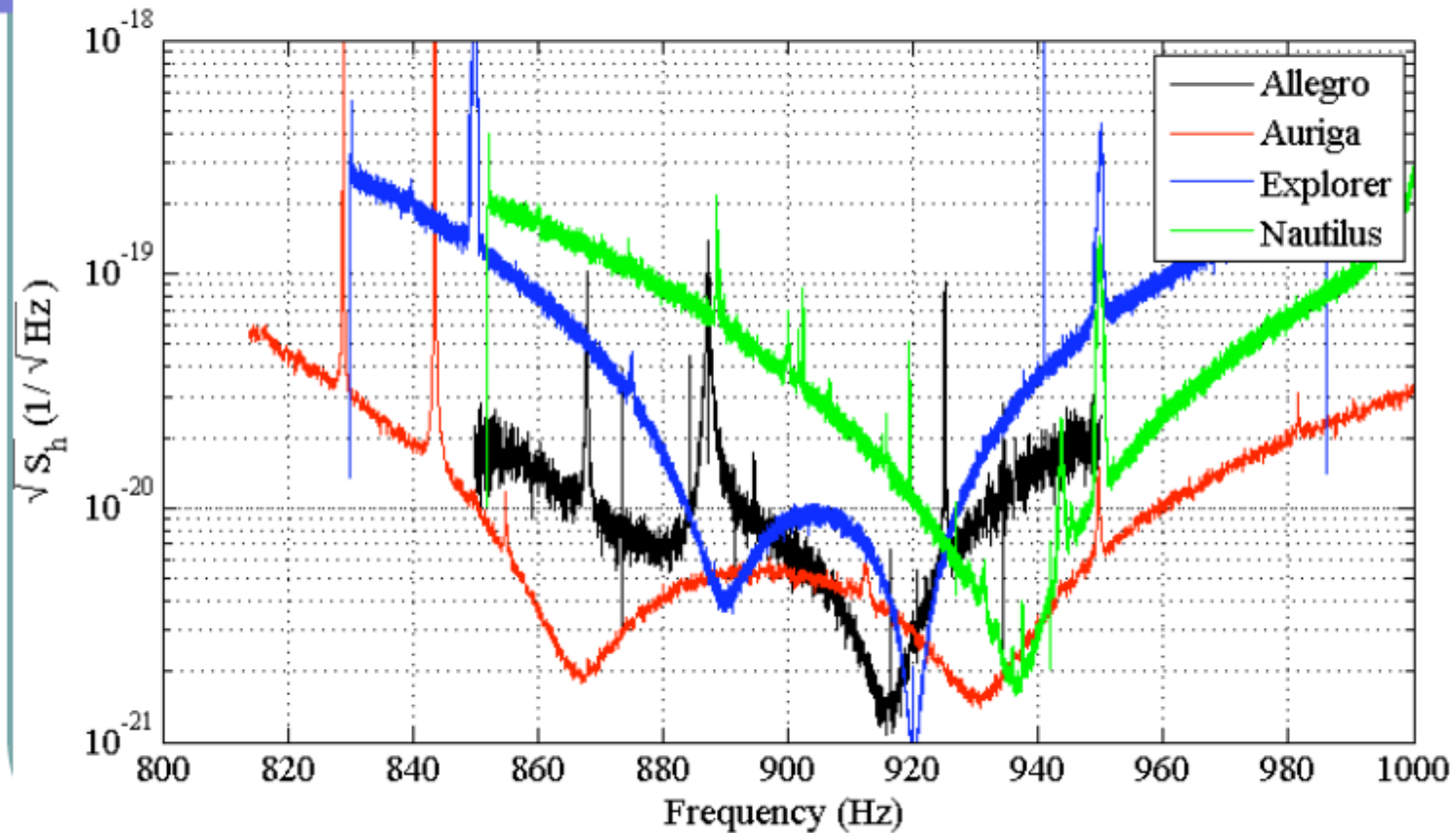
Niobe
Australia



•ON times for the various detectors 1997-2003

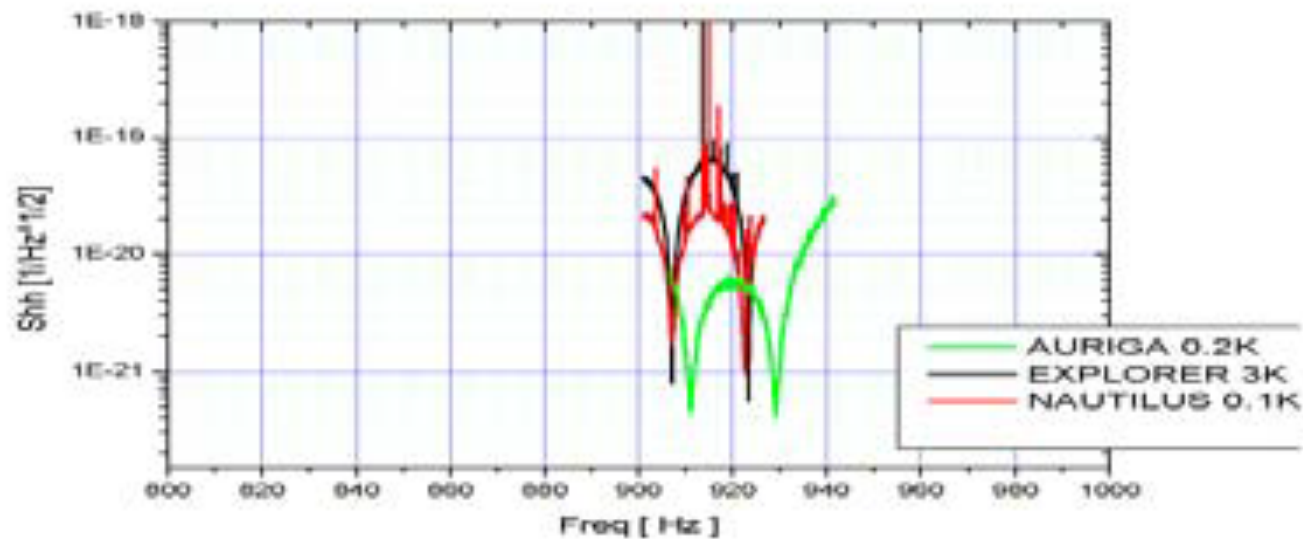


Sensitivity of Resonant Detectors

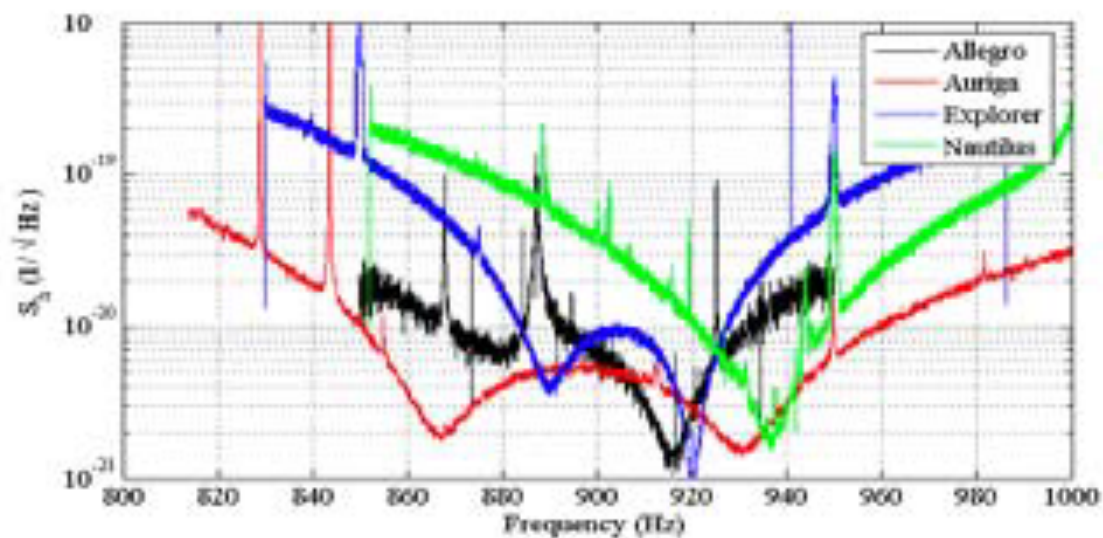


Courtesy of the IGEC2 collaboration

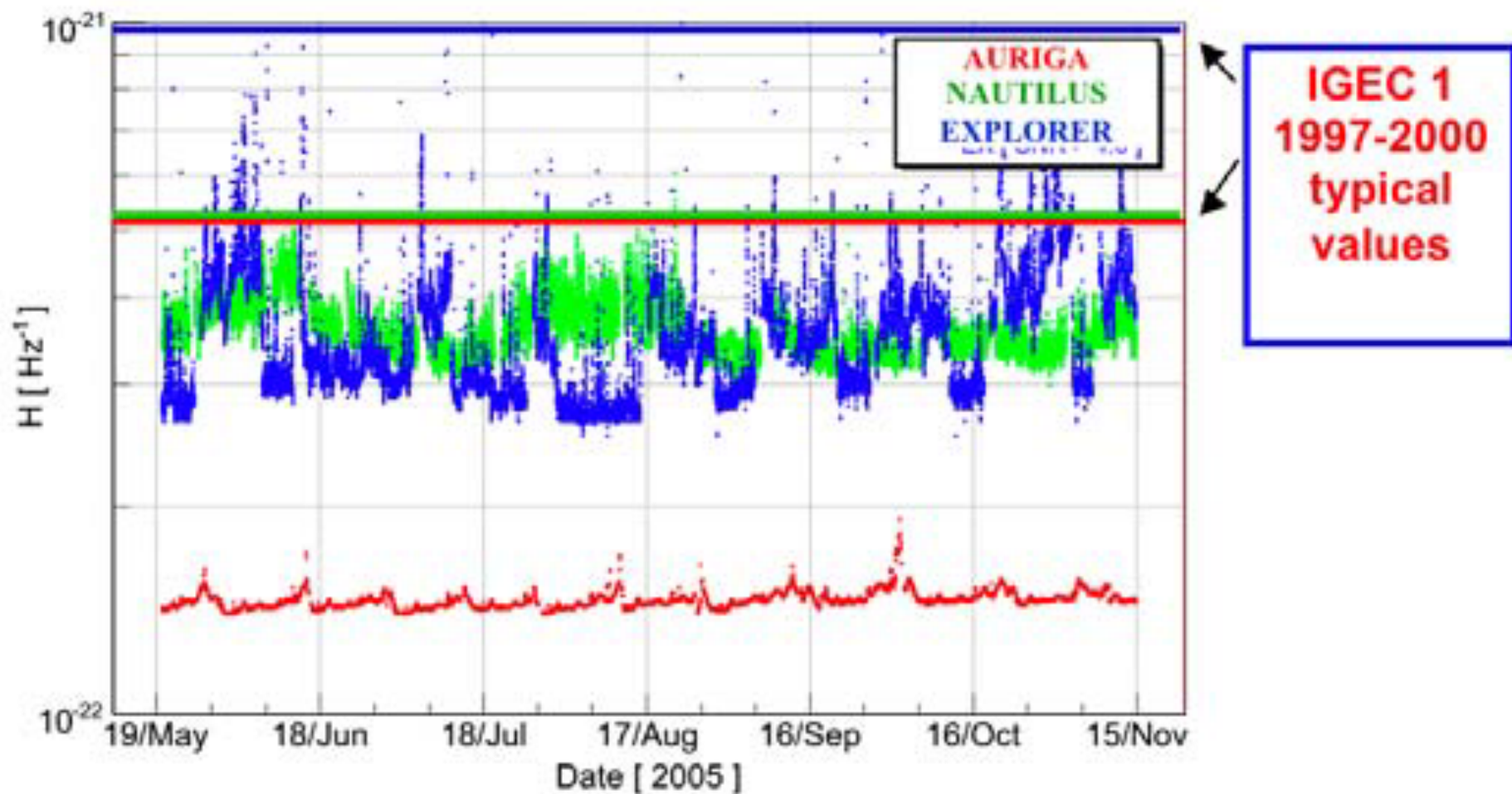
**IGEC 1
1997-2000**



**IGEC 2
2005**



Courtesy of the IGEC2 collaboration



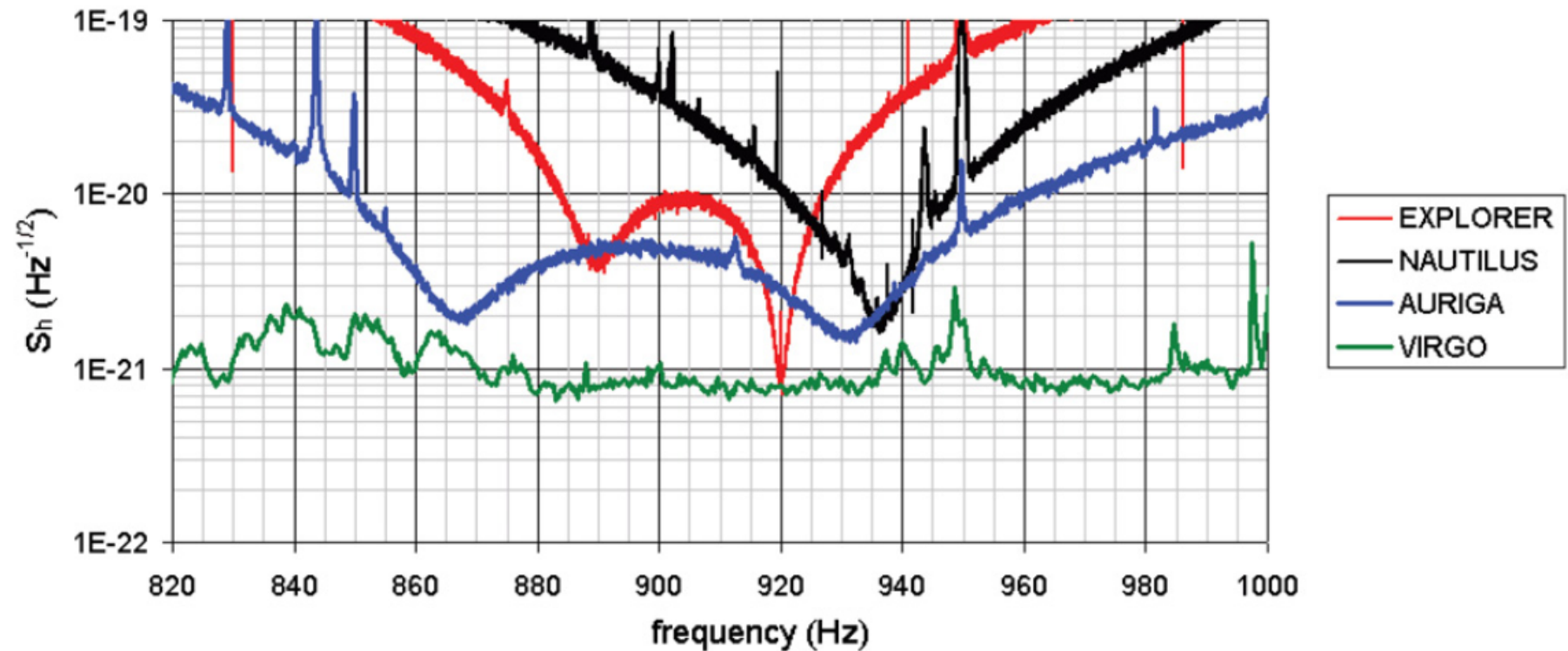


Figure 1. Typical spectral density of calibrated noise for the three resonant bar detectors during 2005 and for the Virgo interferometer in September 2005.

by Arlette de Waard

Gravitational Wave Detectors

● Interferometric

● Resonant-Mass

● LISA

Mario Schenberg,
Brasil



MiniGRAIL
Holanda

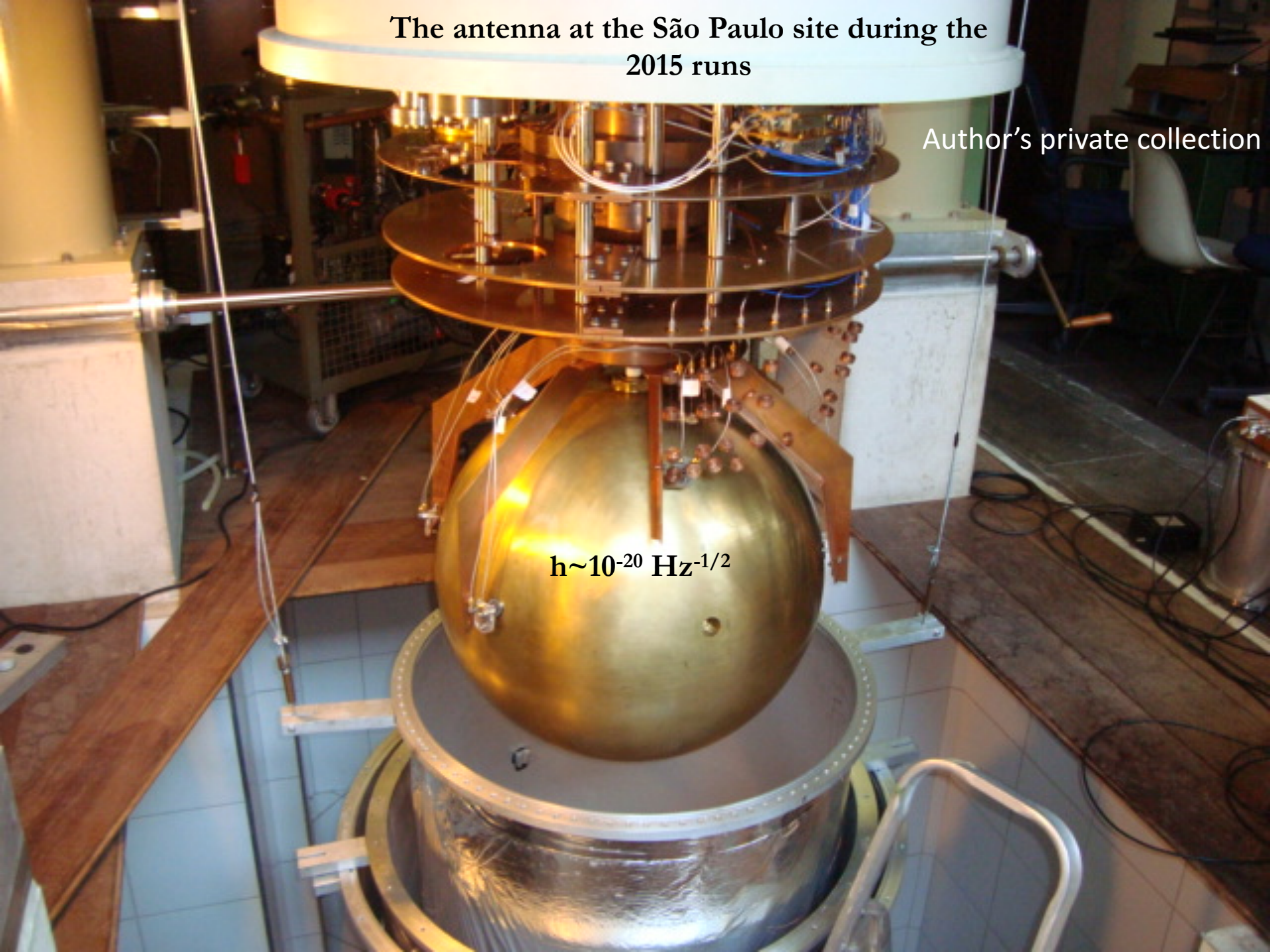
Sfera, Itália



The antenna at the São Paulo site during the
2015 runs

Author's private collection

$h \sim 10^{-20} \text{ Hz}^{-1/2}$



For a detailed gravitational detection history
see Harry Collins Gravity's Shadow
and
Aguiar, O D.

Past, present and future of the Resonant-
Mass gravitational wave detectors,
Research in Astron. Astrophys. 2011 Vol. 11
No. 1, 1–42

Thanks for your attention!

Gravitational Wave Detection History

Lecture 2

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Credit: LIGO lab

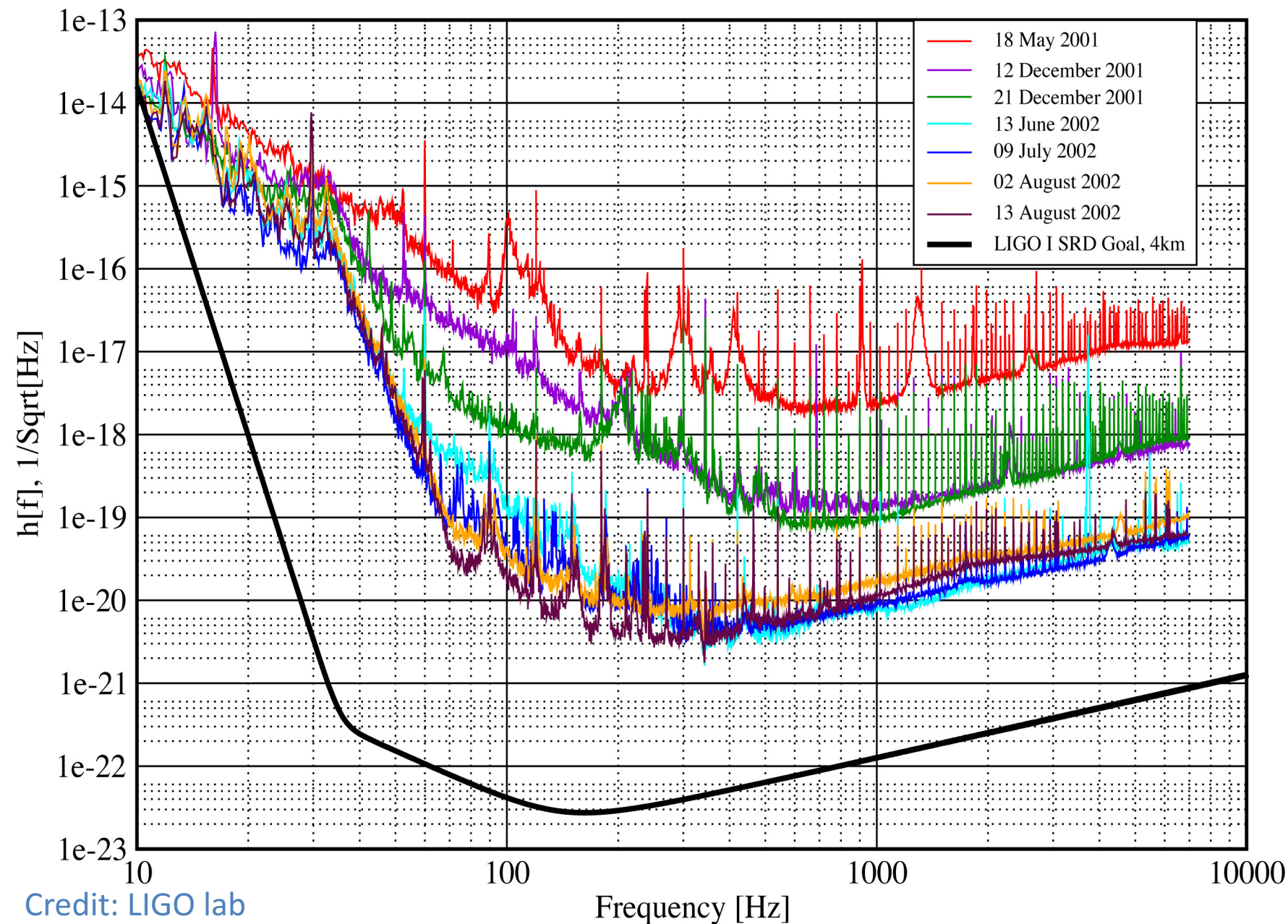
LIGO Timeline (<https://www.ligo.caltech.edu/page/timeline>)

1970s	Early work on gravitational-wave detection by laser interferometers, including a 1972 MIT study describing a kilometer-scale interferometer and estimates of its noise sources
1979	National Science Foundation (NSF) funds Caltech and MIT for laser interferometer research and development
1983	MIT and Caltech jointly present results of the kilometer-scale interferometer study to NSF. Receive NSF committee endorsement on new large programs in physics.
1984	LIGO founded as a Caltech/MIT project. National Science Board approves LIGO development plan.
1986	Physics Decadal Survey and special NSF panel on gravitational wave interferometers endorse LIGO
1990	National Science Board (NSB) approves LIGO construction proposal, which envisions initial interferometers followed by advanced interferometers
1992	NSF selects LIGO sites in Hanford, Washington, and Livingston, Louisiana. LIGO Cooperative Agreement signed by NSF and Caltech.
1994-95	Site construction begins at Hanford and Livingston locations
1997	The LIGO Scientific Collaboration (LSC) is established and expands LIGO beyond Caltech and MIT, including the British/German GWO Collaboration, which operates the GEO600 interferometer in Hannover, Germany.
1999	LIGO inauguration ceremony
2002	First coincident operation of initial LIGO interferometers and the GEO600 interferometer
2004	NSB approves Advanced LIGO
2006	LIGO design sensitivity achieved. First gravitational wave search at design sensitivity. Science Education Center inaugurated at the LIGO Livingston Observatory.
2007	Joint data analysis agreement ratified between LIGO and the Virgo Collaboration, which operates the Virgo interferometer in Cascina, Italy. Joint observations with enhanced initial LIGO interferometer and Virgo.
2008	Construction of Advanced LIGO components begins
2010	Initial LIGO operations conclude; Advanced LIGO installation begins at the observatories.
2011 - 2014	Advanced LIGO installation and testing
2014	Advanced LIGO installation complete
2014-2015	Advanced LIGO sensitivity surpasses Initial LIGO
Sept 14, 2015	Advanced LIGO detects gravitational waves from collision of two black holes
Dec 26, 2015	LIGO observes a second binary black hole coalescence
Jan 12, 2016	First observing run of LIGO advanced detectors ends
Jan 4, 2017	LIGO observes its third binary black hole coalescence
Aug 14, 2017	Gravitational waves from a binary black hole merger observed by LIGO and Virgo
Aug 17, 2017	LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars
Aug 25, 2017	Second observing run of LIGO advanced detectors ends
Oct 3, 2017	LIGO co-founders Rainer Weiss, Barry Barish, and Kip Thorne are awarded the 2017 Nobel Prize in Physics

Strain Sensivities for the LIGO Livingston 4km Interferometer, E7 to S1

18 May 2001 - 13 August 2002

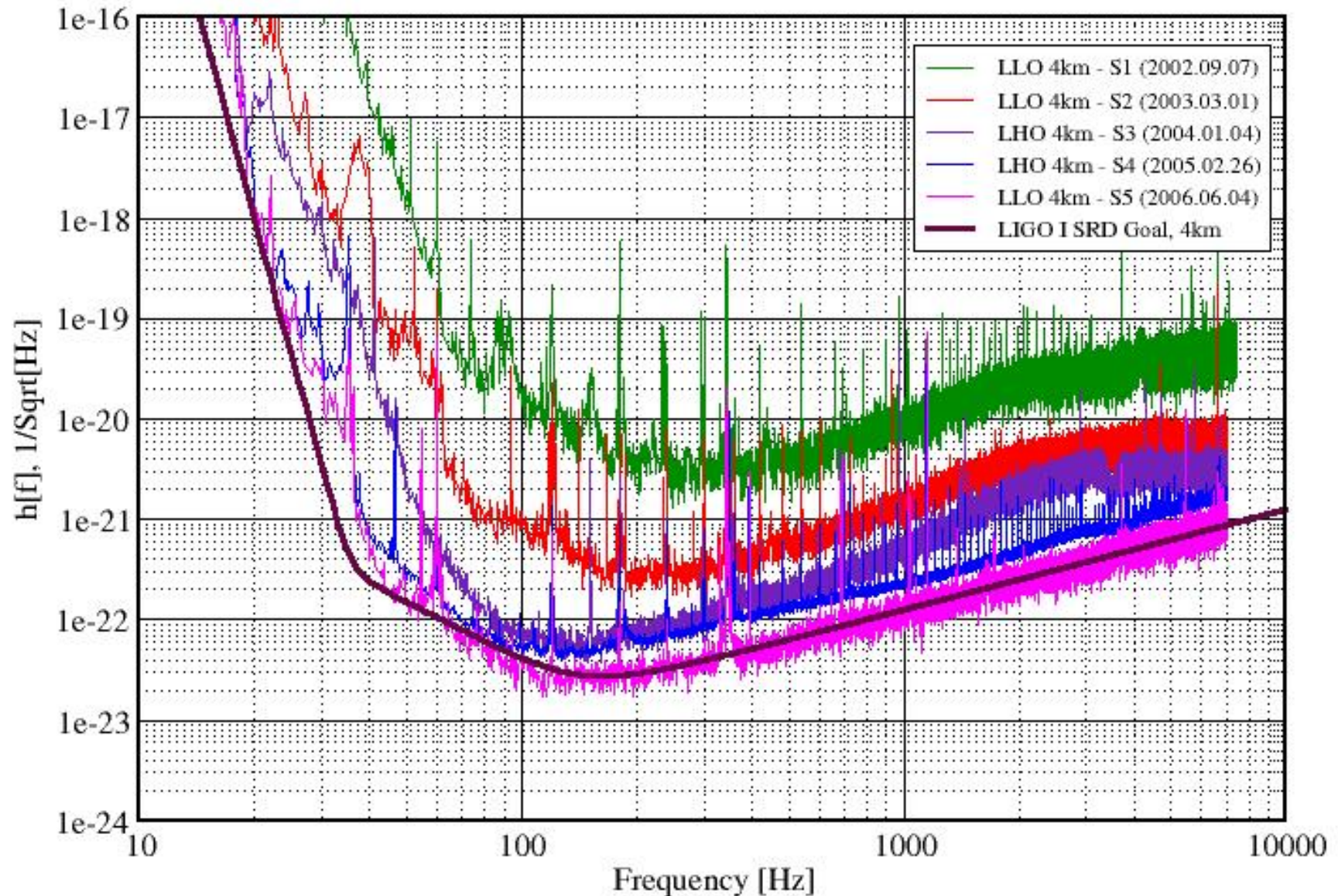
LIGO-G020451-00-E



Best Strain Sensivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs

LIGO-G060009-02-Z



The Japanese Program on Laser Interferometer (credit TAMA/KAGRA groups)

TAMA 20 (1991-1994) (at Mitaka campus of the National Astronomical Observatory of Japan, in Tokyo)

TAMA 300 - Construction started in 1995. Data were collected from 1999 to 2004.

CLIO - a 100 m *Cryogenic Laser Interferometer Observatory* prototype in Kamioka mine.

KAGRA (*Kamioka Gravitational Wave Detector*):

The excavation phase of tunnels was started in May 2012 and was completed on 31 March 2014.

TAMA (Japanese) $L=300m$

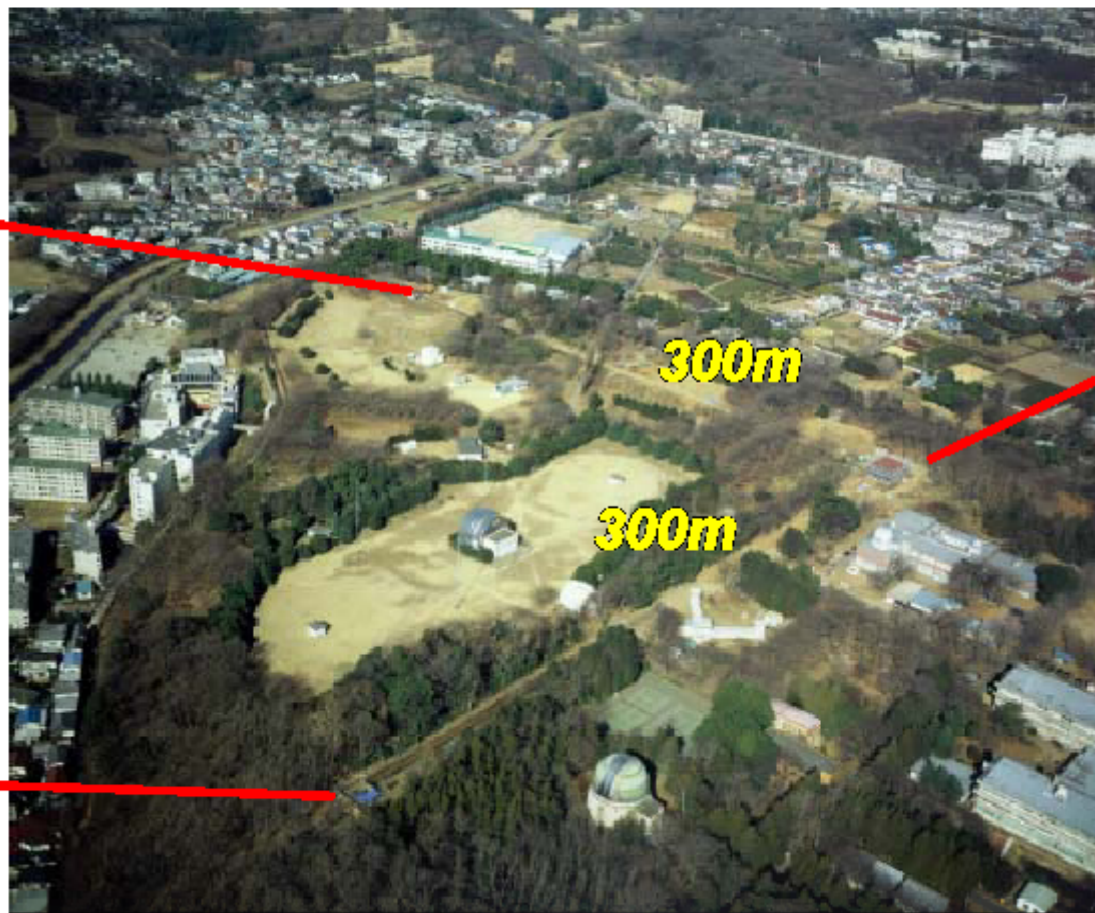
- サイト: 国立天文台三鷹キャンパス(東京)

(E139.32.21 N35.40.25)

West
End
Room

Center
Room

South
End
Room



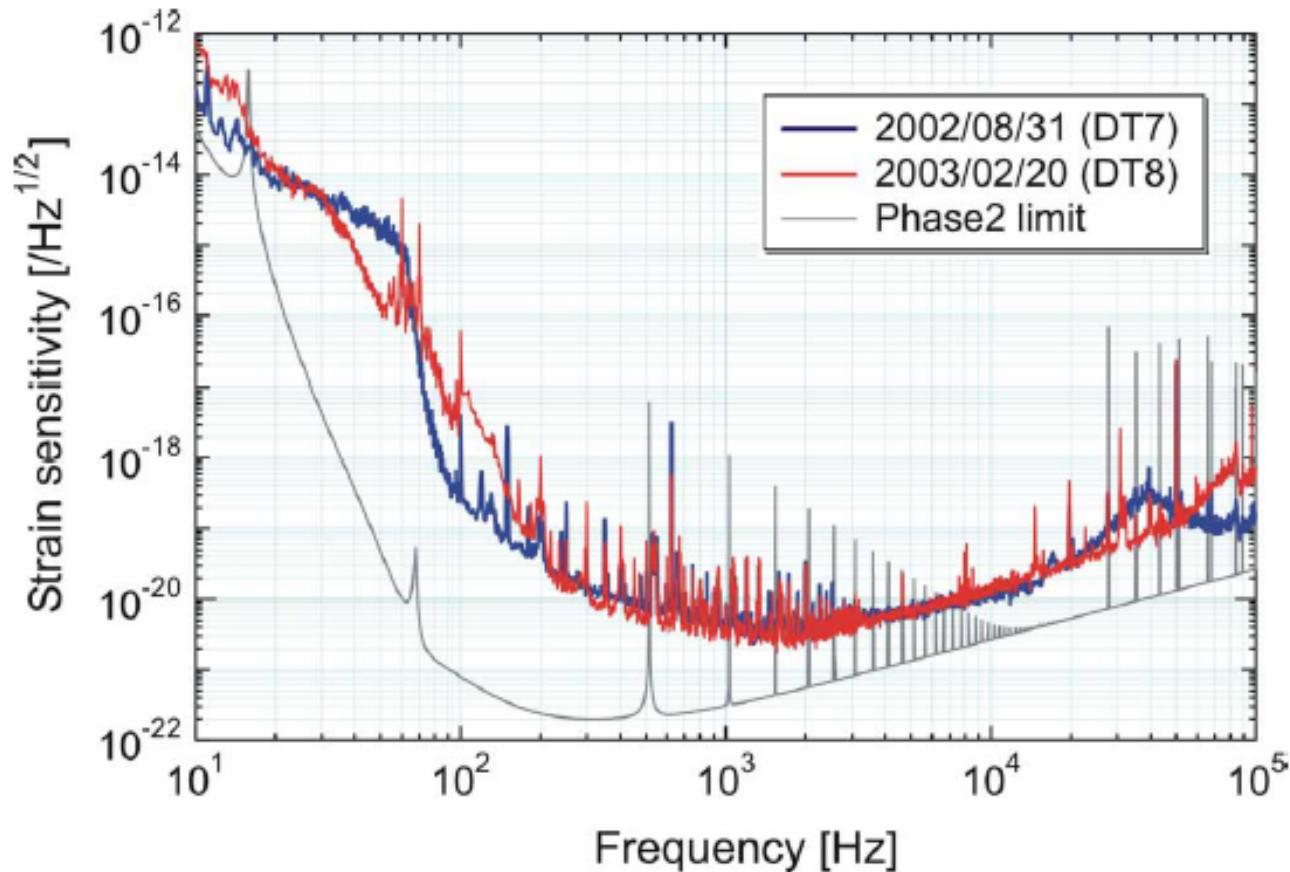
市街地の真っ只中に位置・交通量多し

Credit: TAMA group

Sensitivity in DT8

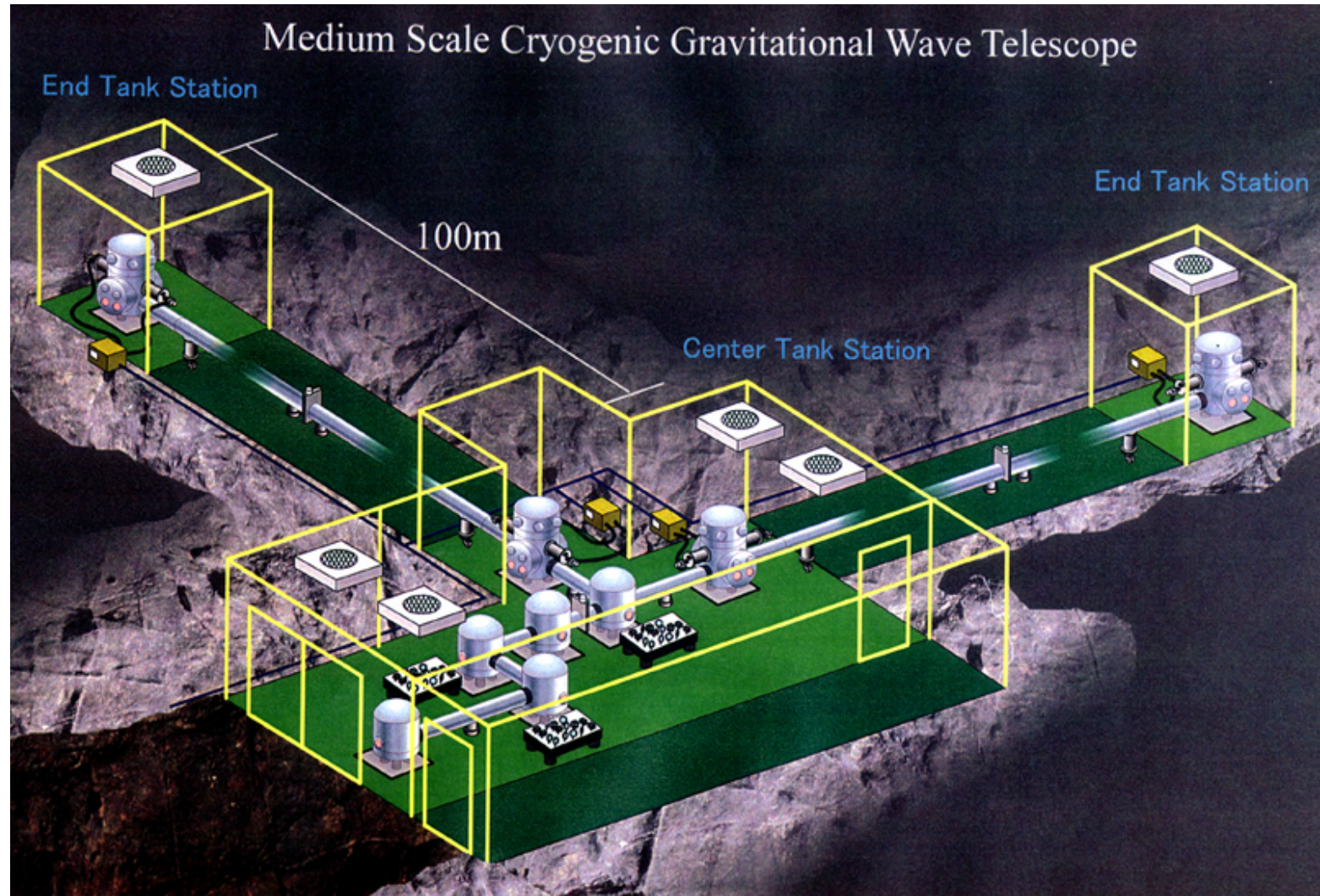
Reduced non-stationary fluctuation owing to wide band filters for the alignment control

Improved strain sensitivity: $h=2.7 \times 10^{-21} \text{ /Hz}^{1/2} \text{ @2kHz}$



Future Laser Interferometer *criogenic mirrors*

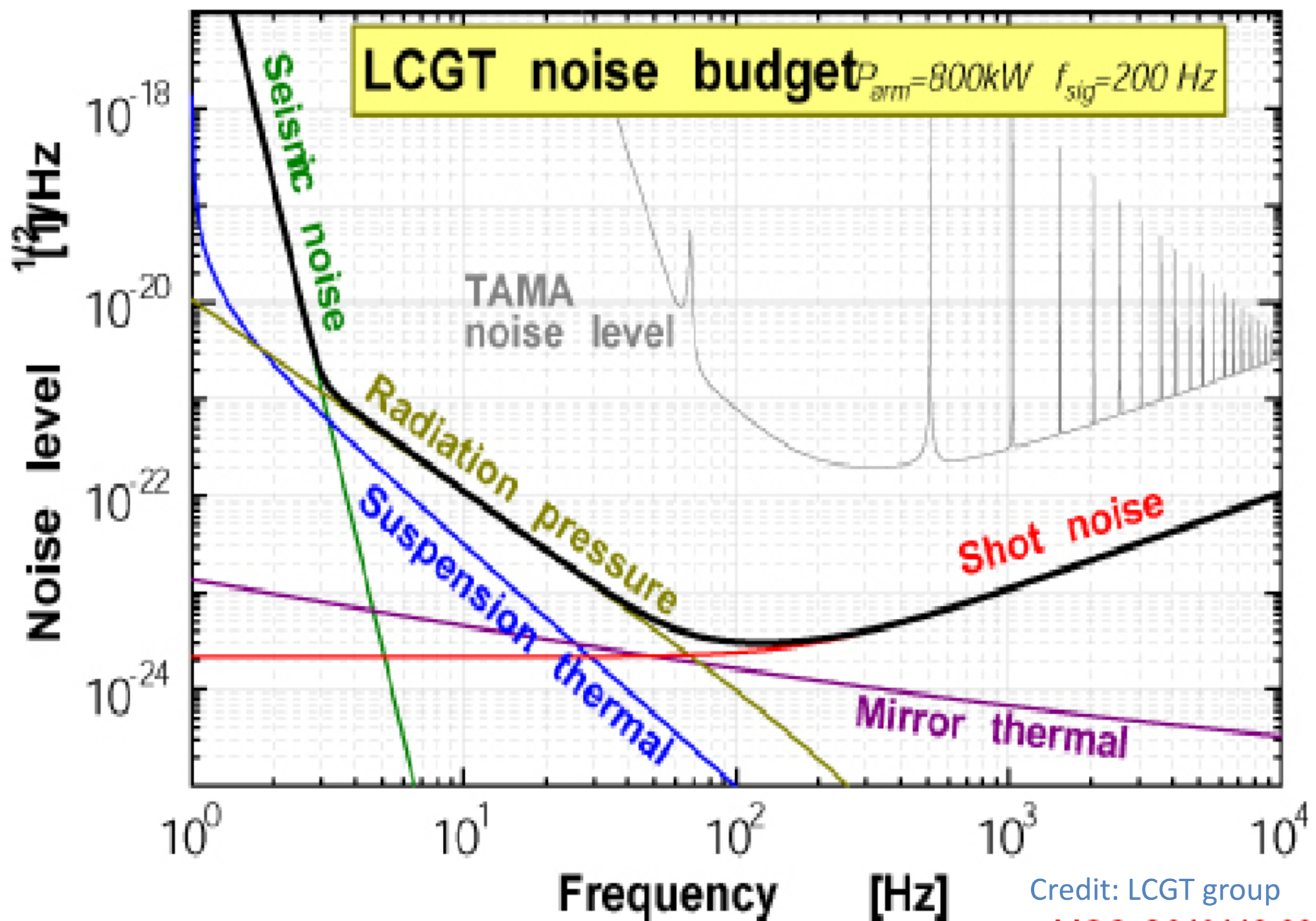
Credit: CLIO group



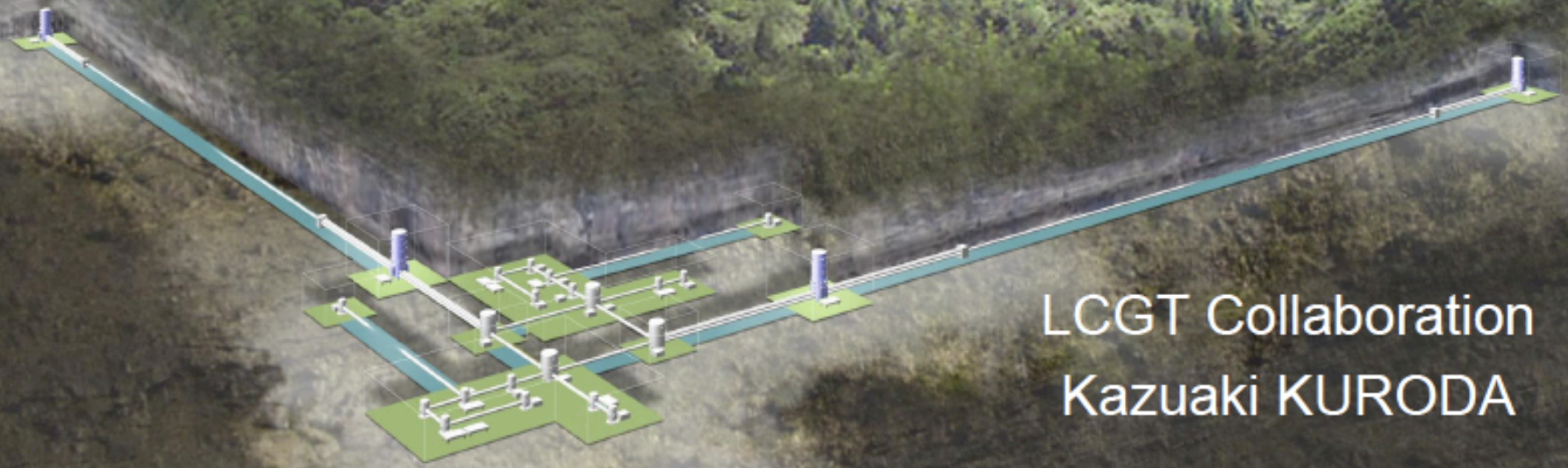
CLIO

- 100m cryogenic prototype in Kamioka mine

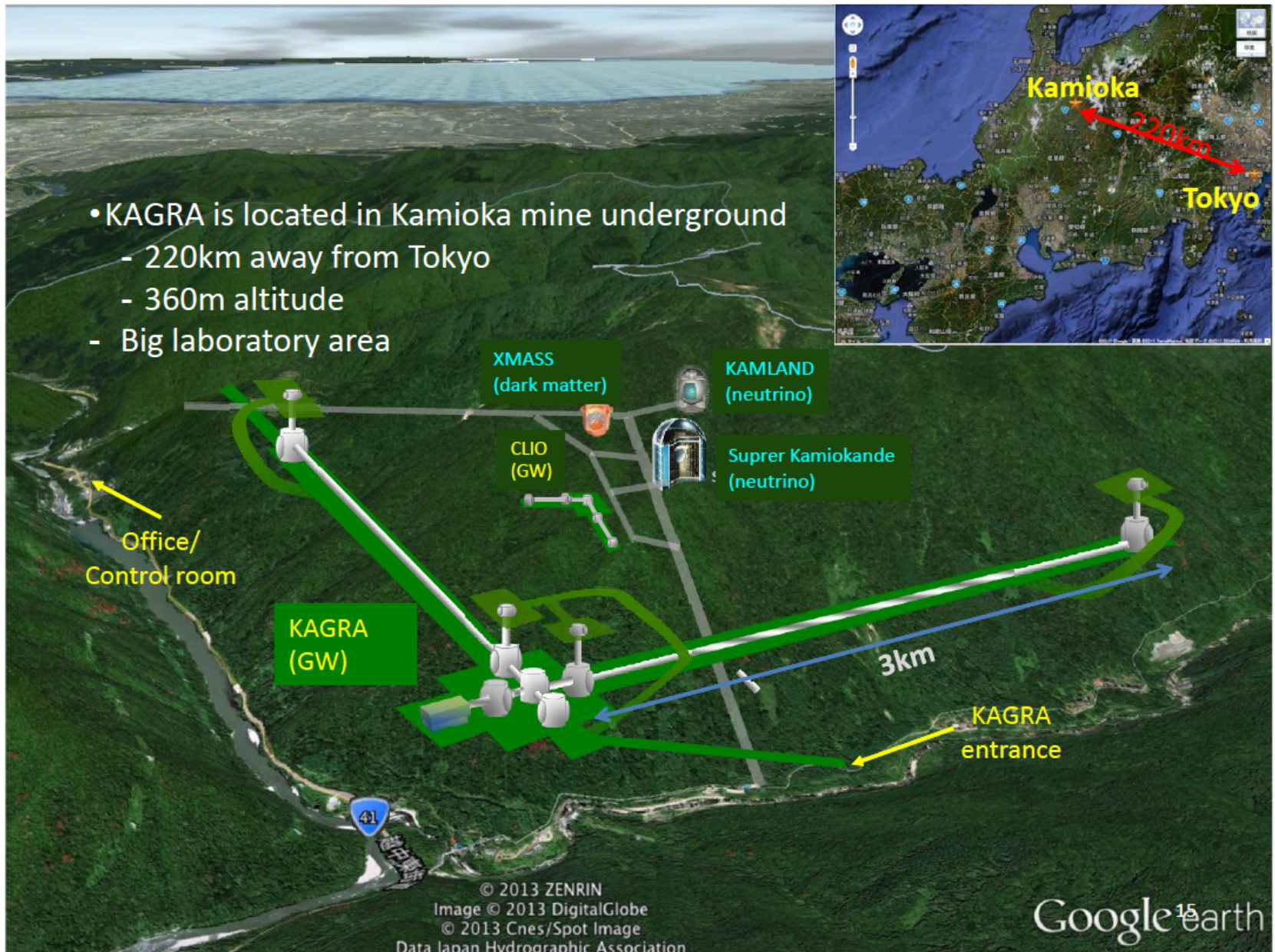




Present Status of LCGT



LCGT Collaboration
Kazuaki KURODA



GEO Diary (http://www.geo600.org/1297795/GEO_Diary)

2006

May 2006: GEO600 joins the S5 science run

2005

Science run 4: February and March, 2005.

2004

Most of the time in 2004 has been spent to upgrade the detector.

2003

Science run 1 and science run 3.

2002

Improvement of the GEO sensitivity and science run 1.

2001

Installation of optical components and their suspensions, and the laser.

2000

Installation of suspensions, testing of new control system

1999

Installation of modecleaner tank TCMA, test run of the main suspension

1998

Final design review and installation of the modecleaner double pendulums, GEO600 has been registered as one of the Projects of the World Exposition EXPO 2000 in Hannover

1997

Welding of the second tube, installation of the cleanroom facilities for the central station, insertion of the liners, wrapping the tube,

1996

Erection of buildings, ramming of the trench, installation of the rail in the trench,

1995

GEO600 Groundbreaking Party, building of the central house and the eastern end house,

GEO Diary (http://www.geo600.org/1297795/GEO_Diary)

November 2016 – Advanced LIGO detectors begin second observation run “O2”

GEO600 taking data simultaneously with Advanced LIGO instruments

February 2016 – direct detection of gravitational waves

Predicted by Einstein 100 years ago, gravitational waves have now been directly detected for the first time. The signal of two merging black holes has been found by the LIGO detectors in Hanford and Livingston, USA.

September 2015

GEO600 taking data simultaneously with advanced LIGO

2015

Spatially resolved heating of the beam-splitter

2014

Towards a darker dark port – installation of a new thermal compensation system

2013

Squeezing was used over one complete year in GEO600

2012

Upgrading the modecleaner optics for higher laser power

2011

GEO600-Virgo 3-month joint run

2010

Summer 2010: Implementation of squeezed light in GEO600

2009

July 2009: Start of S6/VSR2

2008

Astrowatch

2007

Damages at the control system, short circuits, and preparations for a maintenance period.

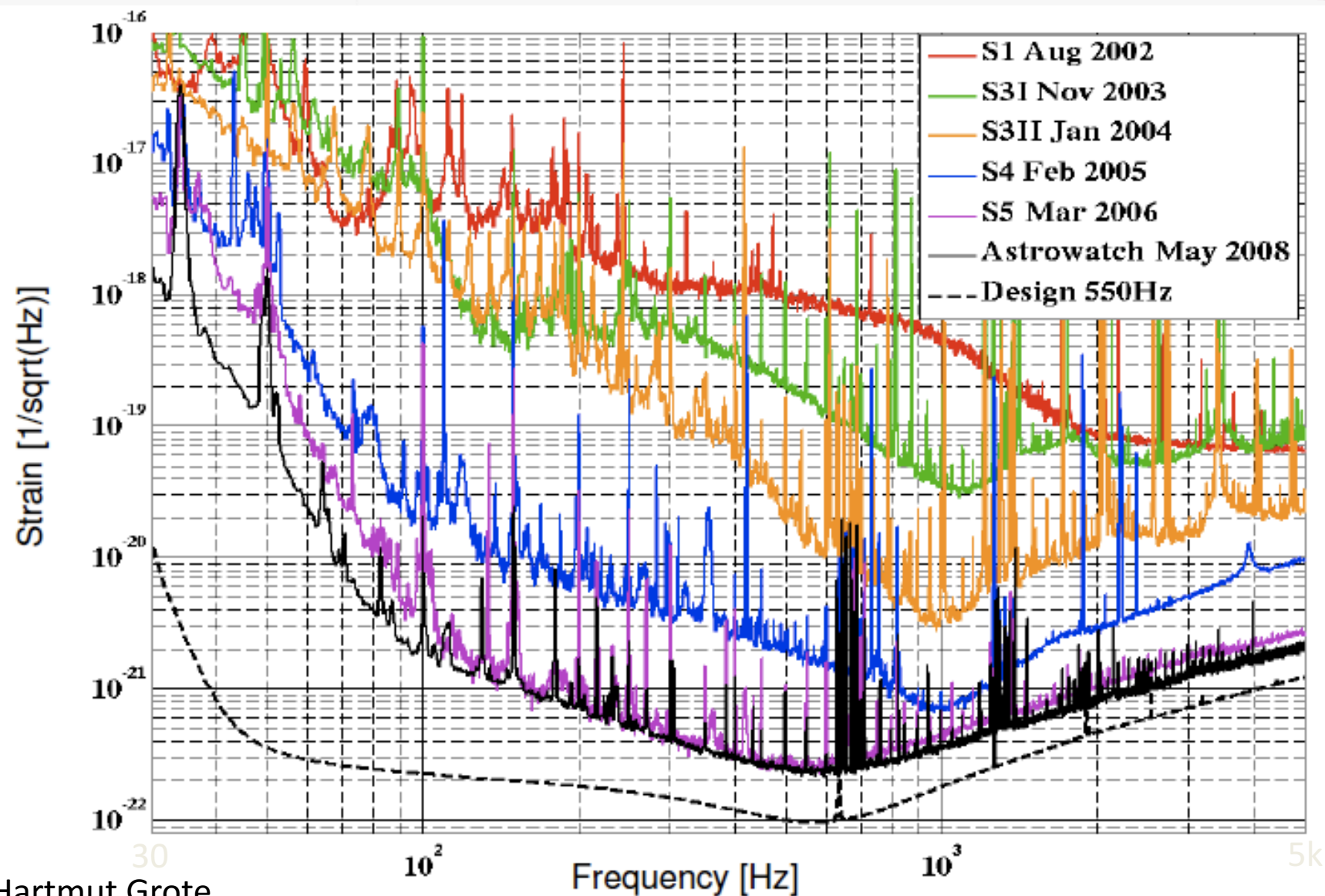
GEO 600

German-British collaboration
Site in Hanover (Germany)



Credit: GEO 600 group

GEO Sensitivities



Virgo Interferometer History (credit Virgo group)

“The Virgo project was approved in 1993 by the French CNRS and in 1994 by the Italian INFN, the two institutes at the origin of the experiment.

The construction of the detector started in 1996 in the Cascina site near Pisa, Italy.

In December 2000, CNRS and INFN created the European Gravitational Observatory (EGO consortium), later joined by the Netherlands, Poland, Hungary and Spain.

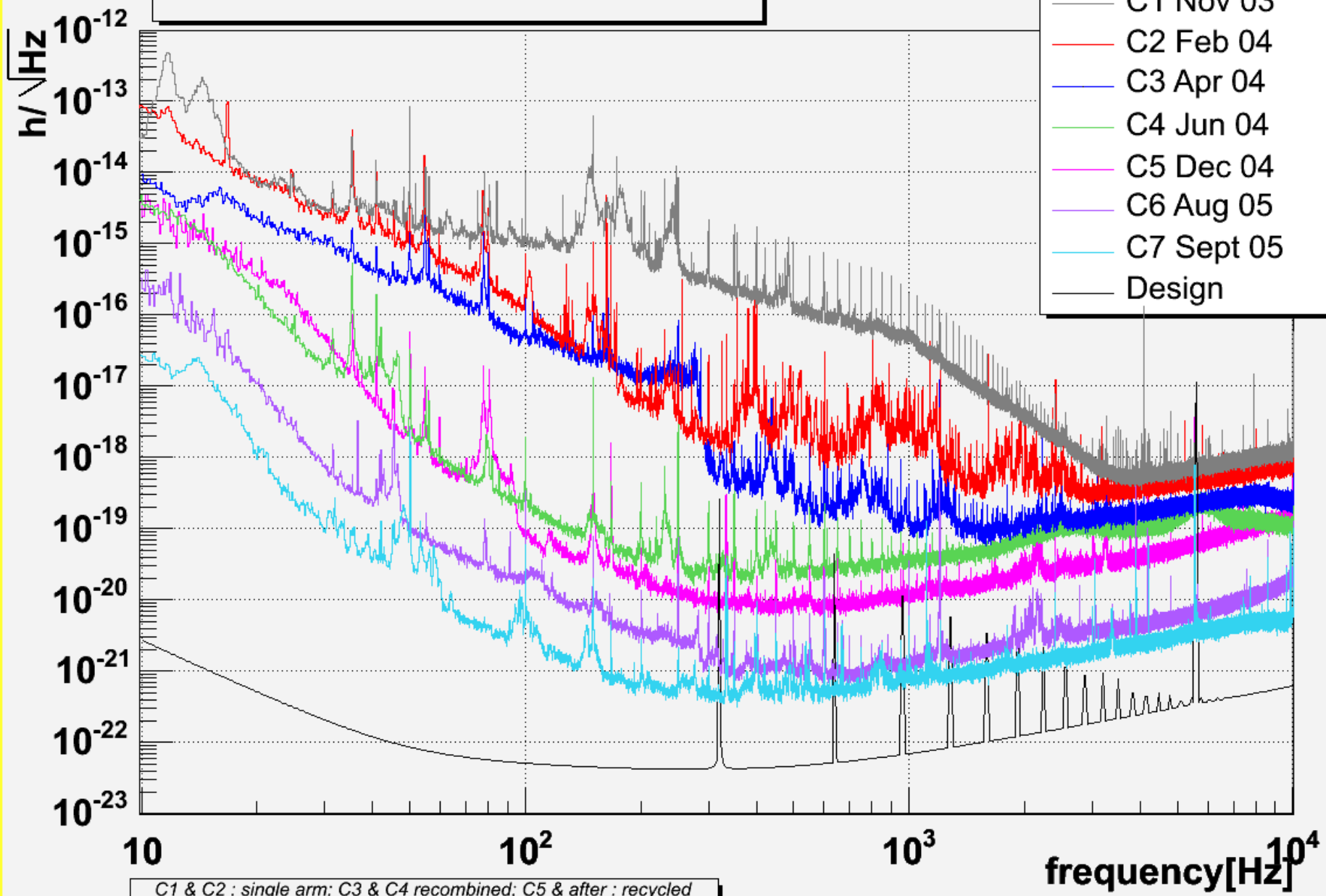
By December 2015, 19 laboratories plus EGO were members of the Virgo collaboration.

In the 2000s, the "initial" Virgo detector was built, commissioned and operated.

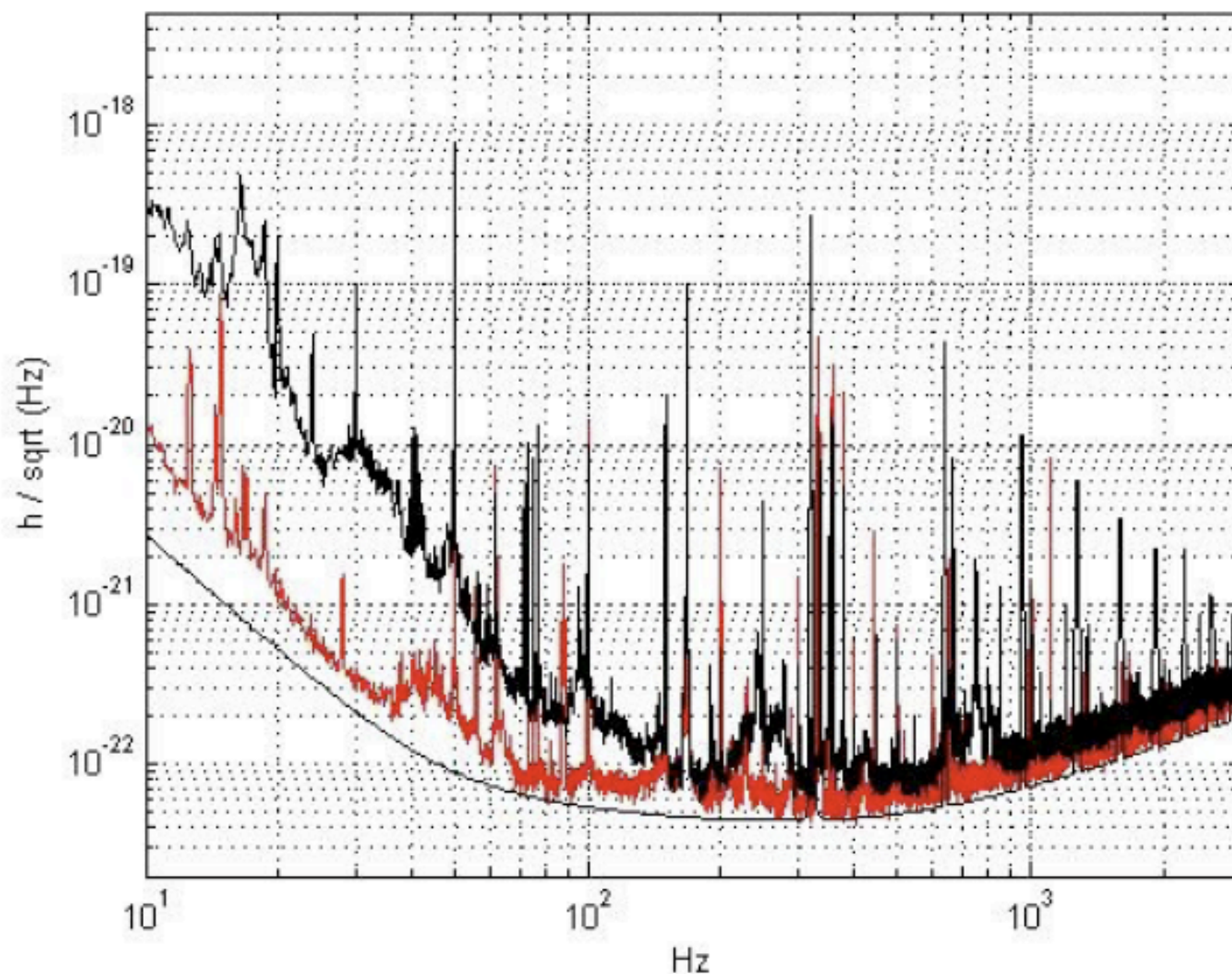
The construction of the initial Virgo detector was completed in June 2003 and several data taking periods followed between 2007 and 2011. Some of these runs were done in coincidence with the two LIGO detectors. Then a long upgrade to the second generation detector, called Advanced Virgo, started in 2011.”

It returned back with high sensitivity on August 1st, 2017, and in the August 14 and August 17 of 2017, it detected GW events together with LIGO.

Virgo Commissioning Runs Sensitivities



Sensitivity



May 2007: ~ 3 Mpc

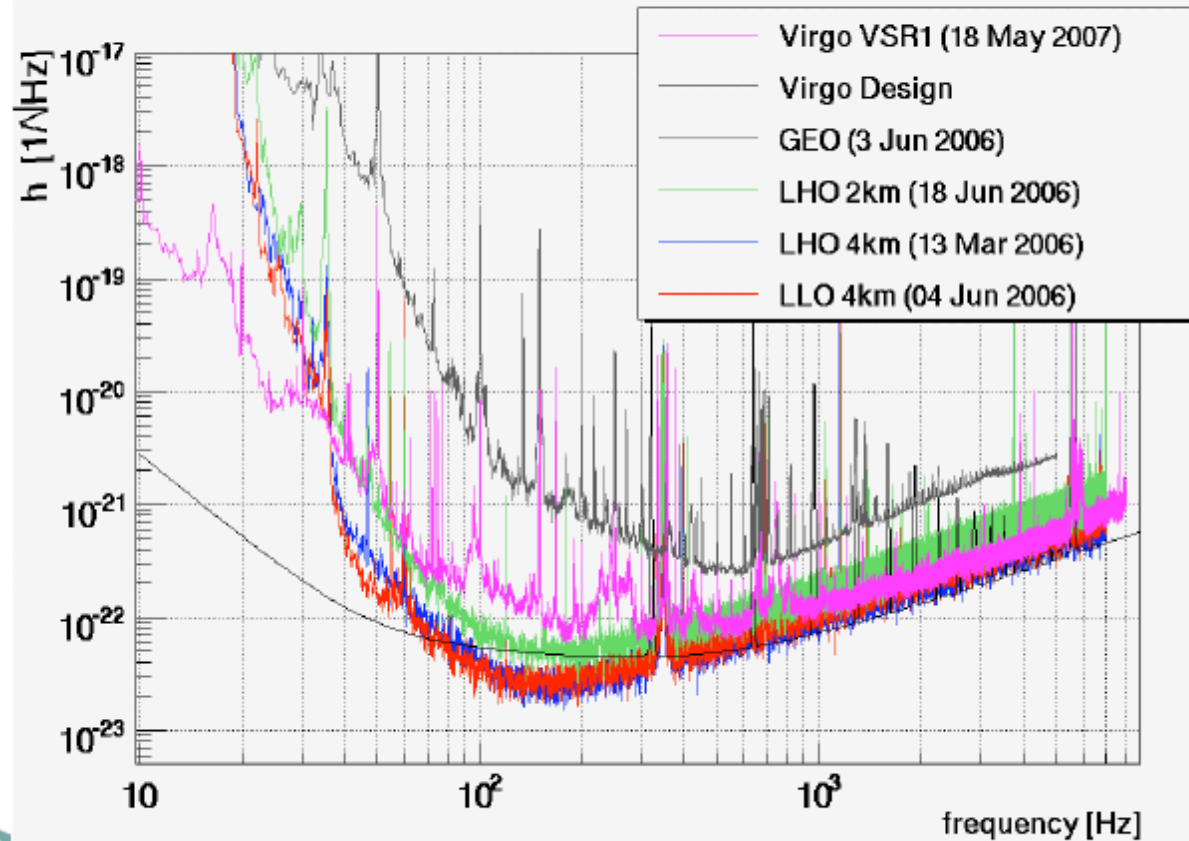
May 2009: ~ 8 Mpc

AIGO (Australian International Gravitational-wave Observatory)

- 8km x 8km AIGO site 70km north of Perth
- Currently operating 80m High Optical Power interferometer test facility in collaboration with LIGO.



GW network sensitivity



by Arlette de Waard



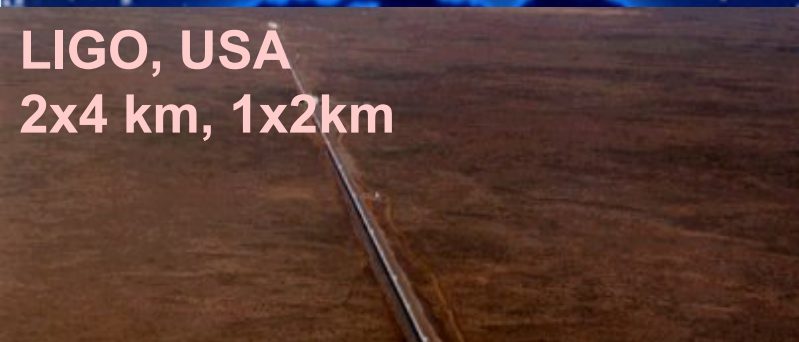
VIRGO, Itália
3 km



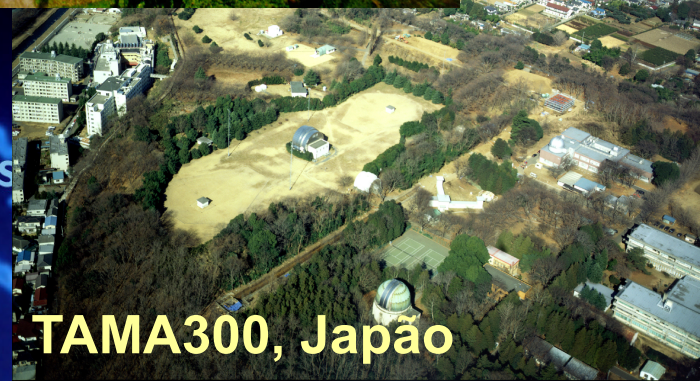
GEO600
Alemanha

tectors

LIGO, USA
2x4 km, 1x2km



MINIGRAIL
GEO
XPLORER AURIGA
VIRGO NAUTILUS



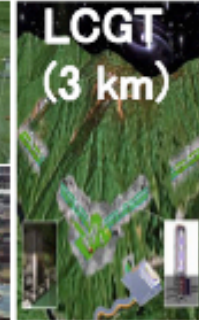
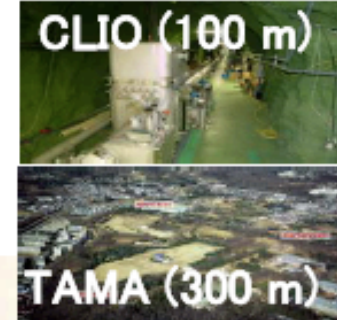
TAMA300, Japão



AIGO, Austrália



Detectors around the world





Barry C. Barish (Caltech)



Kip S. Thorne (Caltech)



Rainer Weiss (MIT)



2017 Nobel Prize in Physics

Multimessenger Astrophysics: Simultaneous search with instruments in the electromagnetic window

Less than two years after the inauguration of the gravitational wave astrophysics, GW170817 marks a new era of discover.



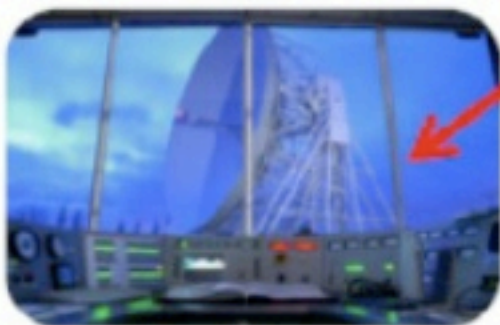
optical



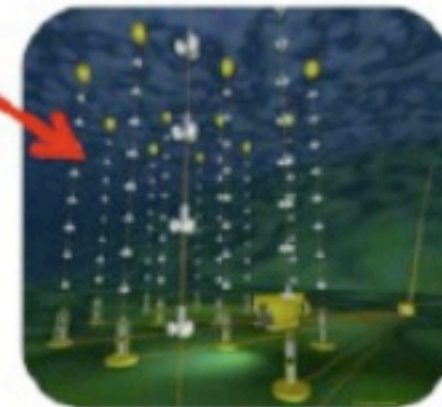
gamma rays,
x-rays

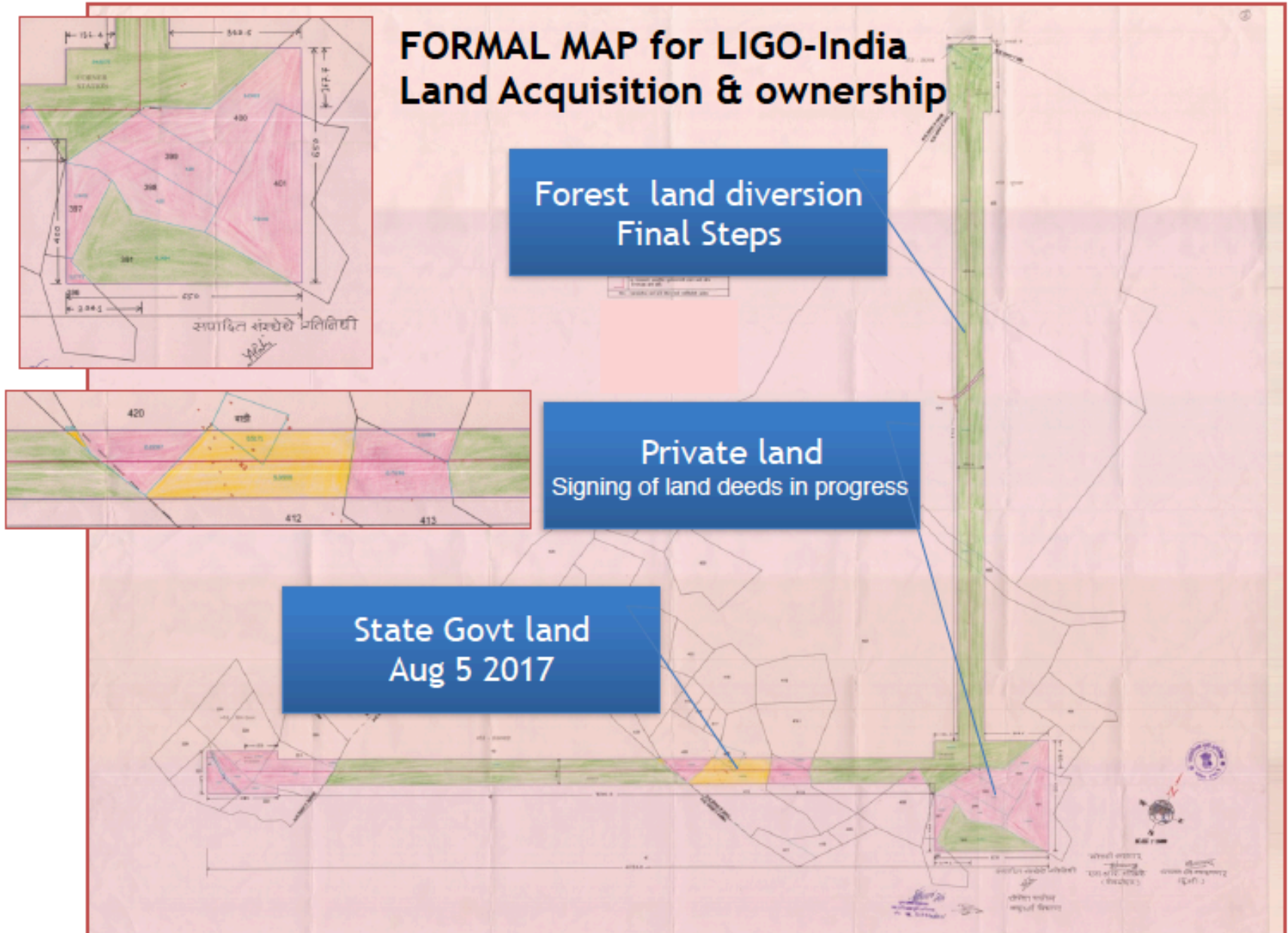


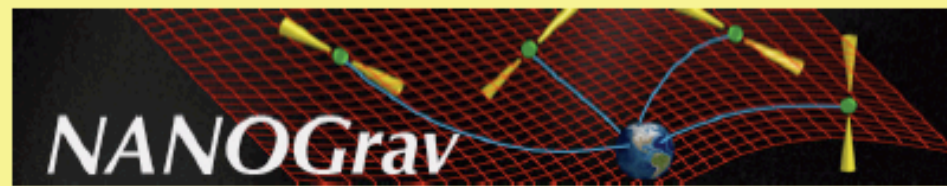
radio



neutrinos







International Pulsar Timing Array (IPTA)

- **NANOGrav**
- **Parkes Pulsar Timing Array (PPTA)**
(See talk by Joris Verbiest)
- **European Pulsar Timing Array (EPTA)**
(See talk by Robert Ferdman)

All members of GWIC



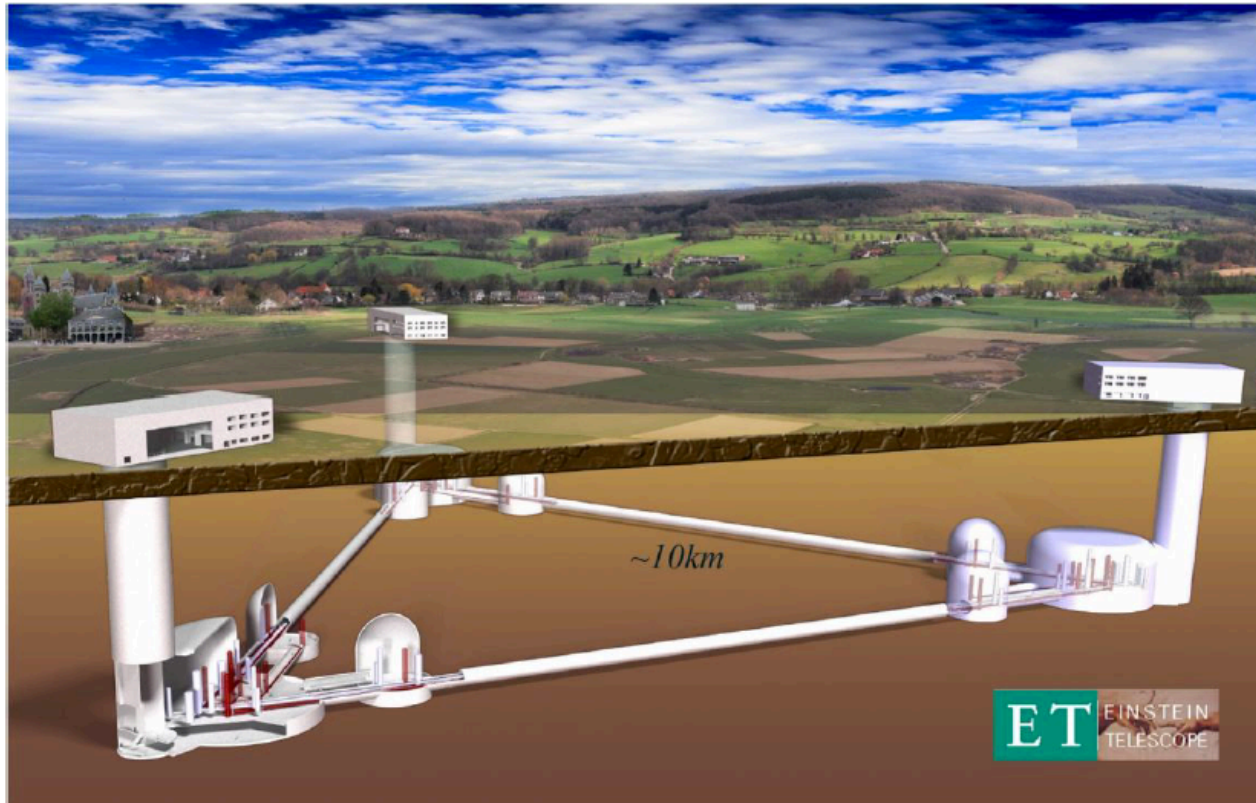
Cosmic Explorer (US)

- Third-generation GW observatory
- Target sensitivity a factor of > 10 improvement in comparison to current advanced detectors
- Above ground, 40 km arm length, L configuration

Formal Design Study: not yet, but proposal under development (M. Evans, MIT, PI)



The Einstein Telescope



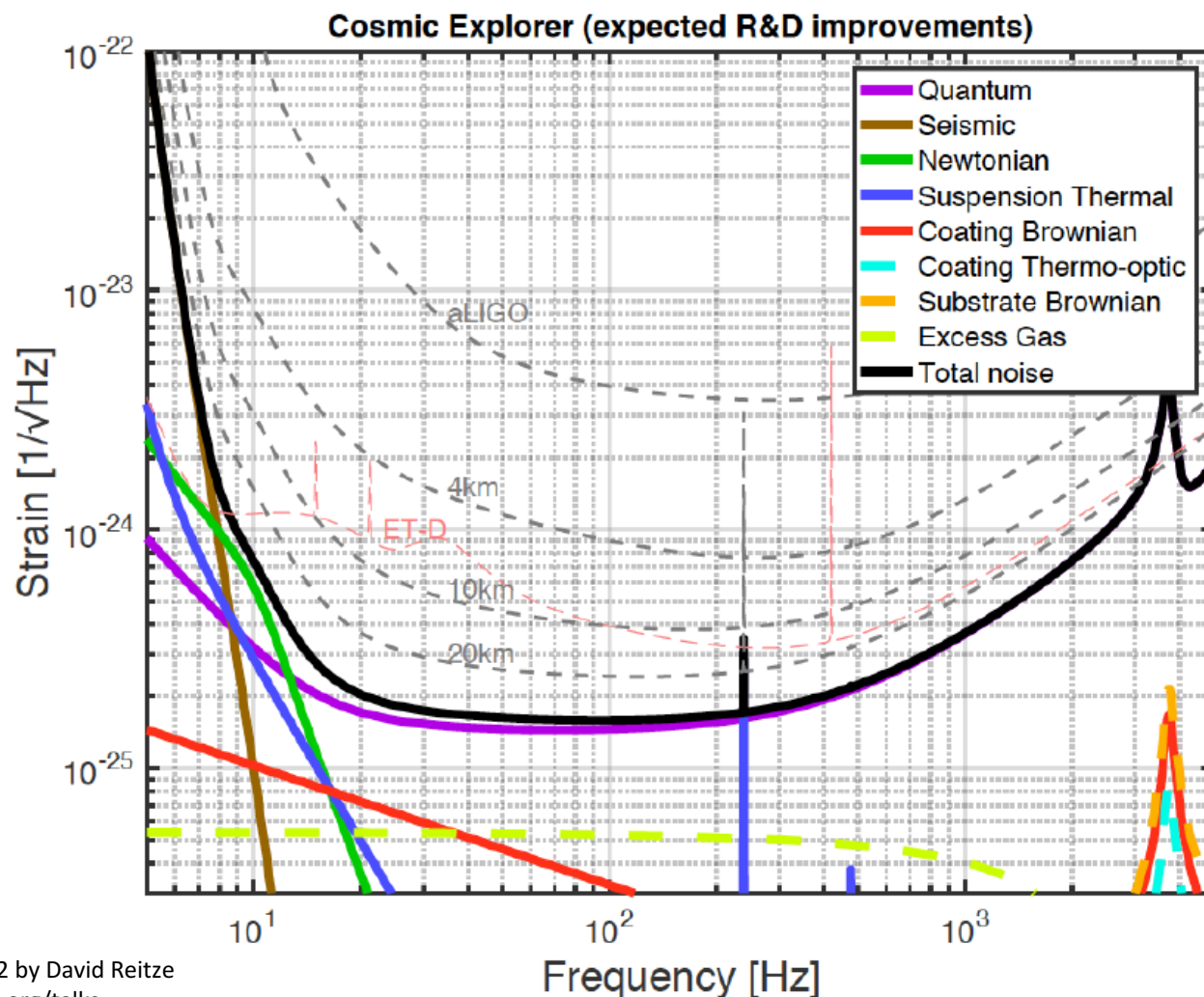
Scientific objectives of Einstein Telescope

Sathyaprakash, B. and Ajith, P. and Corsi, A. and Favata, M. and Harms, J. and Ott, C. D. and Santamaría, L.
(2012) *Scientific objectives of Einstein Telescope*. Classical and Quantum Gravity

Abstract

The advanced interferometer network will herald a new era in observational astronomy. There is a very strong science case to go beyond the advanced detector network and build detectors that operate in a frequency range from 1 Hz to 10 kHz, with sensitivity a factor 10 better in amplitude. Such detectors will be able to probe a range of topics in nuclear physics, astronomy, cosmology and fundamental physics, providing insights into many unsolved problems in these areas.

The 3G Sensitivity Horizon (circa 2017)

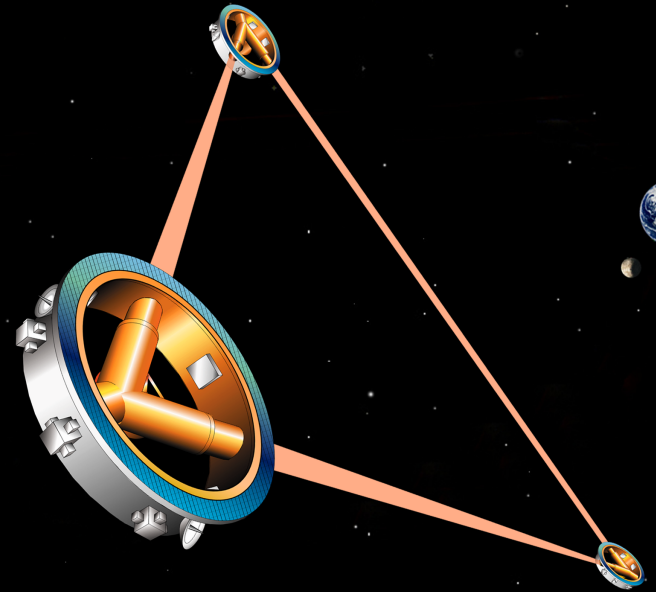


Presented at Amaldi12 by David Reitze
<http://www.amaldi12.org/talks>

LSC Instrument Science White Paper 2017-2018, LIGO-T1700231-v2

Space Interferometers:

**LISA, ALIA
and BBO**



Credit: LISA consortium

For a detailed gravitational detection history
see Harry Collins Gravity's Shadow
and
Aguiar, O D.

Past, present and future of the Resonant-
Mass gravitational wave detectors,
Research in Astron. Astrophys. 2011 Vol. 11
No. 1, 1–42

Thanks for your attention!