LIGO's first detection of gravitational waves and the development of KAGRA

KMI2017
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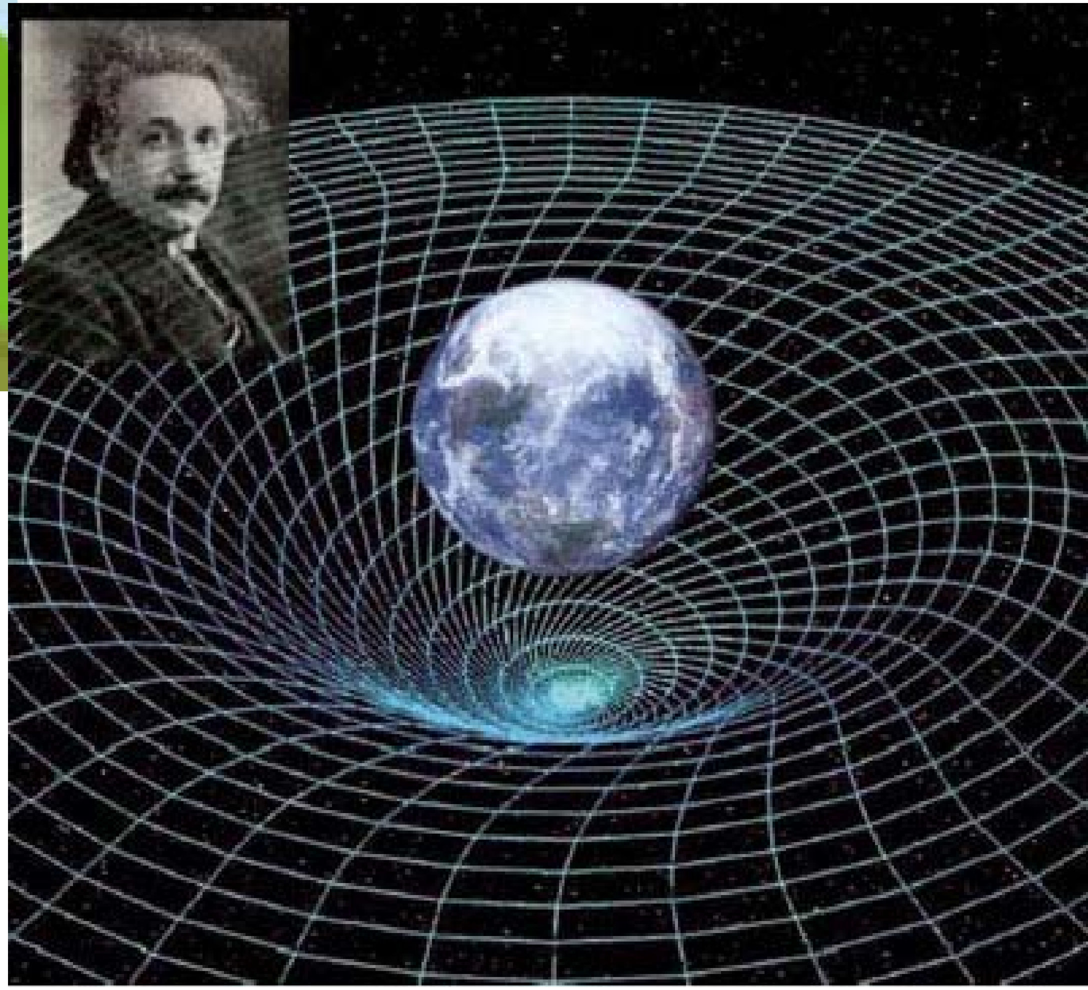
Self Introduction

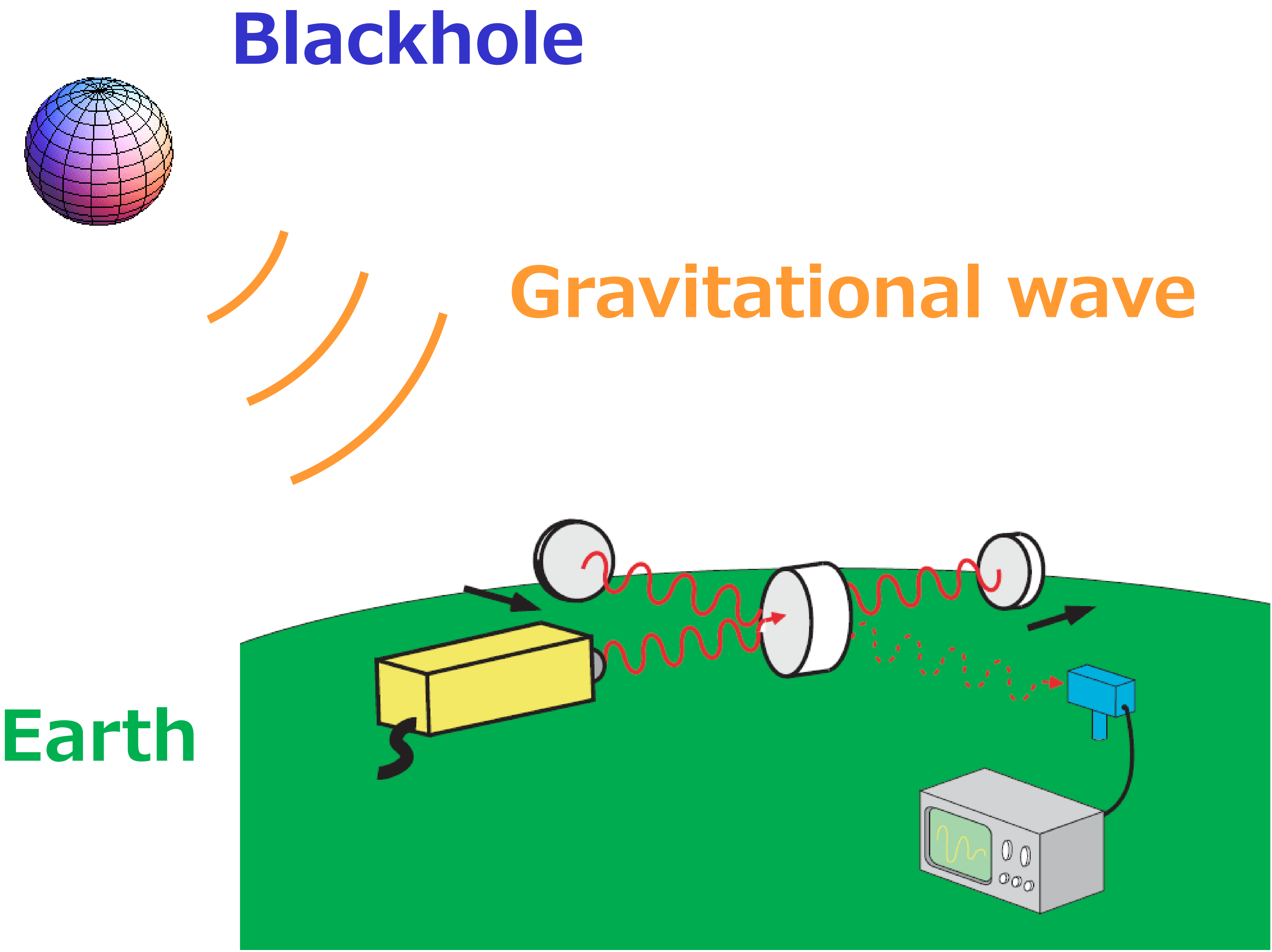
- Applied Physics (U Tokyo)
- NAOJ 2000-04
- Albert-Einstein Institute 2005-07

- Caltech 2008-2009
- WIAS 2010
- Tokyo Tech 2011~

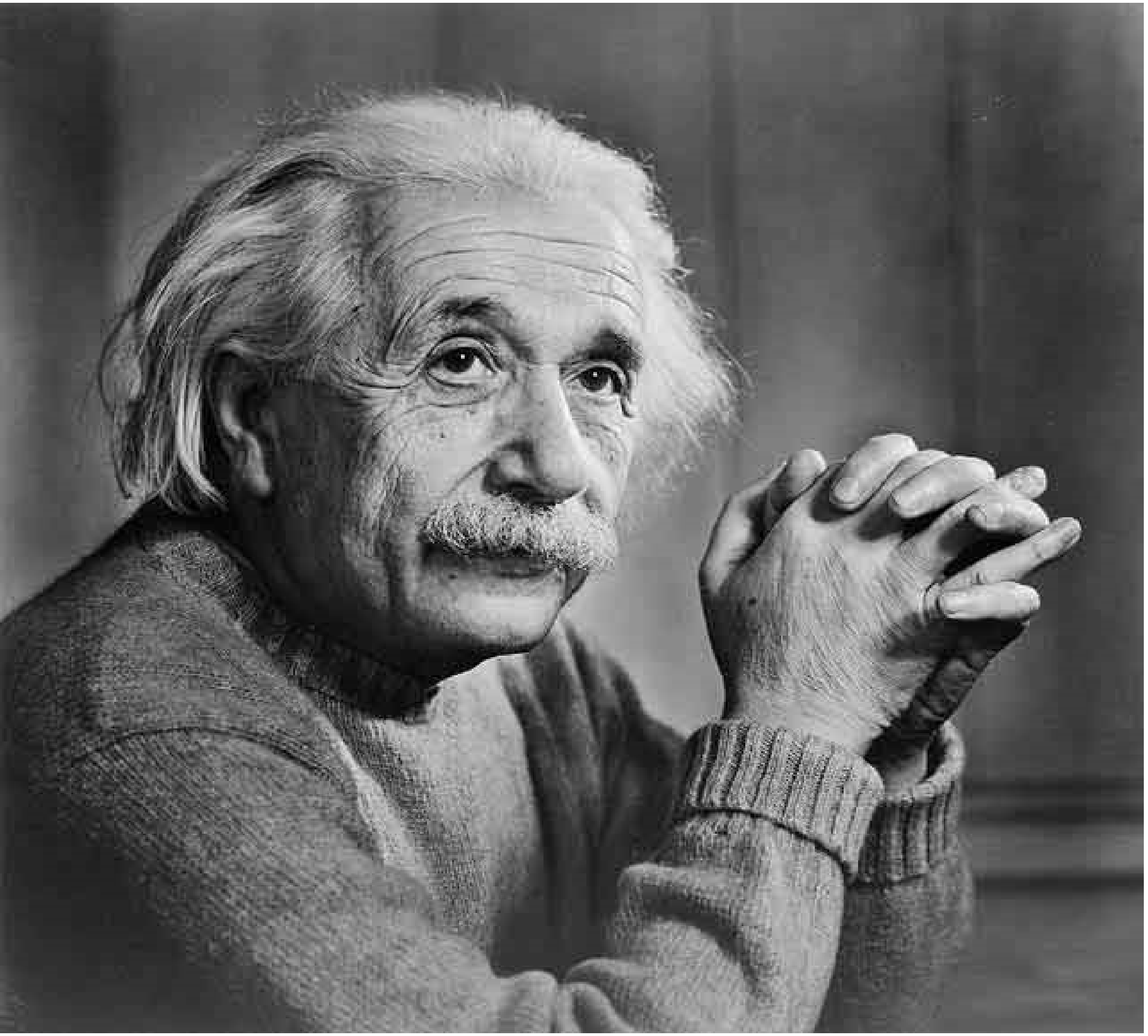
Gravity



Spacetime



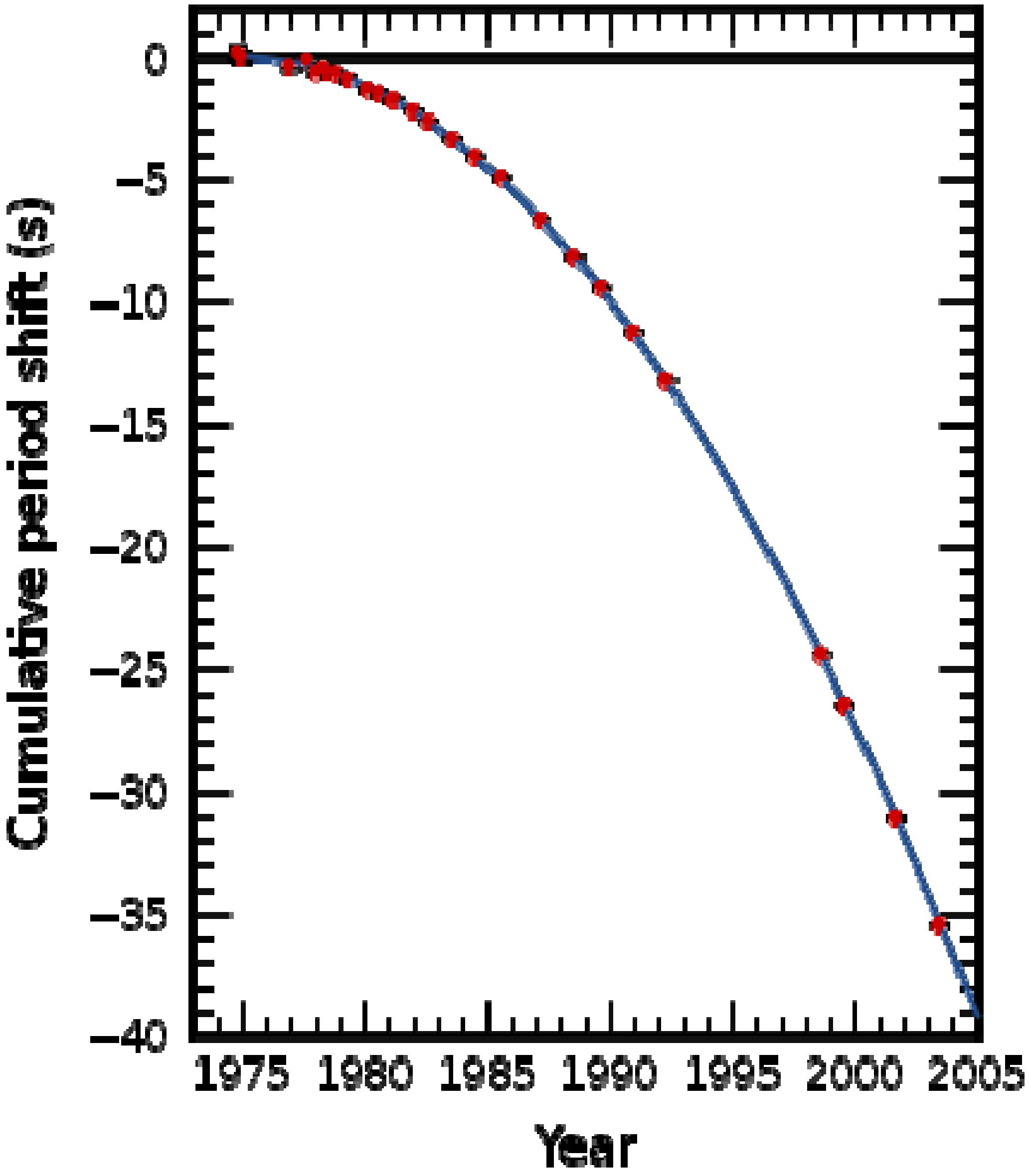
Blackhole
Gravitational wave
Earth



1916 Einstein

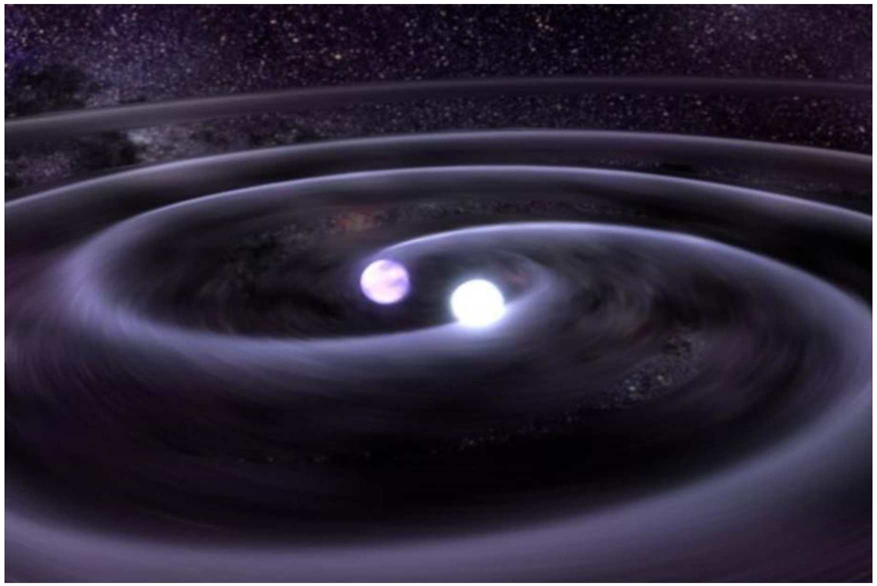
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

1969 Weber

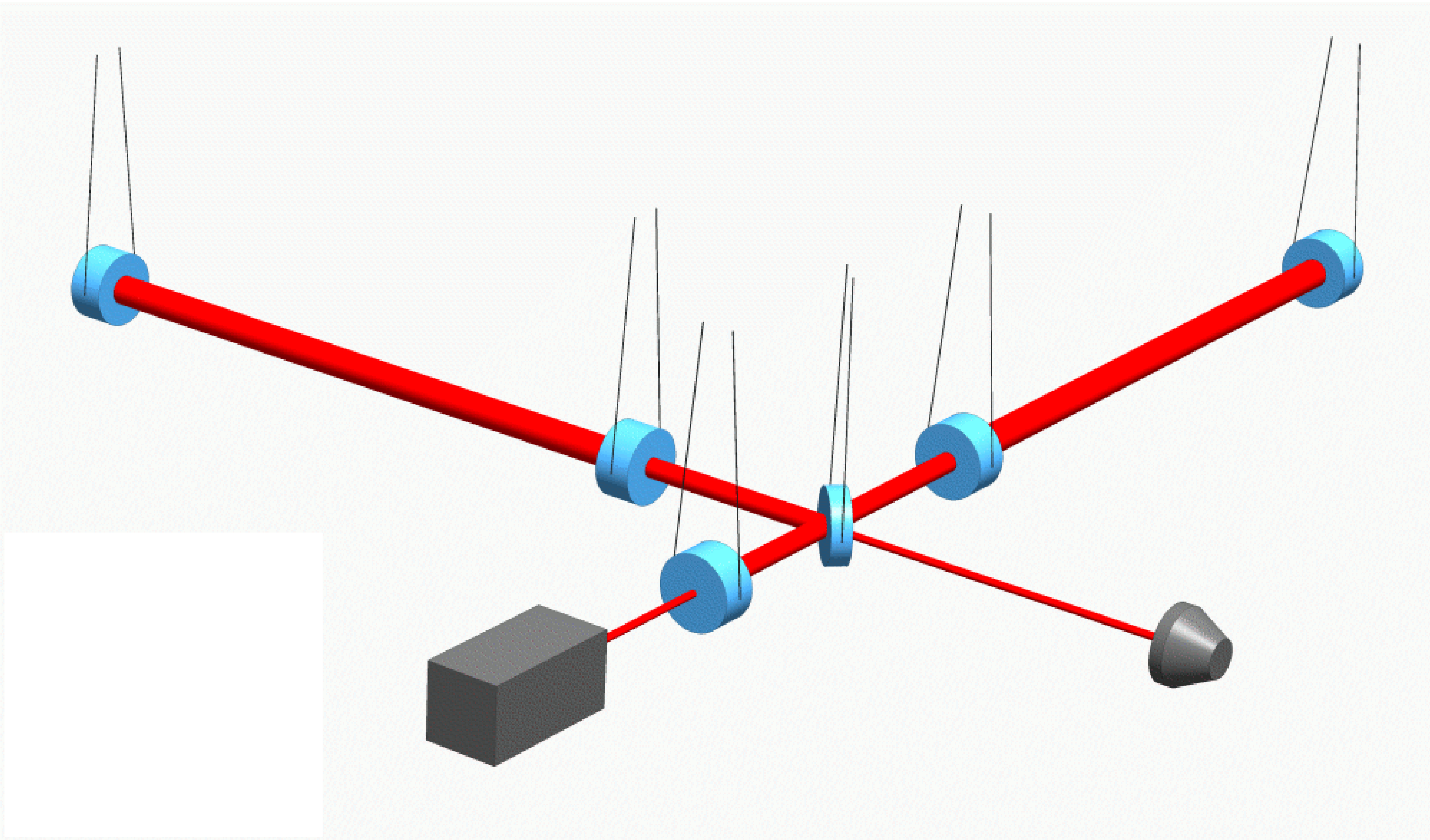


1974 Hulse & Taylor

(1993 Nobel Prize)



70's: Interferometric GW detector



1994 TAMA construction

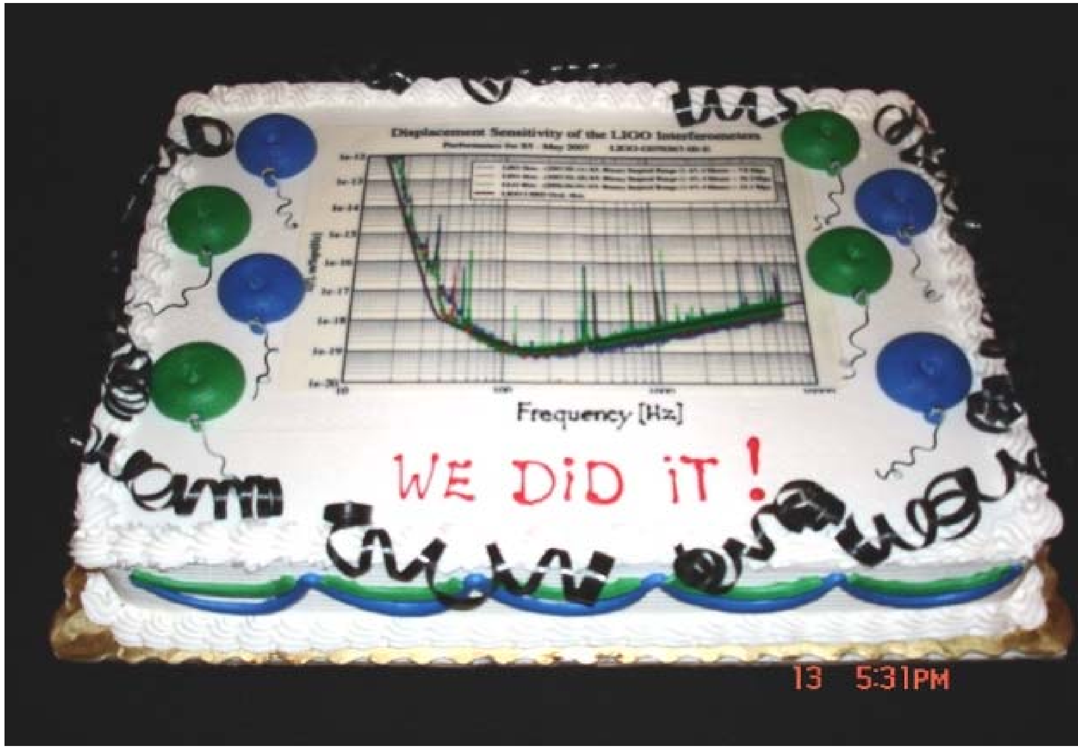
1999 TAMA observation

2002 LIGO (US)

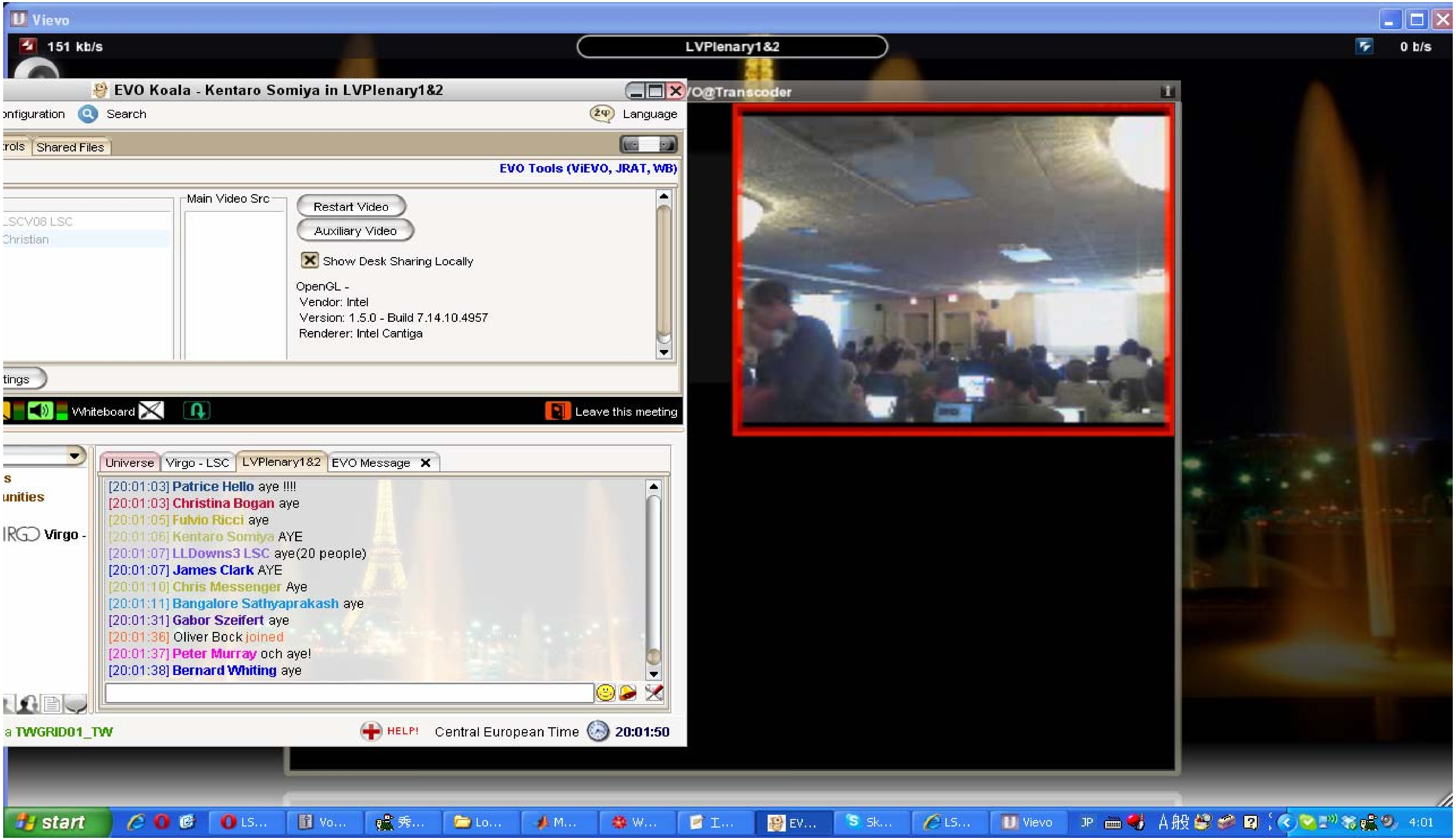
2005 GEO (GE/GB)

2007 Virgo (IT/FR)

Observations started



2010 Internal news of first GW?!

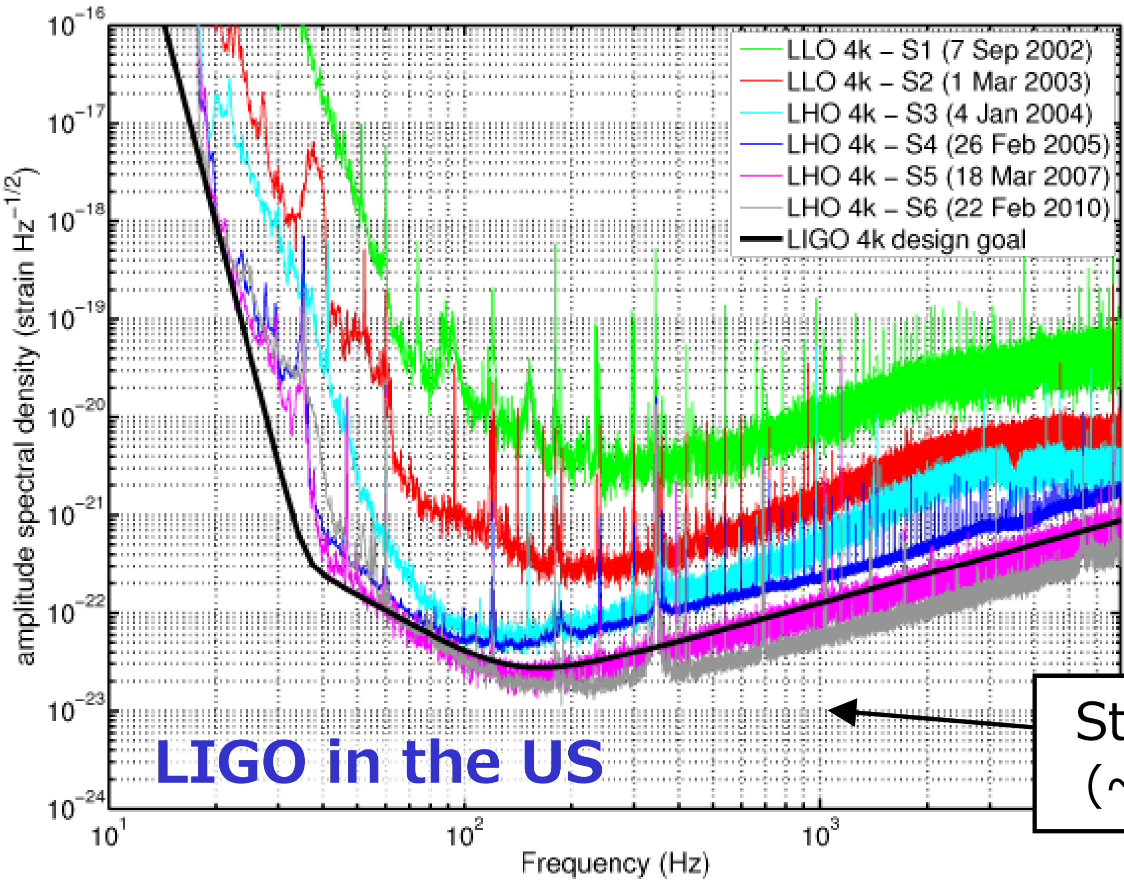


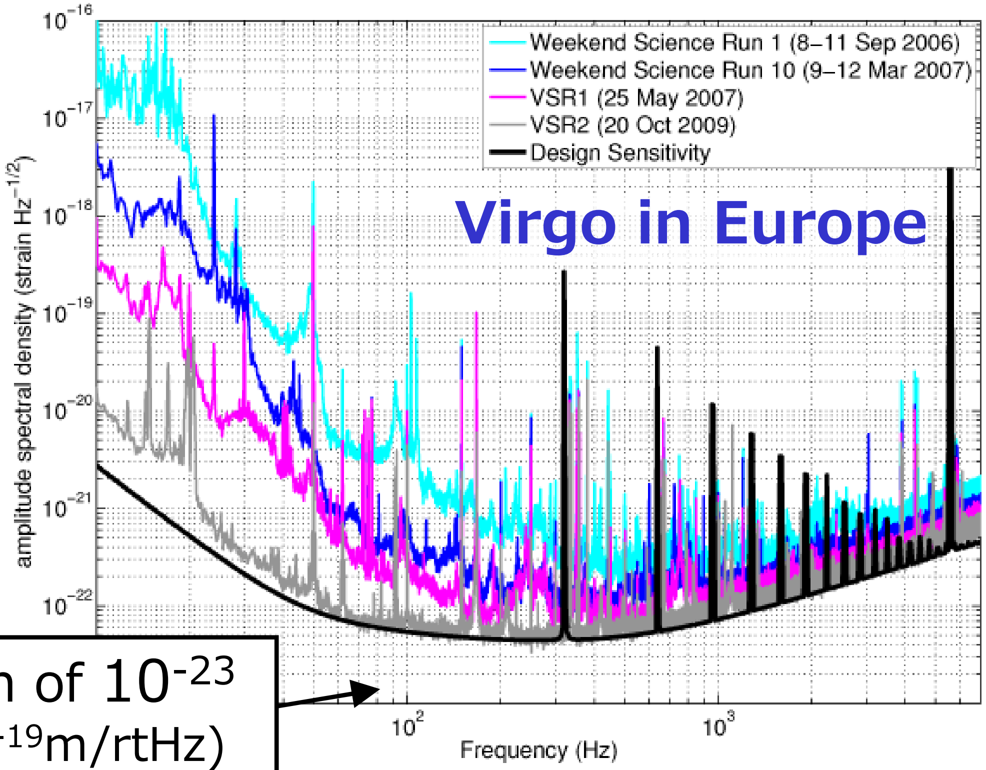
The 1G detectors were able to see GW events of up to 70M lightyears distant, but found no real GW signal.

↓

Decision to upgrade the detectors

Sensitivity of the 1G detectors

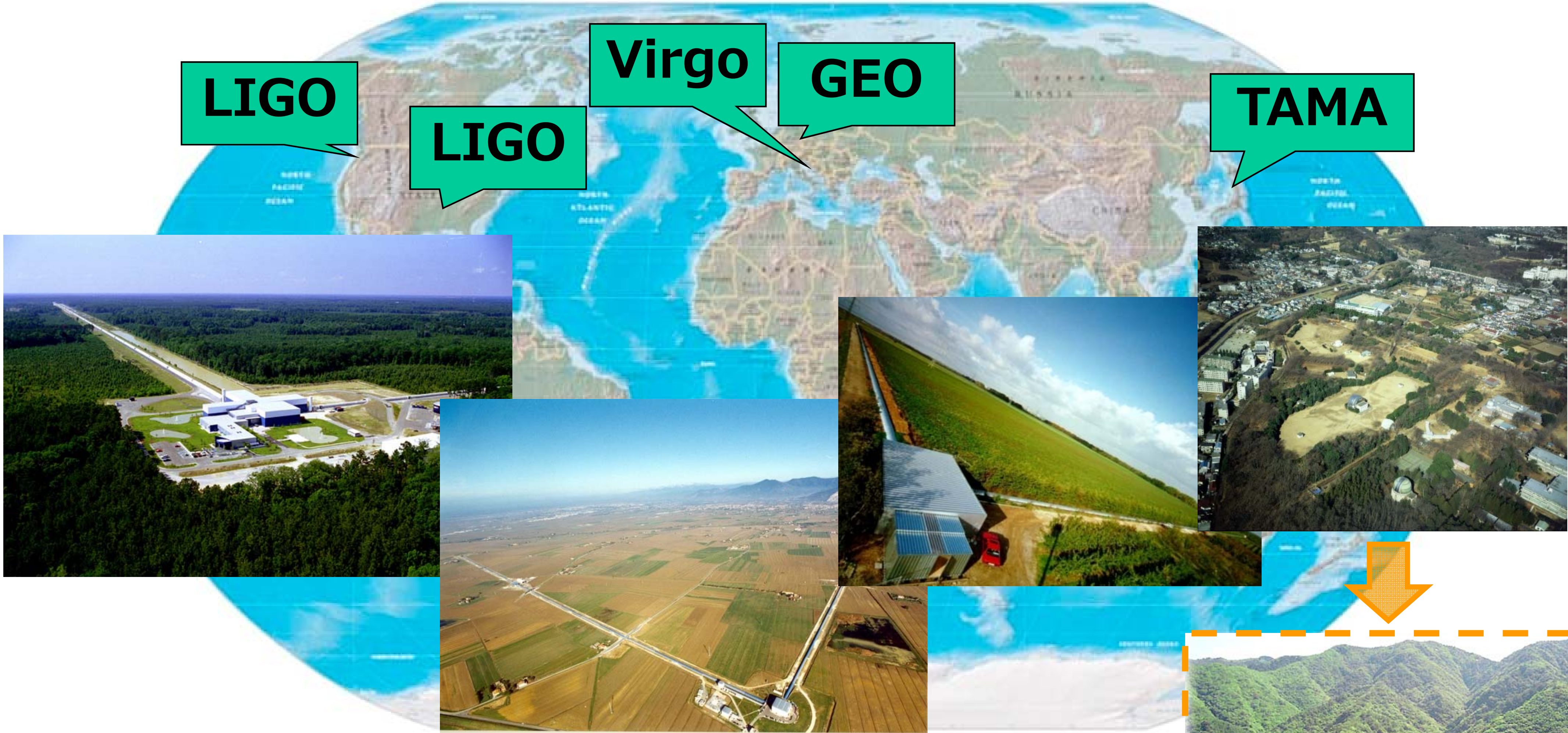




Strain of 10^{-23}
($\sim 10^{-19}$m/rtHz)

Sensitivities are limited by seismic noise, thermal noise, and laser quantum noise.

Upgrade to 2G



LIGO
Virgo
GEO

upgrade

Advanced LIGO
Advanced Virgo
GEO-HF

KAGRA

Big news on Feb 12th 2016

Live streams in US and in Europe

0:30AM: Virgo announced the first detection
0:32AM: NSF person gave a speech in the US
0:35AM: LIGO announced the first detection
1:00AM: LIGO papers were published
1:30AM: Prof Kajita (KAGRA PI) commented in web

Big news on Feb 12th 2016

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

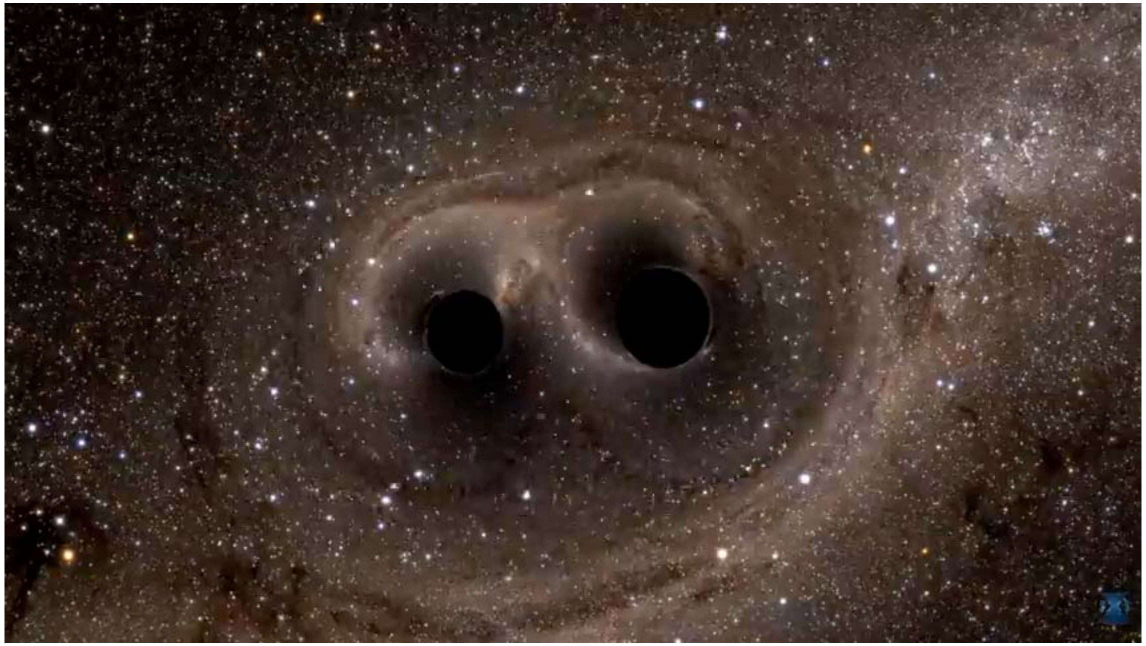
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

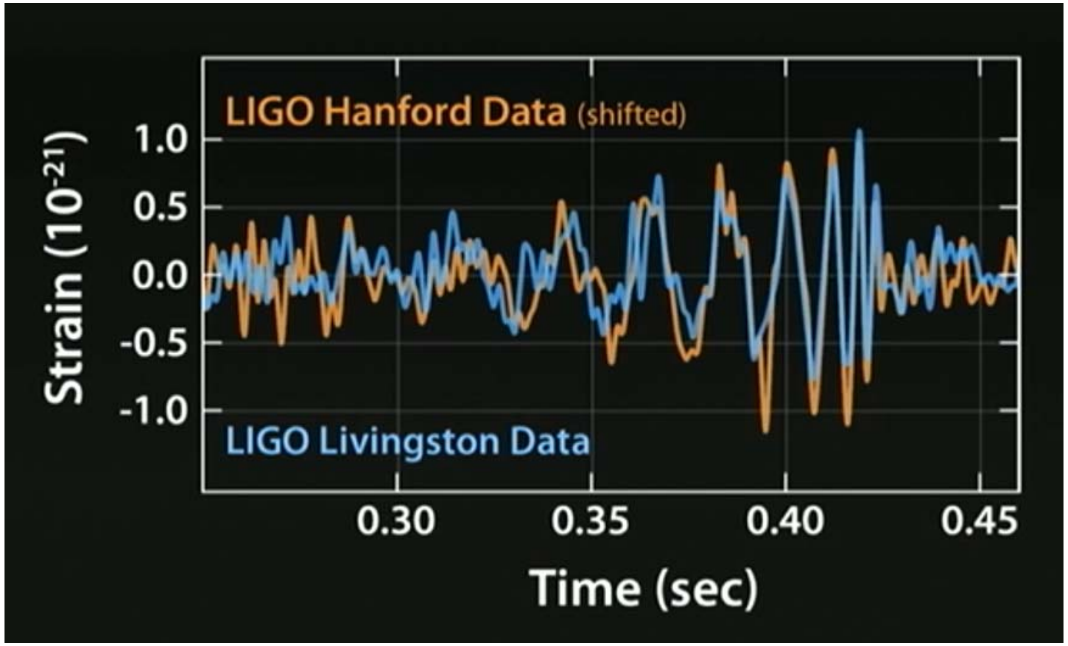
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

36 and 29 Ms BHs merged to make a 62 Ms BH and its inspiral, merger, ringdown signals were observed.

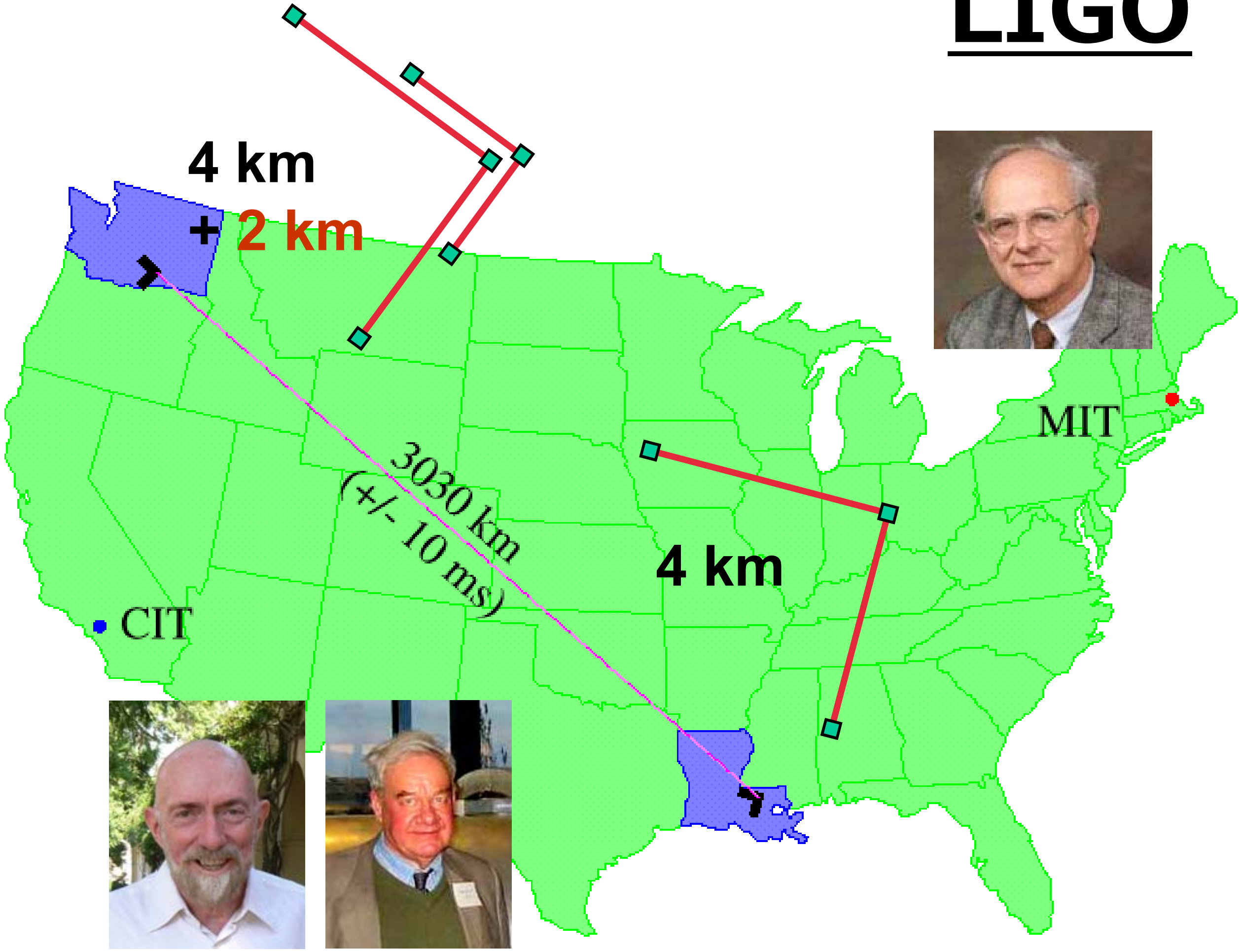
More details about this PRL

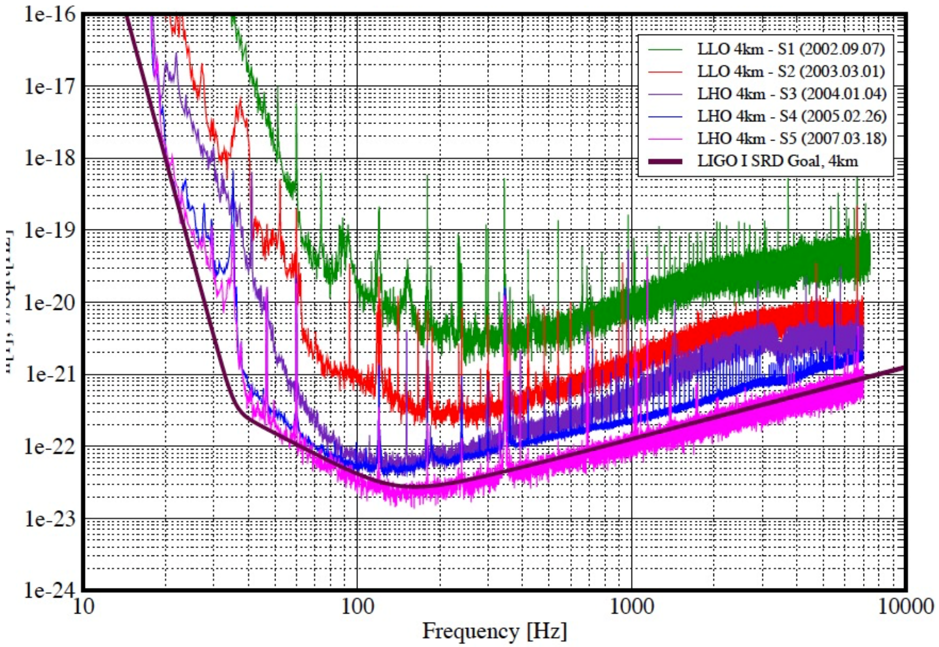




- **Waveform matched to a numerical relativity template**
- **The same waveform was observed by 2 LIGO detectors that are 3000km apart (with 6ms delay)**
- **The distance to the BH is ca 1.3B lightyears**
- **The Signal-to-noise ratio was 24 and the False-alarm rate was calculated to be less than 1 in 200,000 yrs**

LIGO

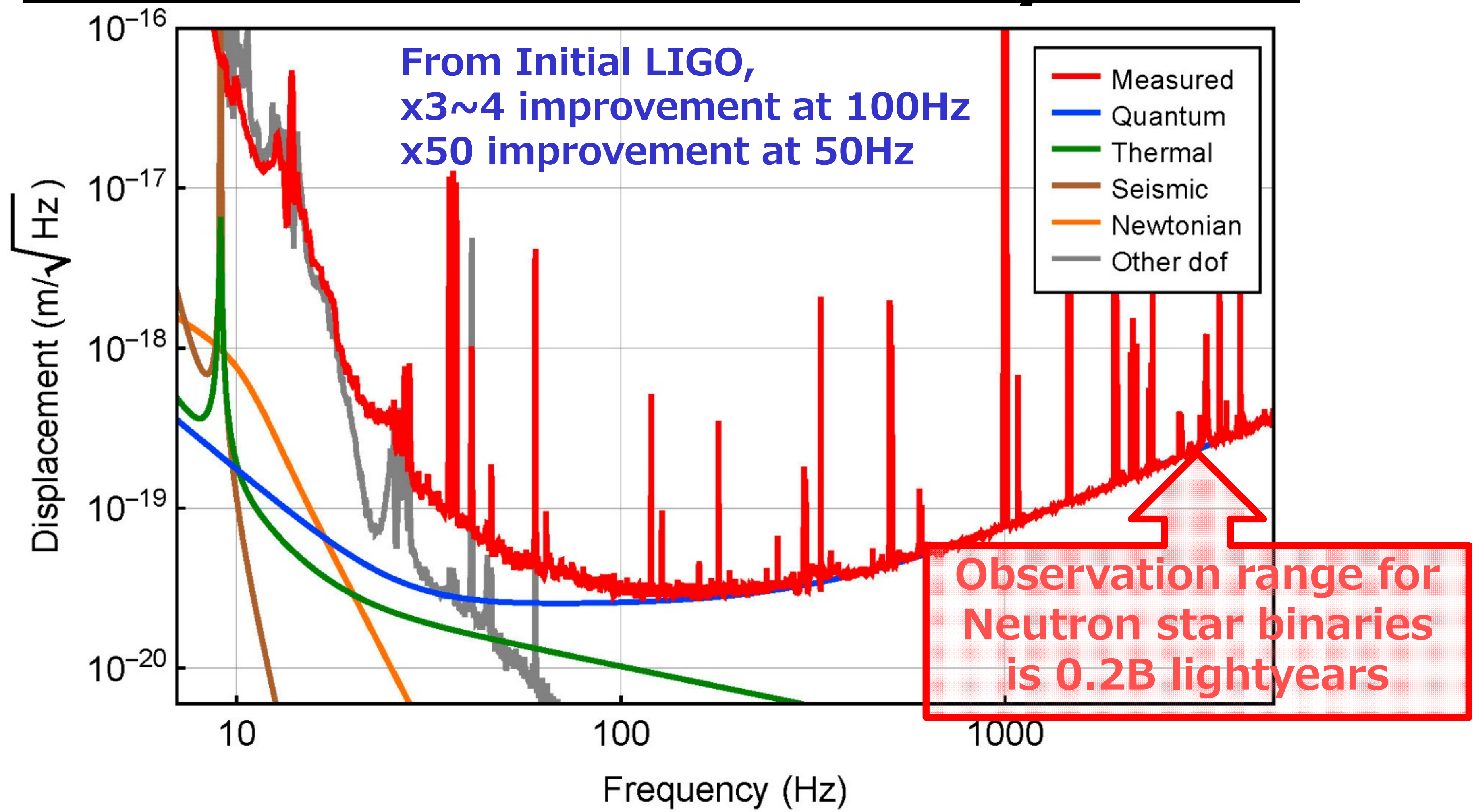




Initial LIGO sensitivity ('02-'07)

- **Current members: 1006 (83 institutes)**
- **Total budget: ca 120B JPY**

Advanced LIGO sensitivity in '15

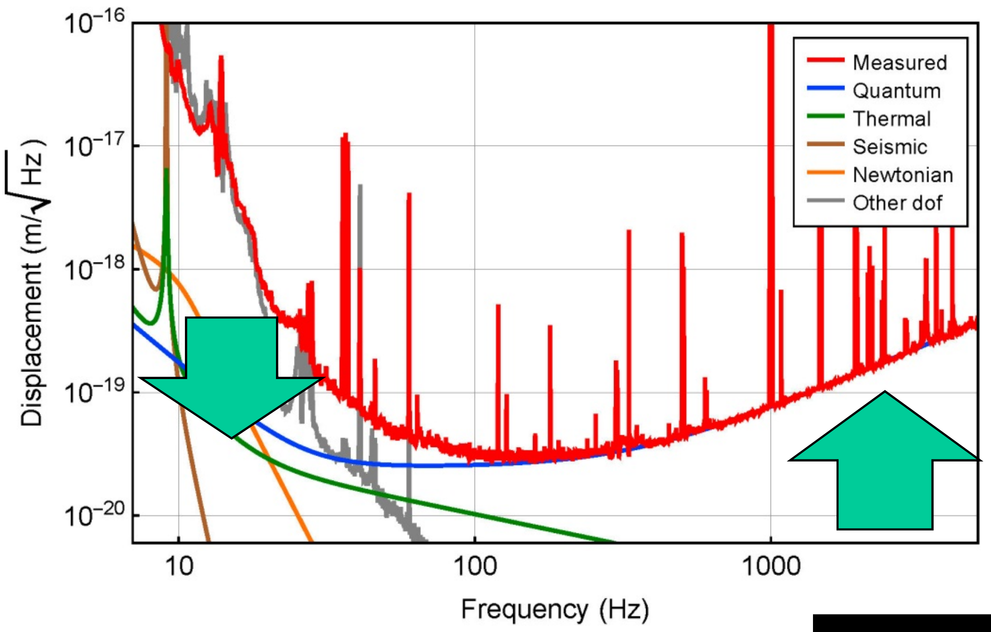


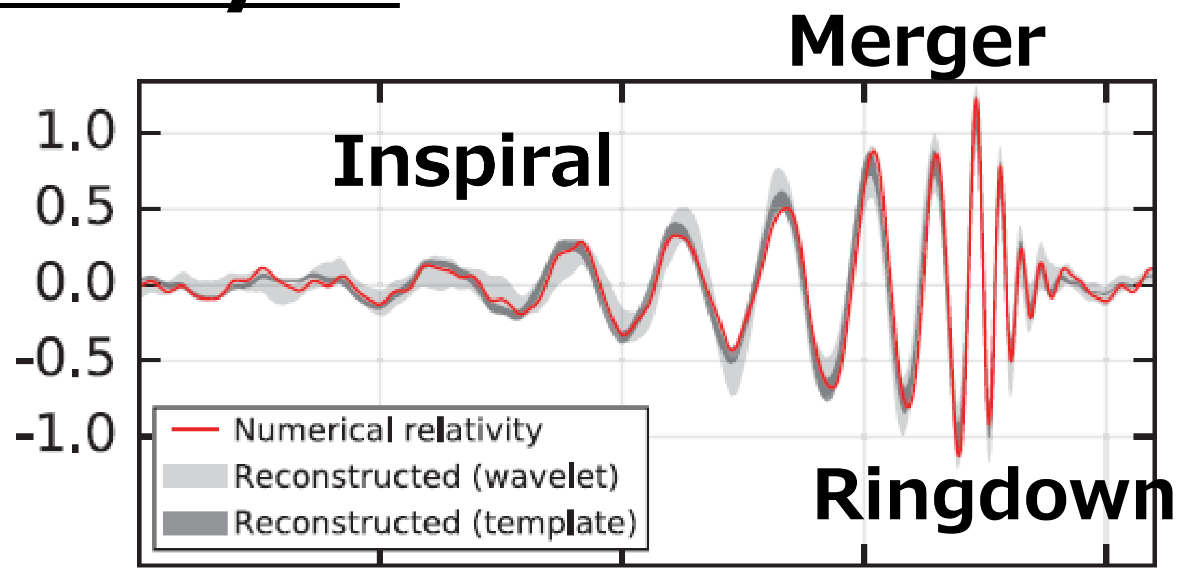
below 20Hz ⇒ Control noise

20~100Hz ⇒ Mystery noise

above 100Hz ⇒ Quantum noise

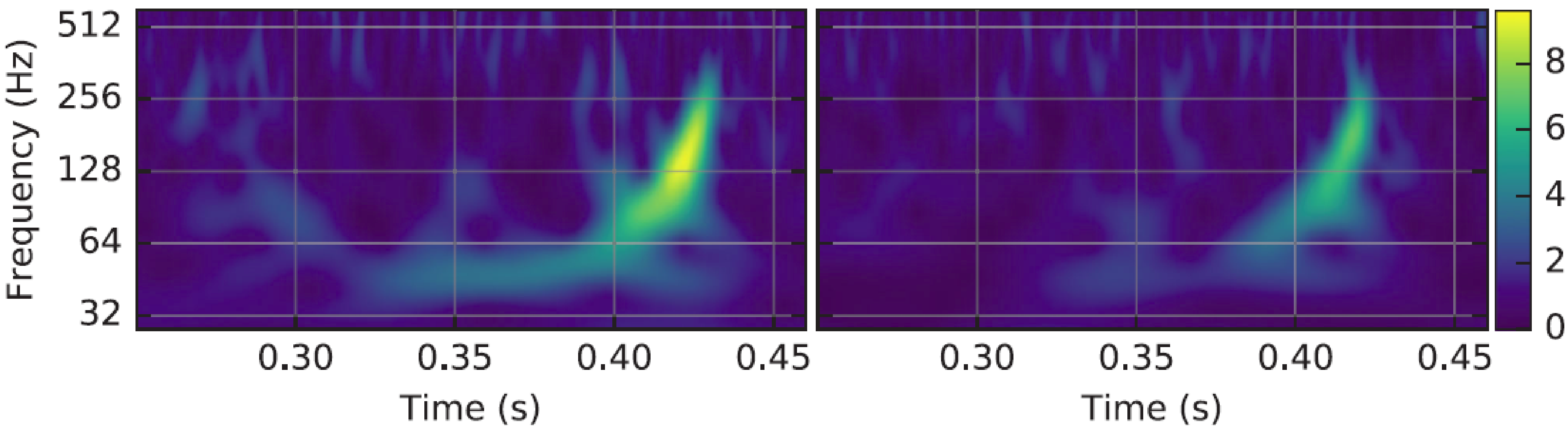
Data analysis



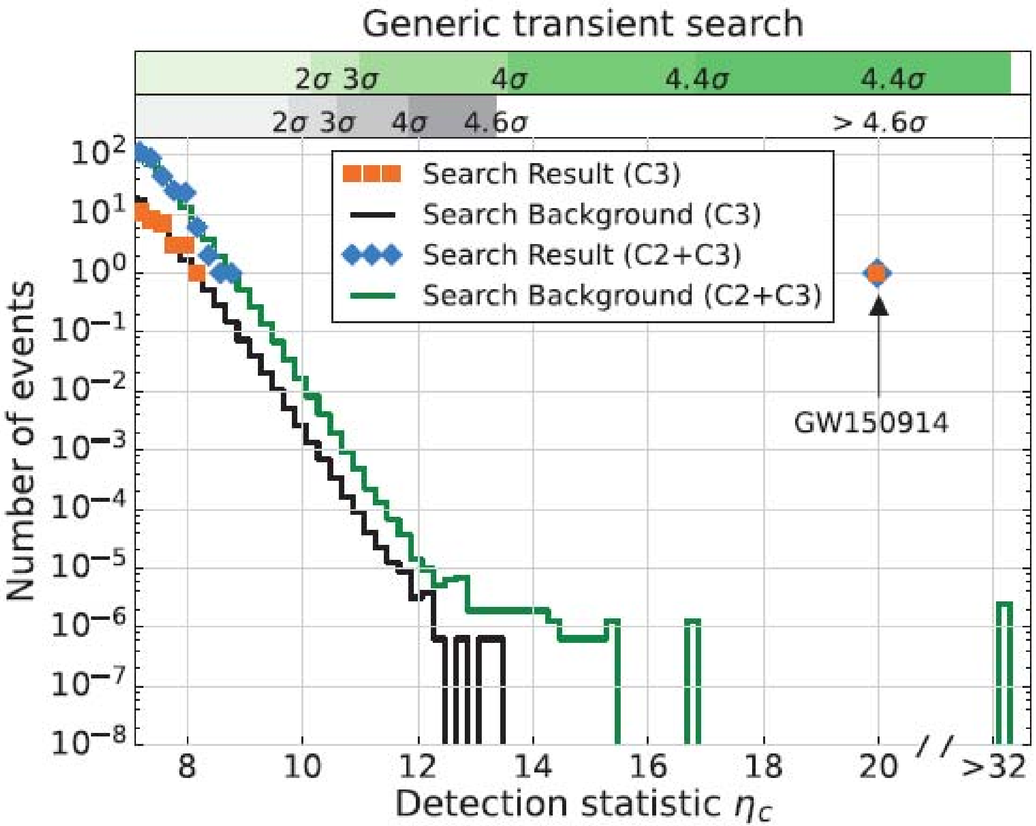


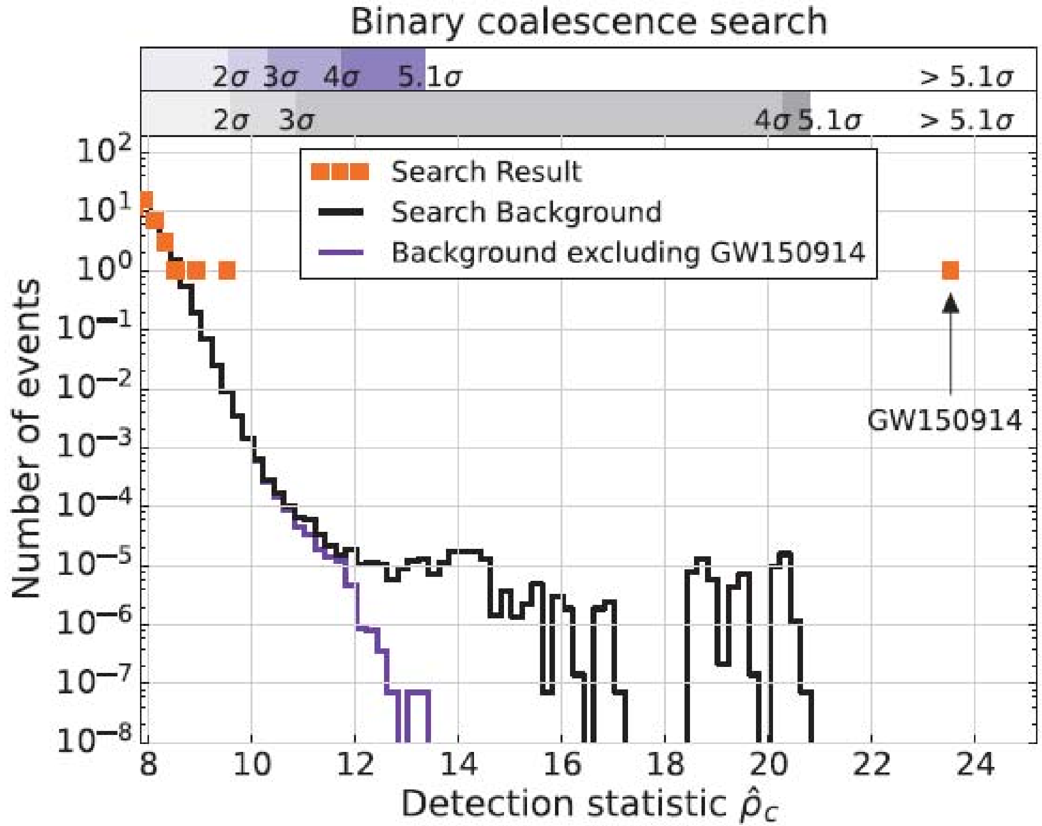
Whitening

Inspiral: 35-150Hz
Ringdown: 250Hz



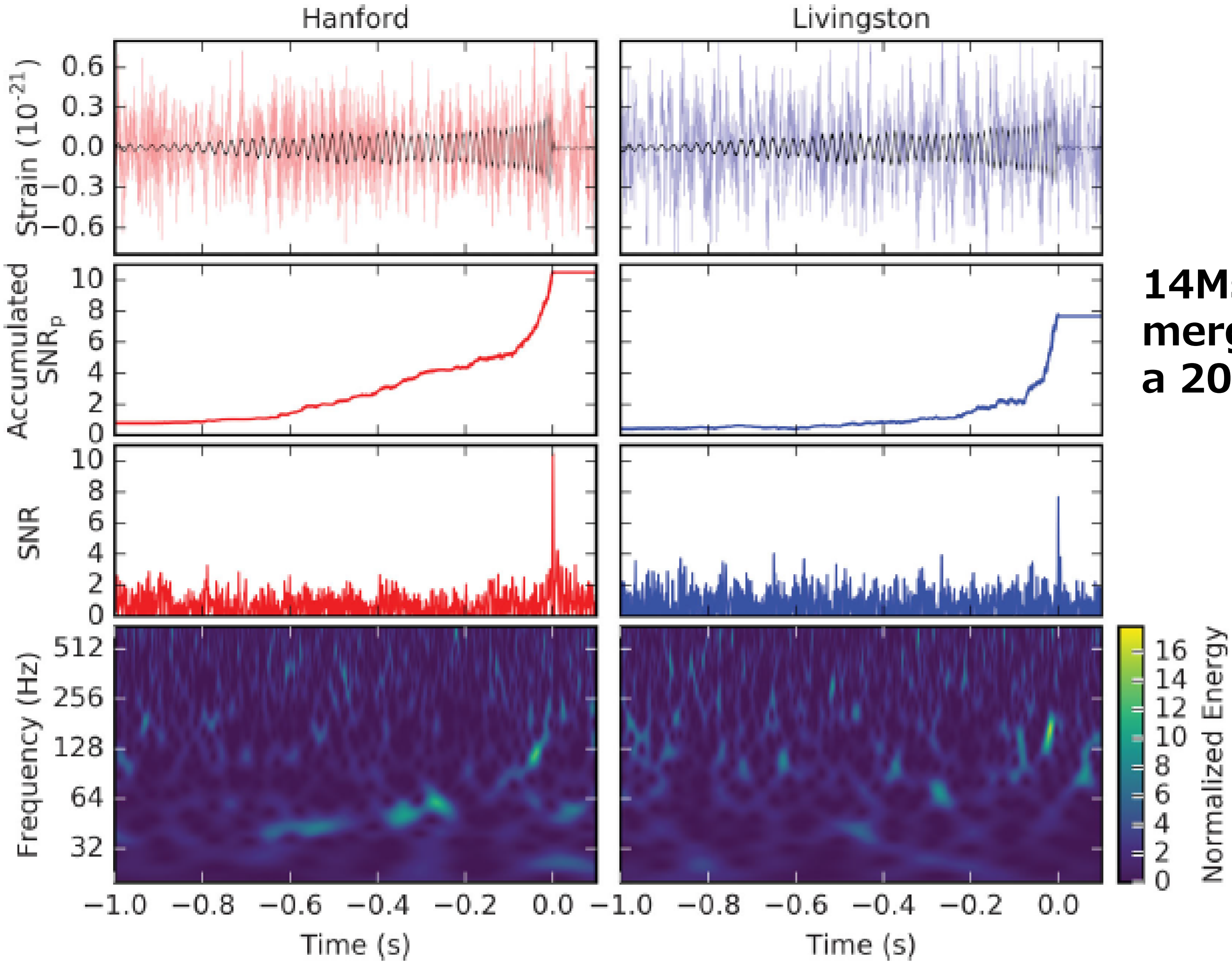
Significance





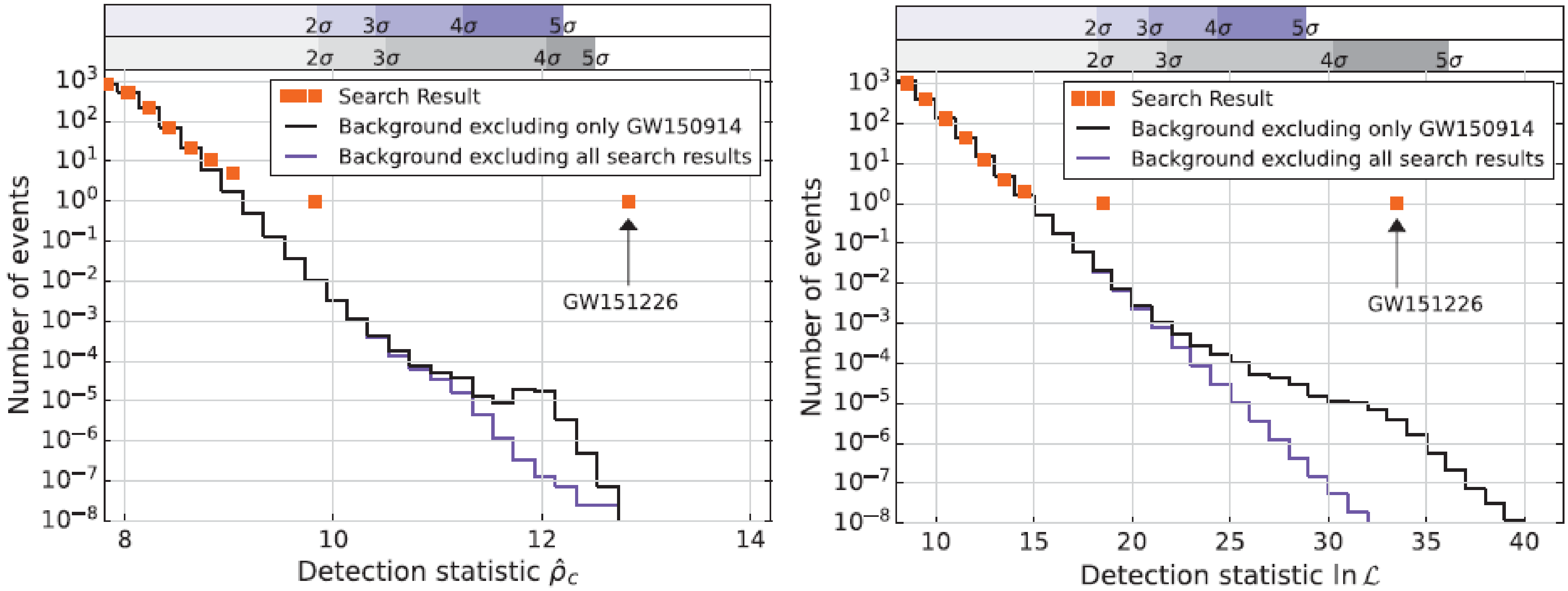
LIGO continued the observation for 2 weeks after the discovery to calculate the significance of this event compared with signal-like noises
⇒ The difference is larger than 5σ

Second GW on Dec 26th 2015



14Ms and 7.5Ms BHs merged to become a 20Ms BH.

Second GW on Dec 26th 2015



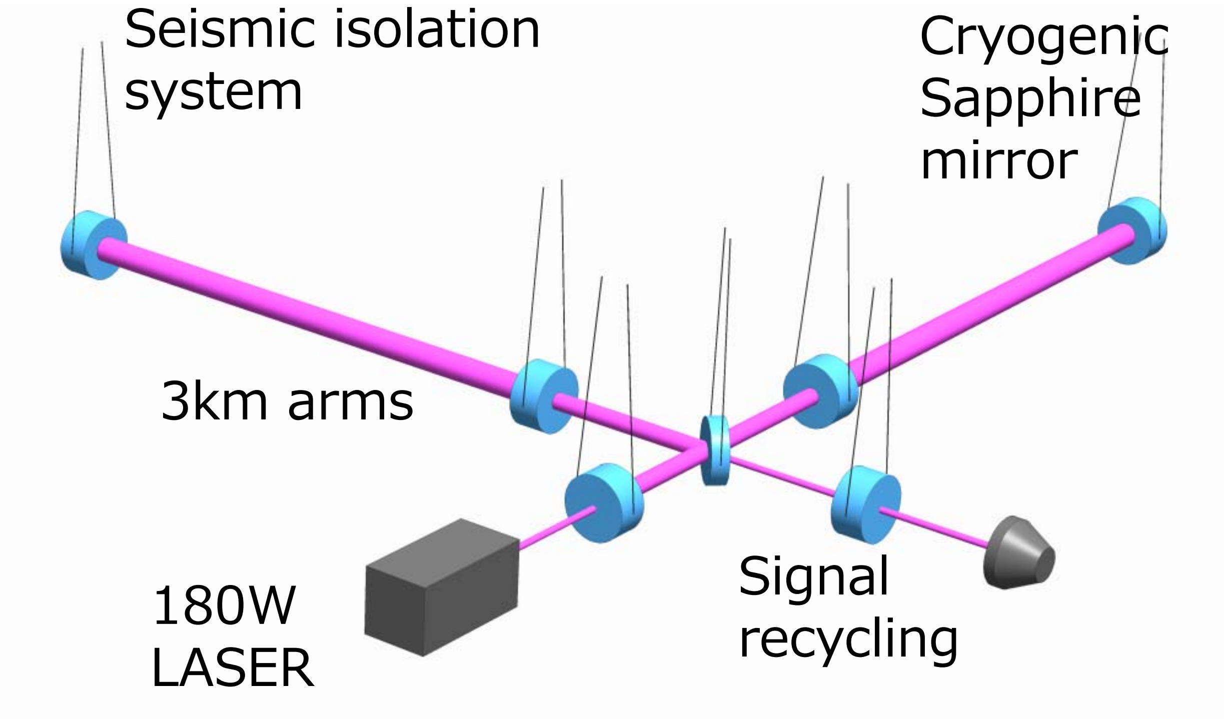
Signal-to-noise ratio was not as high as the first one but the significance was high for its long observation time.

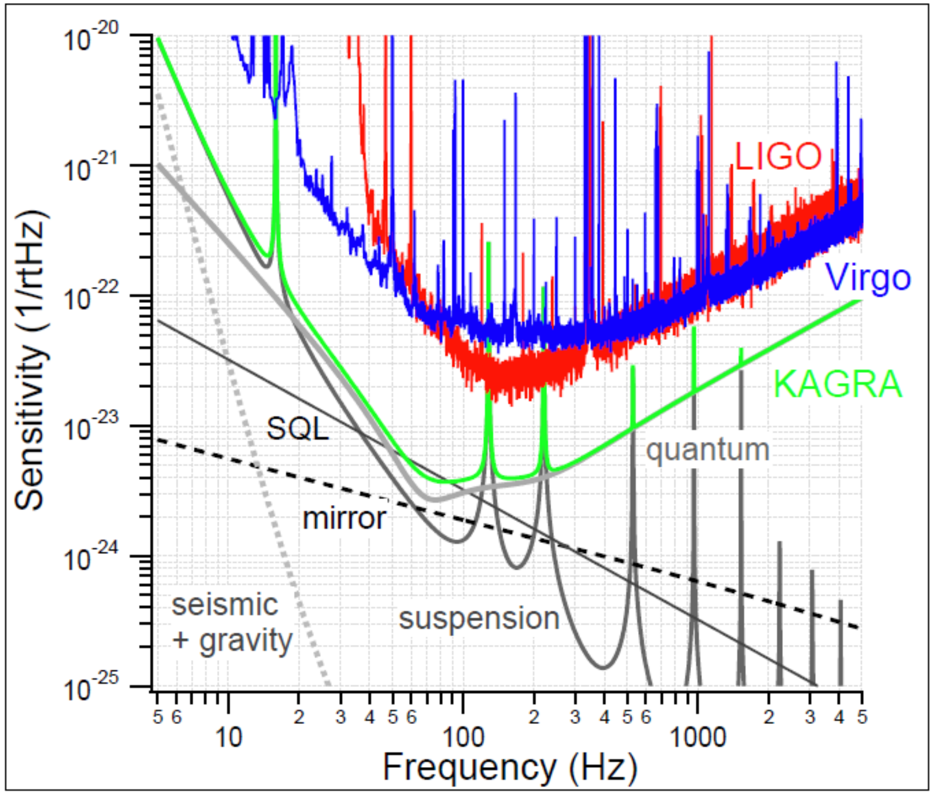
Engineering run and observation run

- **GW150914 was found during the engineering run**
- **The result for the first 2 weeks was published in February (the rest was published in June)**
- **Observation was extended for a few days and the second GW was found in the extended period**
- **The second observation run started Nov 2016.**

KAGRA

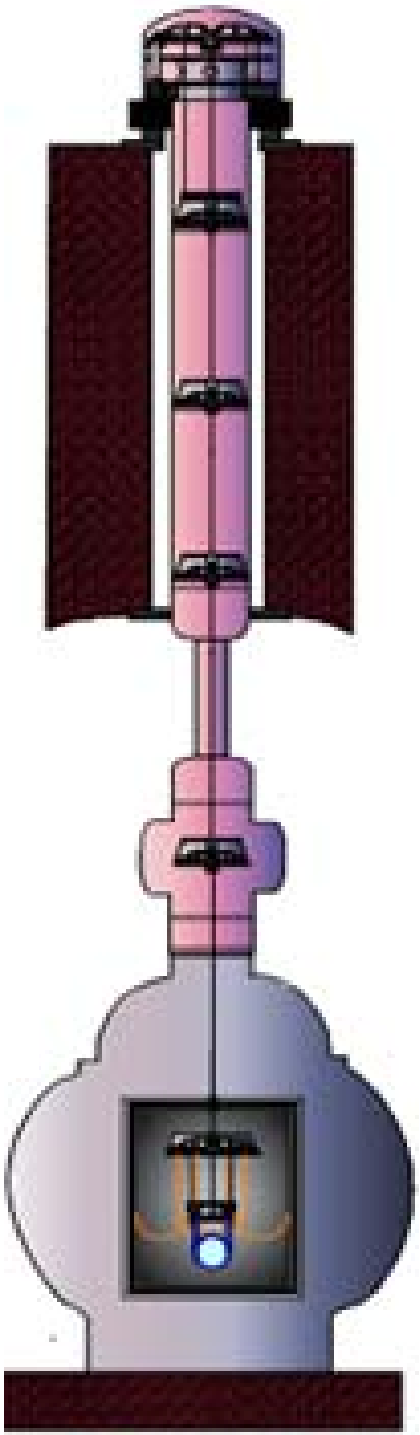
Location: Kamioka, Gifu



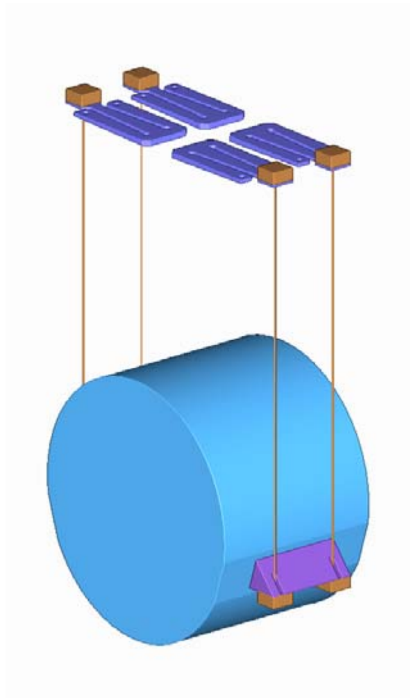


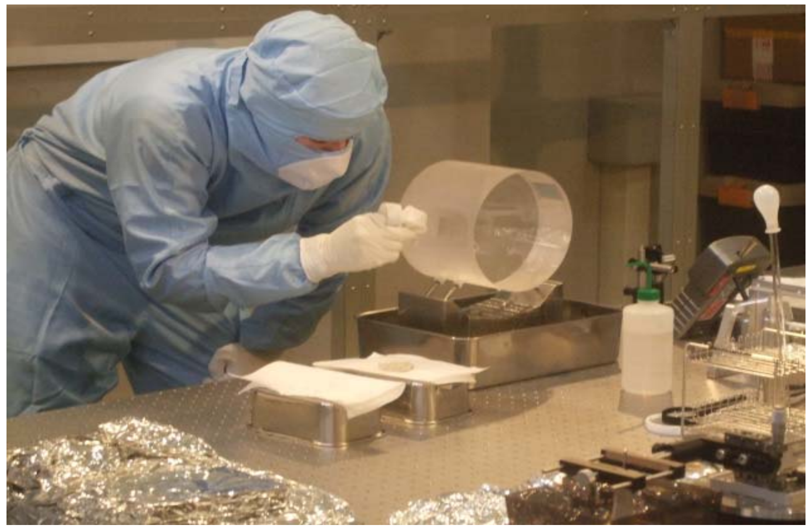
- **Underground facility + Cryogenic mirrors**
- **To start the cryogenic operation in 2018**
- **Observation rage for NS binaries will be 0.5B LY**

Cryogenic system

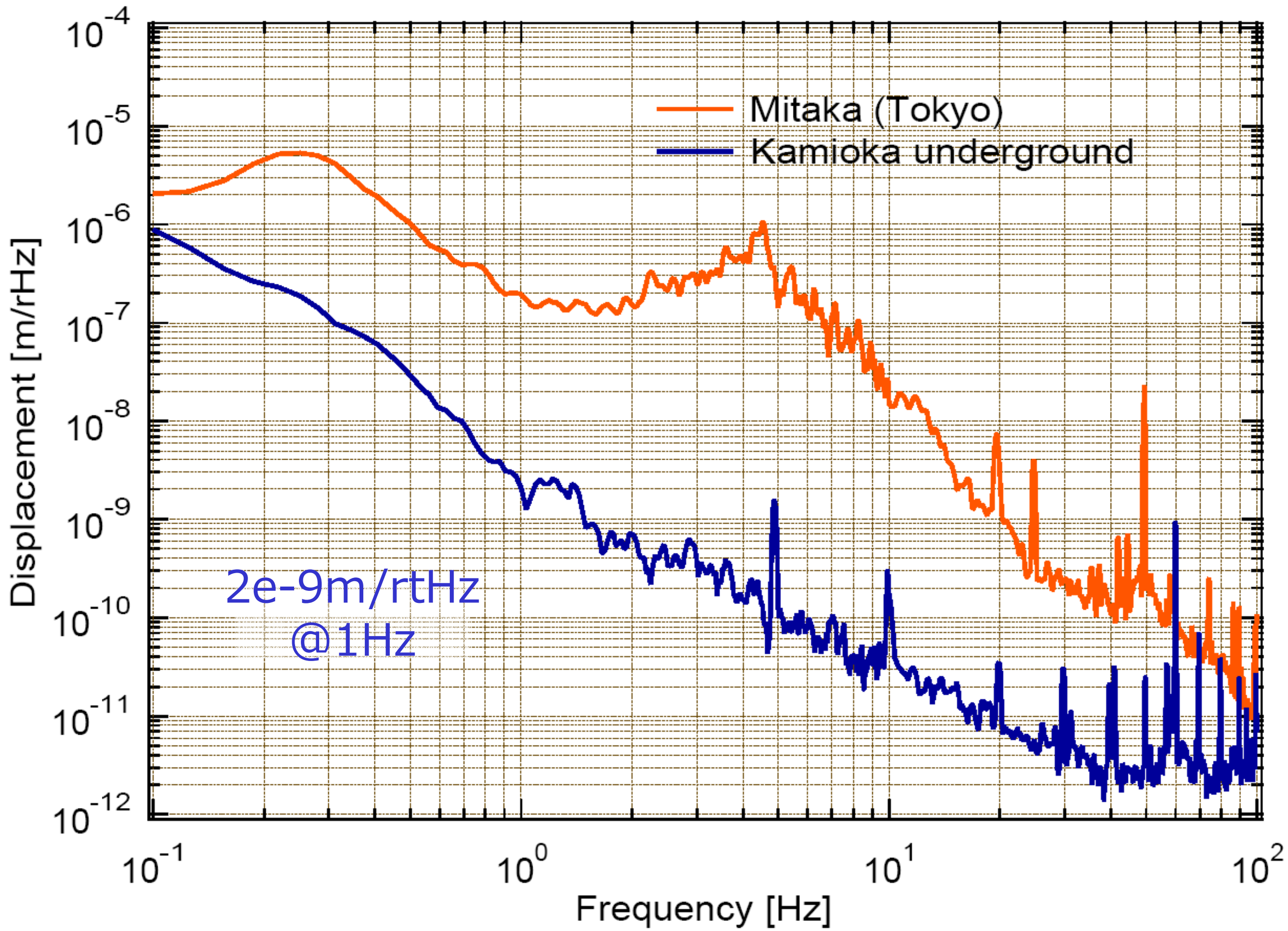


- System in a radiation shield
- Upper mass cooled via 6N Al heat link
- Sapphire test mass cooled in 23K via Sapphire suspension fiber

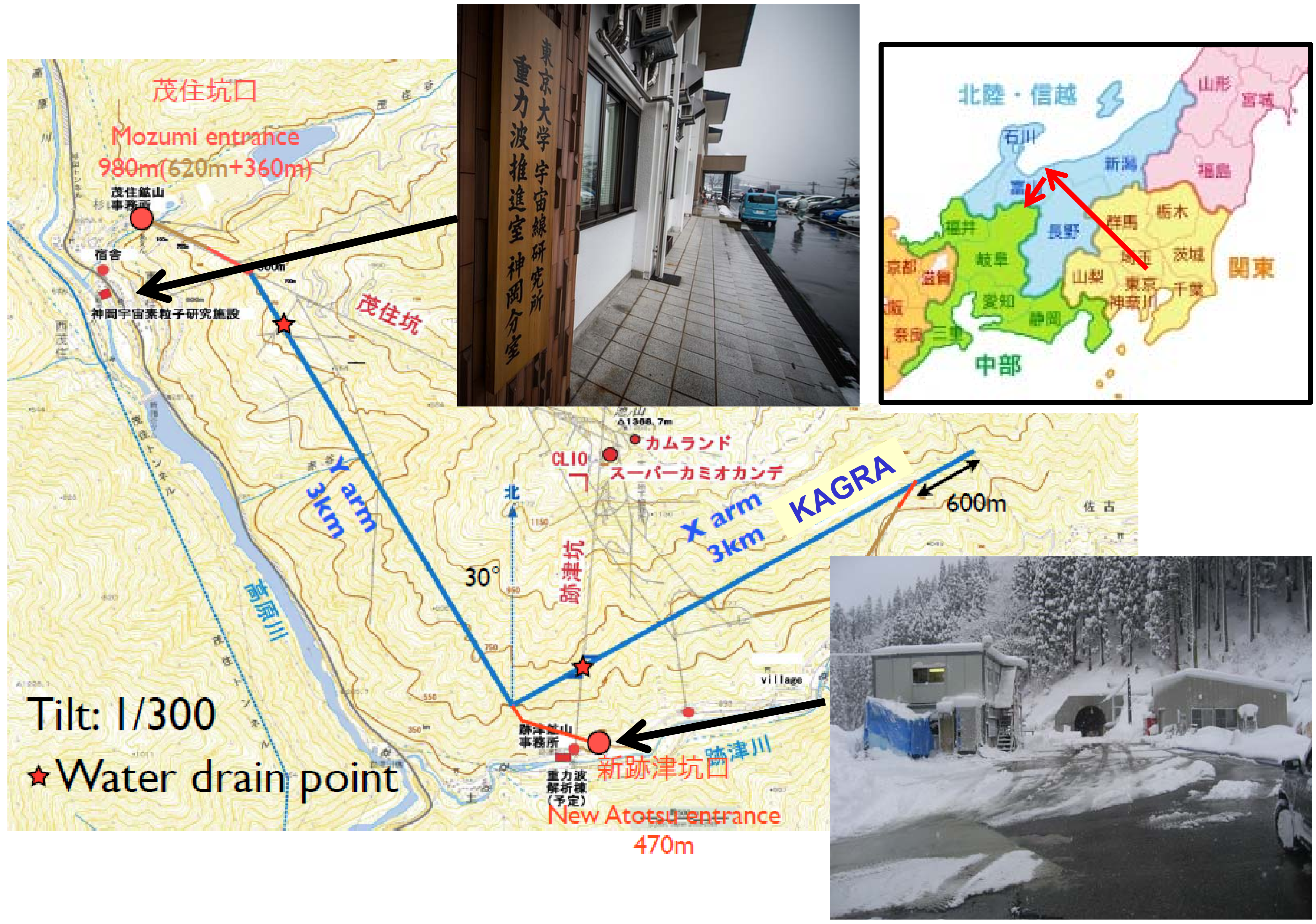




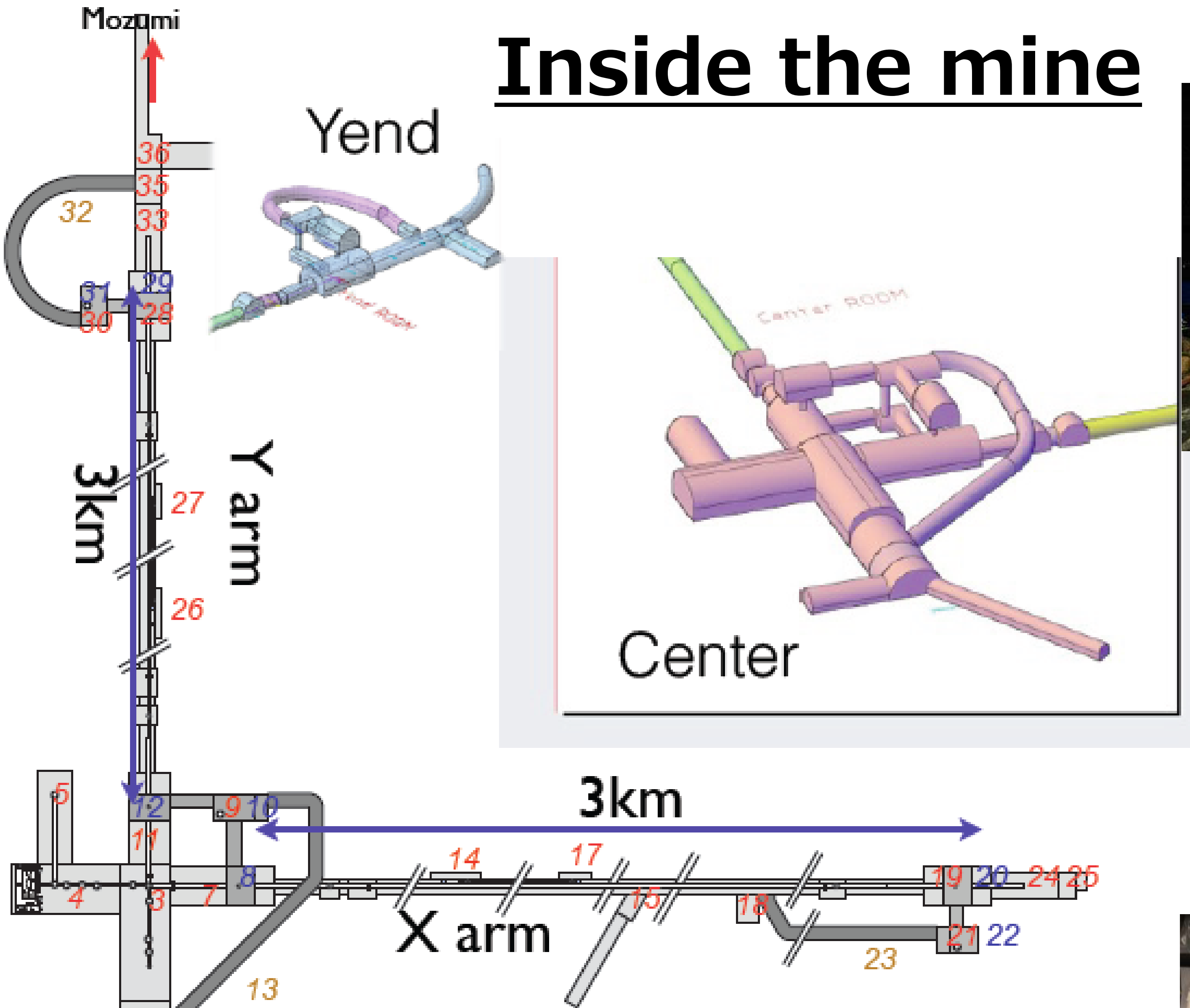
Underground facility

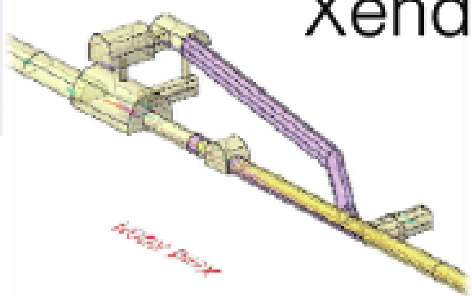


- **Low seismic noise**
- **Low gravity gradient noise**
- **Low control noise due to low RMS motion**

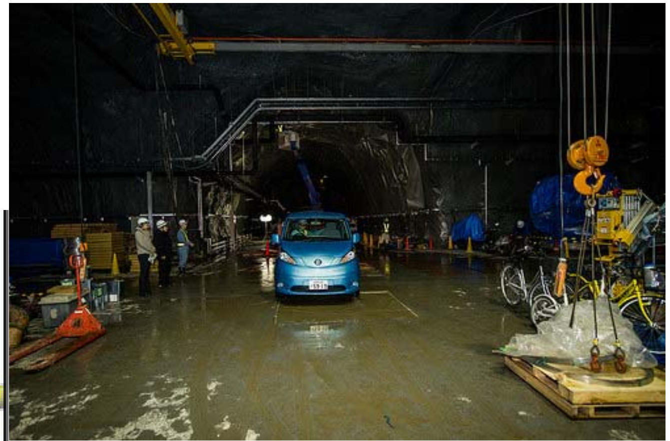

茂住坑口
Mozumi entrance
980m(620m+360m)
茂住鉱山
事務所
宿舎
神岡宇宙素粒子研究施設
茂住坑
Y arm
3km
X arm
3km
KAGRA
600m
北
30°
跡津坑
カムランド
CLIO
スーパーカミオカンデ
高原川
跡津川
village
跡津鉱山
事務所
重力波
解析棟
(予定)
新跡津坑口
New Atotsu entrance
470m
Tilt: 1/300
Water drain point
東京大学宇宙線研究所
重力波推進室 神岡分室
北陸・信越
中部
関東
石川
富山
新潟
福井
岐阜
長野
群馬
栃木
山形
宮城
福島
埼玉
茨城
東京
千葉
神奈川
山梨
愛知
静岡
三重
京都
滋賀
奈良

Inside the mine



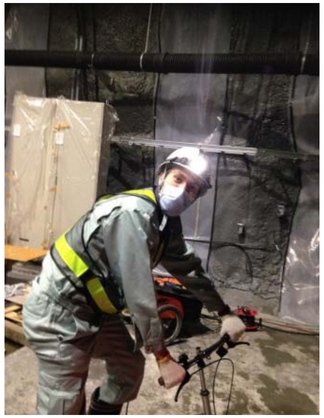


Xend



Electric car

electric scooter

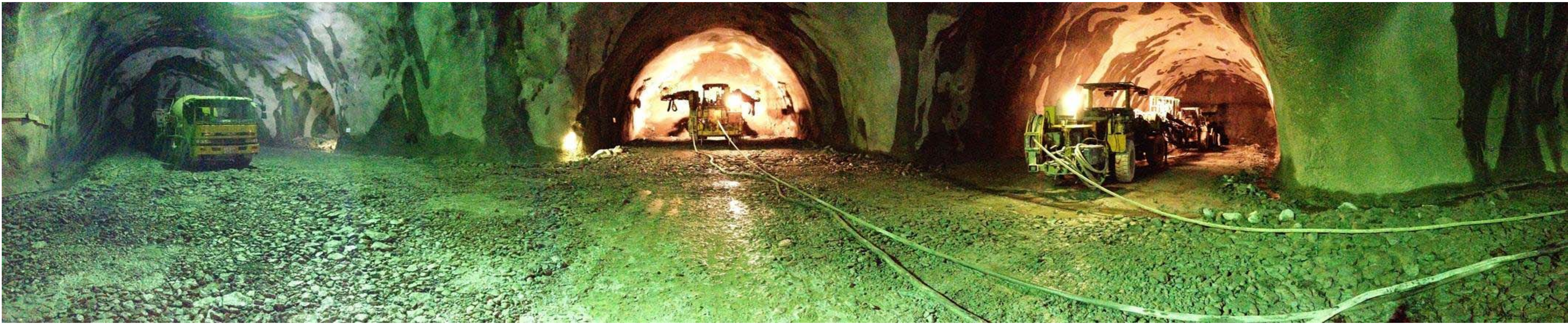


bicycle

Nov 2012
Tunnel excavation

Dec 2012
Cryostat manufacture
(Toshiba factory)

View at the central area

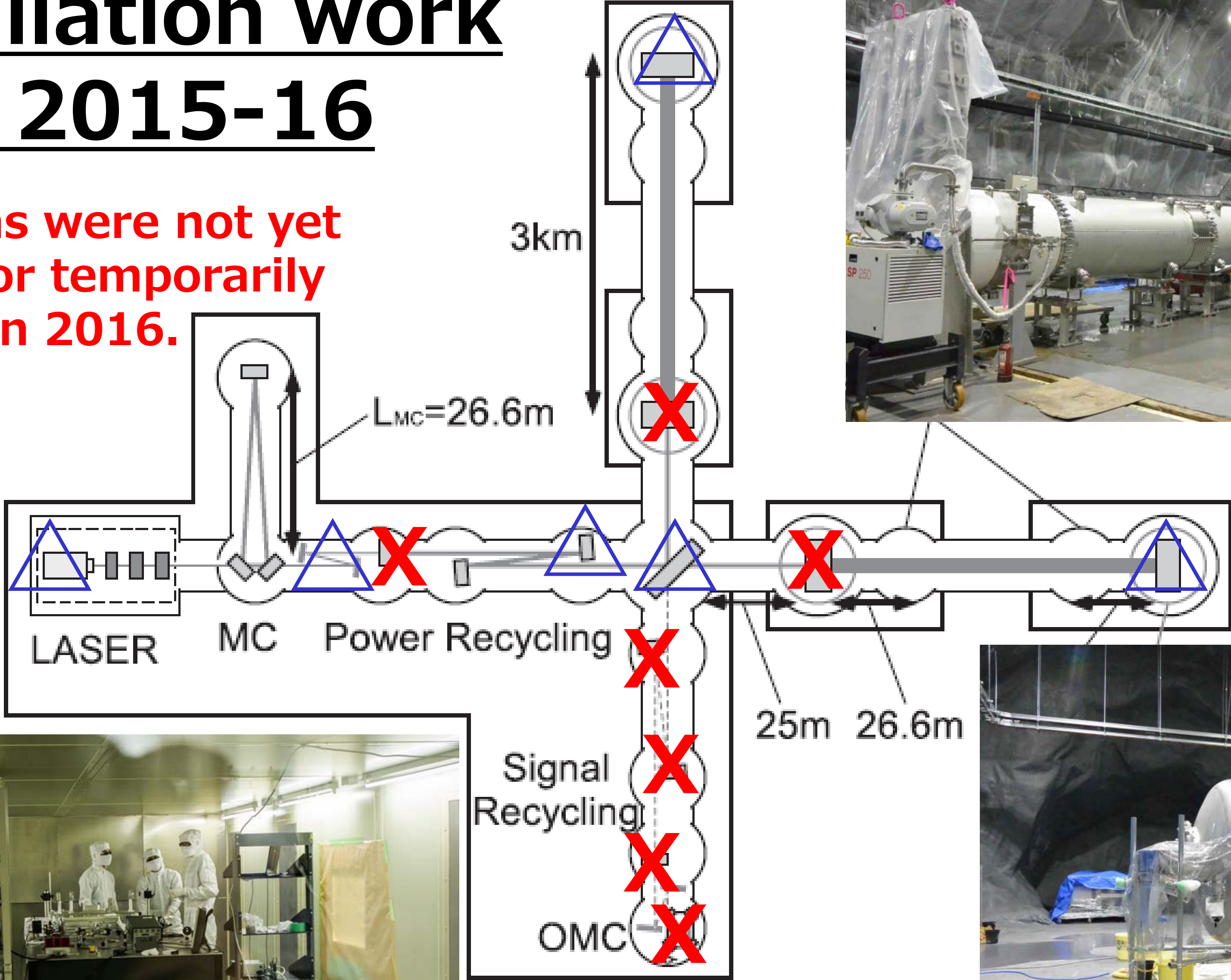


Dec 2012

Jul 2014

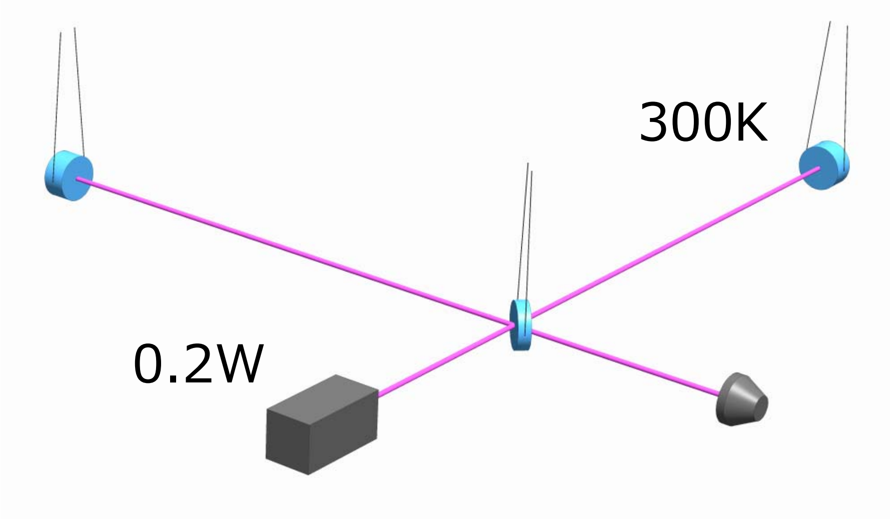
Installation work in 2015-16

Most items were not yet installed or temporarily installed in 2016.

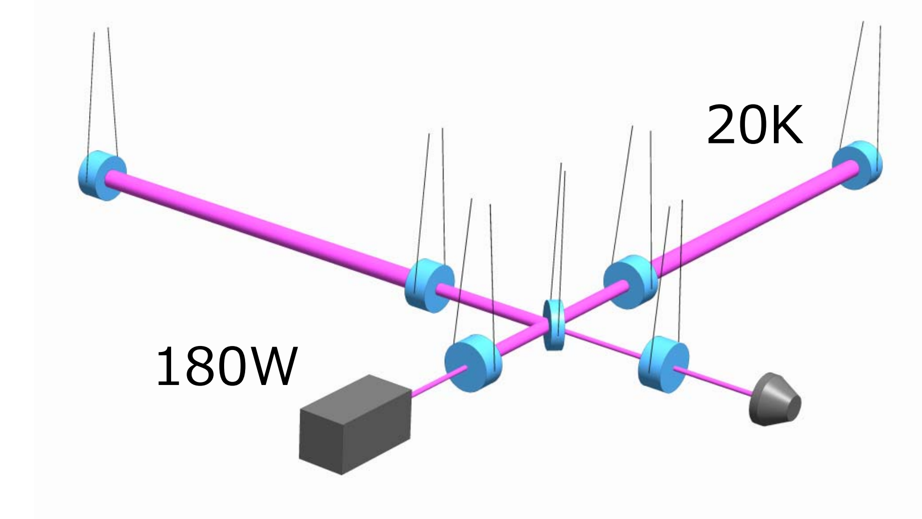


But, facility, digital control system, and infrastructure were installed by 2016.

KAGRA test operation in 2016

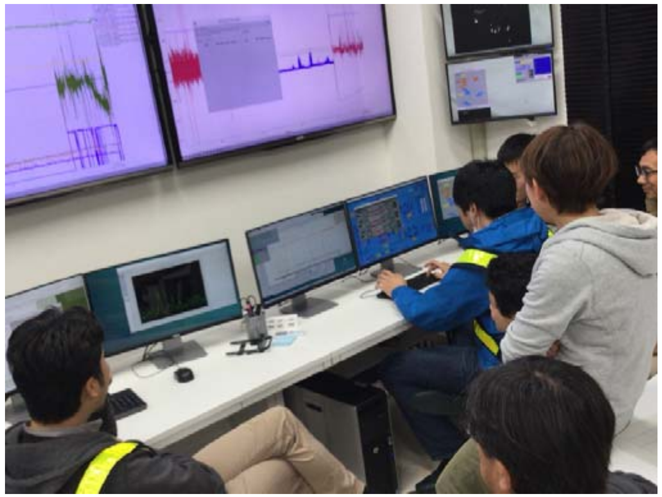


at the test run



final configuration

- 2 x 2week operation in 3/25-4/25
- Test the integrated system
  - control system
  - commissioning
  - observation shift
- World first operation of a km scale underground GW detector



KAGRA schedule

2017: Installation of cryogenic suspensions

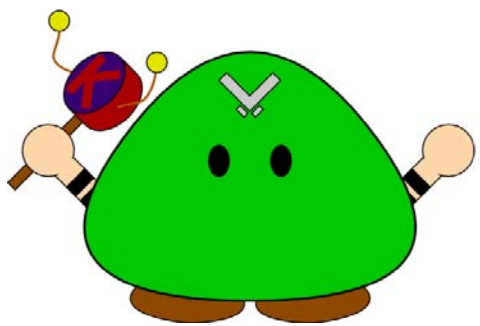
2018: Operation of a cryogenic interferometer

2019: Integration of optical resonators

2019~20: Commissioning and observation

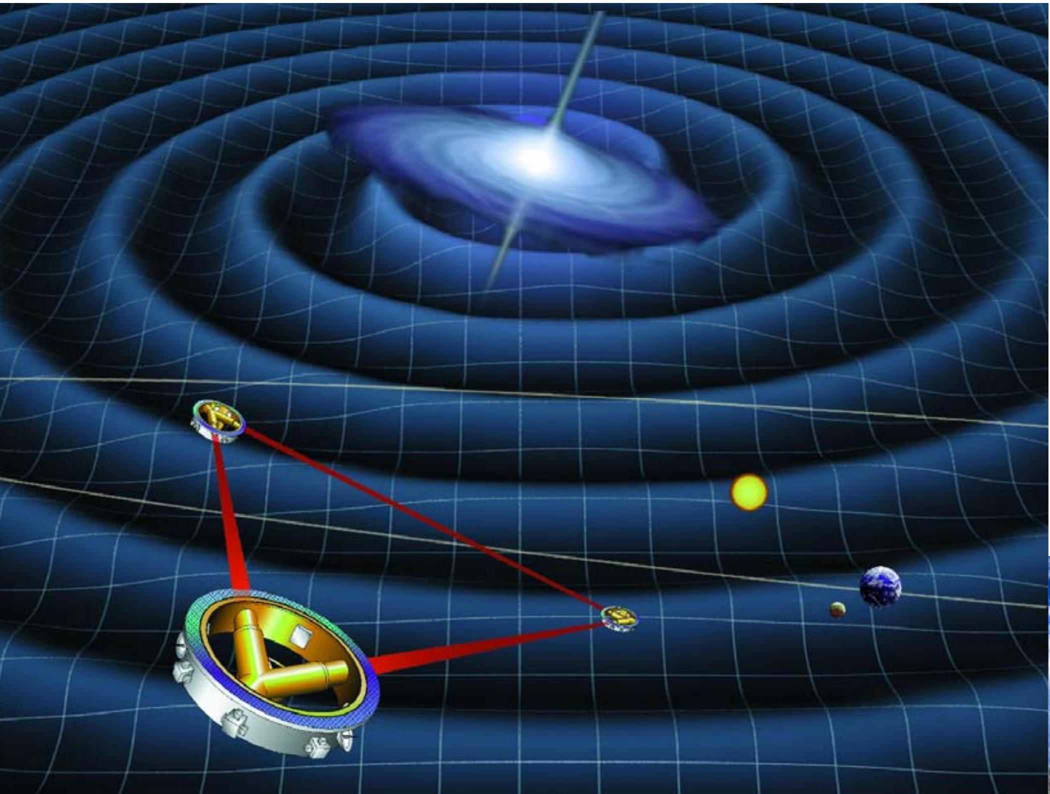
Summary

- Discovery of GW in 2015
- GW astronomy is about to begin
- KAGRA is under development for the first observation in 2019~20

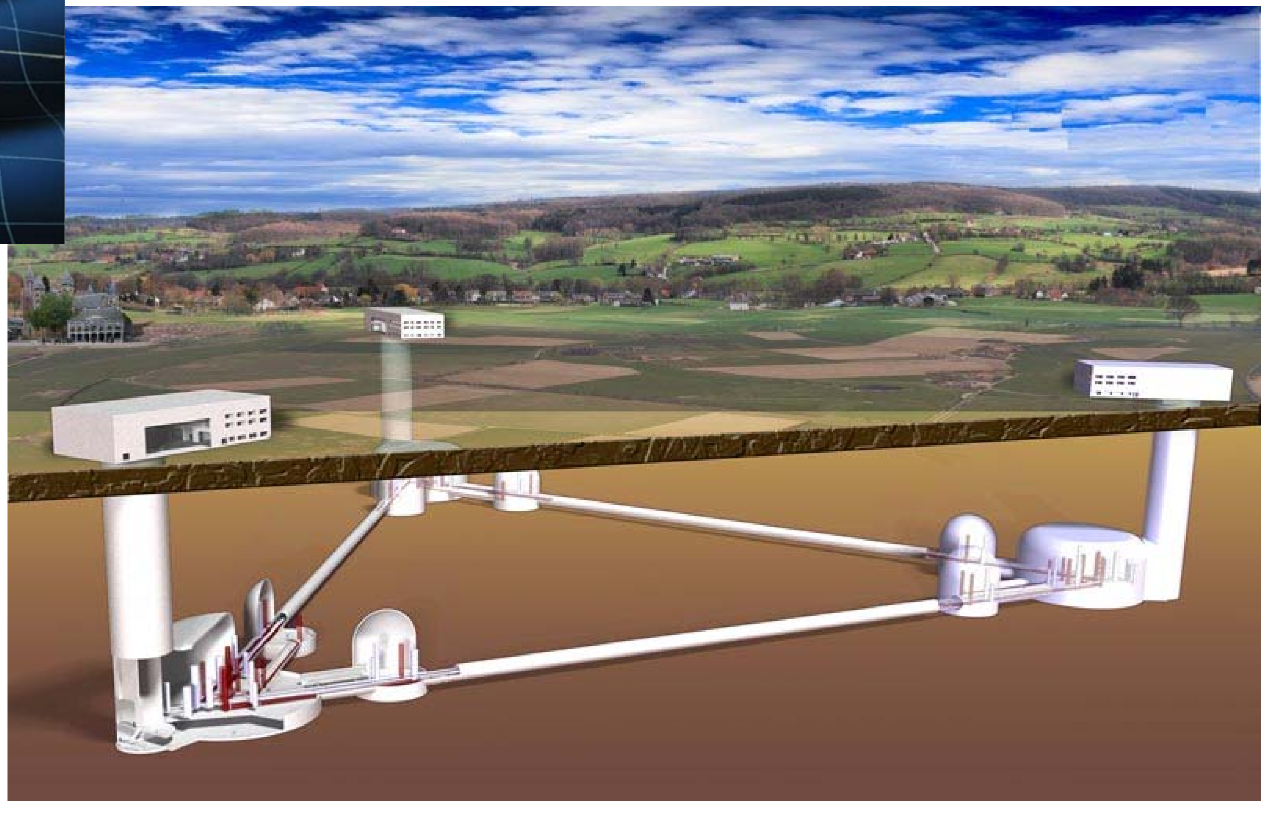


KAGRA-Chan

Future projects



Space detectors
(LISA, DECIGO)



3G detectors
(Einstein Telescope, Cosmic Explorer)