Ground-based Gravitational Wave detectors

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中央研究院
Academia Sinica

Congratulations ! from Taiwan

Colloquium at Institute of Physics, Academia Sinica

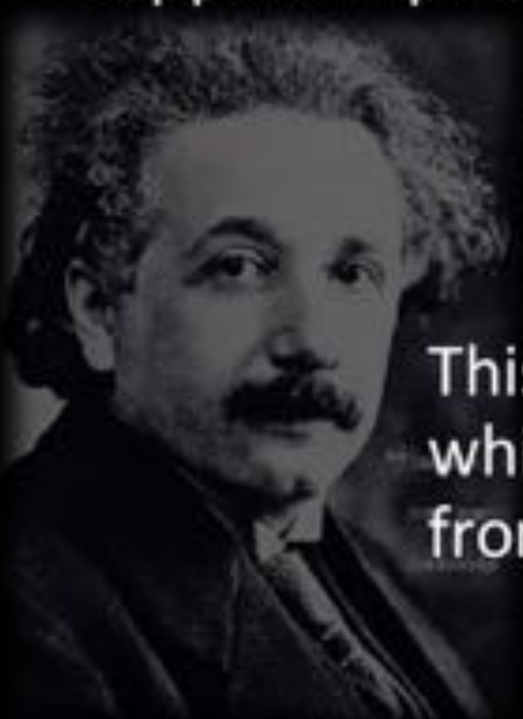
Speaker: Prof. Barry Barish , California Institute of Technology
Time: July 23, Thurs ; 14:00 -16:00
Place: 1st Floor Lecture Hall, Institute of Physics, Academia Sinica
Title:
Gravitational Waves - A New Window on the Universe

July/2015

Gravitational waves (GW)

- Predicted by A. Einstein in 1916

  Ripple of space-time propagating in speed of light

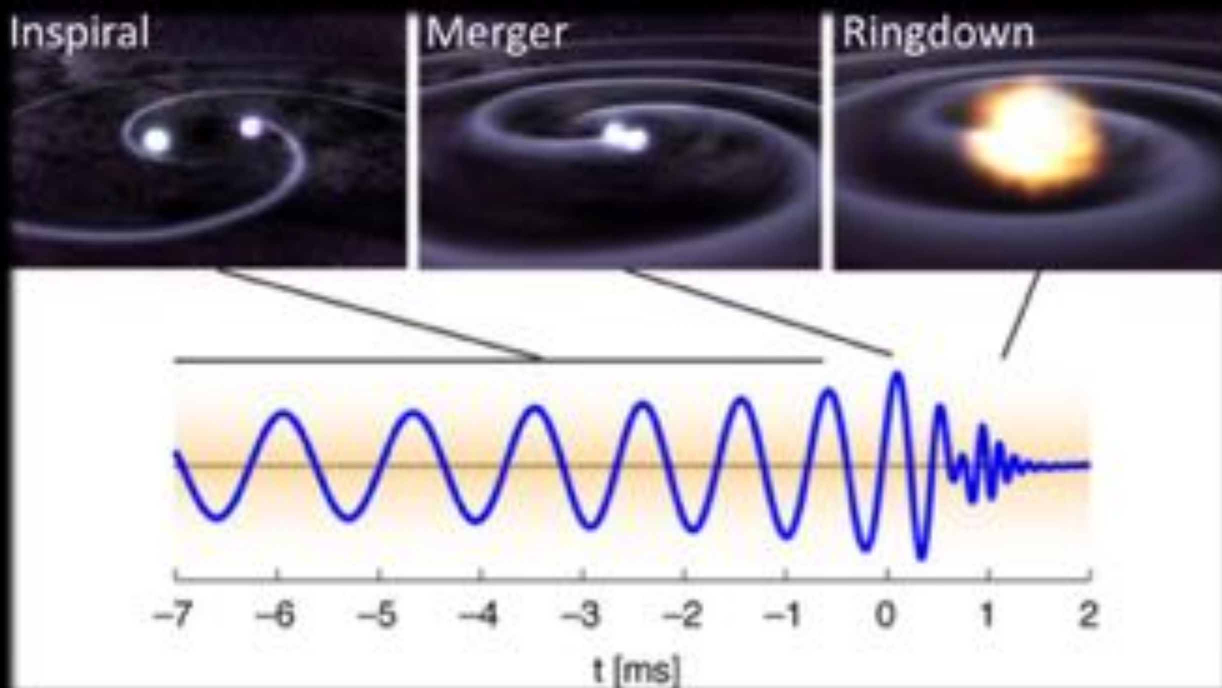


GW is transparent for any material, except gravity sources.

This causes detection to be difficult, while it can bring us information from where we wouldn't see by EM

GW sources and physics

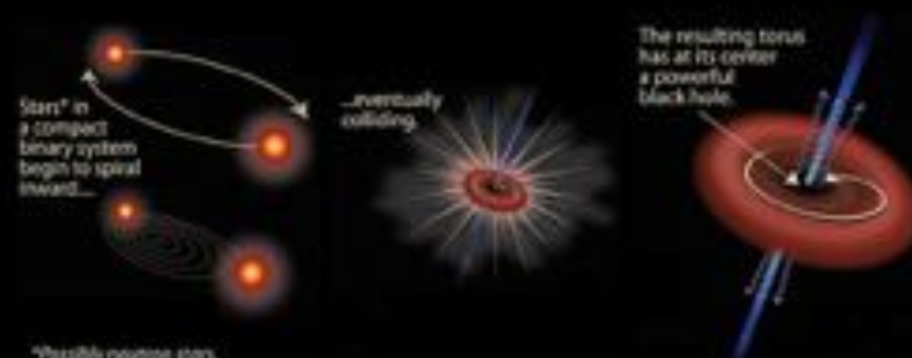
- Compact Binary Coalescences
  Black Holes (BH) and/or Neutron Stars (NS)



GW sources and physics

- Compact Binary Coalescences
  Physics examples

- Test of General Relativity
- Possible progenitor of Gamma-Ray Burst (GBR)
- Determination of cosmological parameters with GW "Standard siren" ⇔ EM "standard candle"

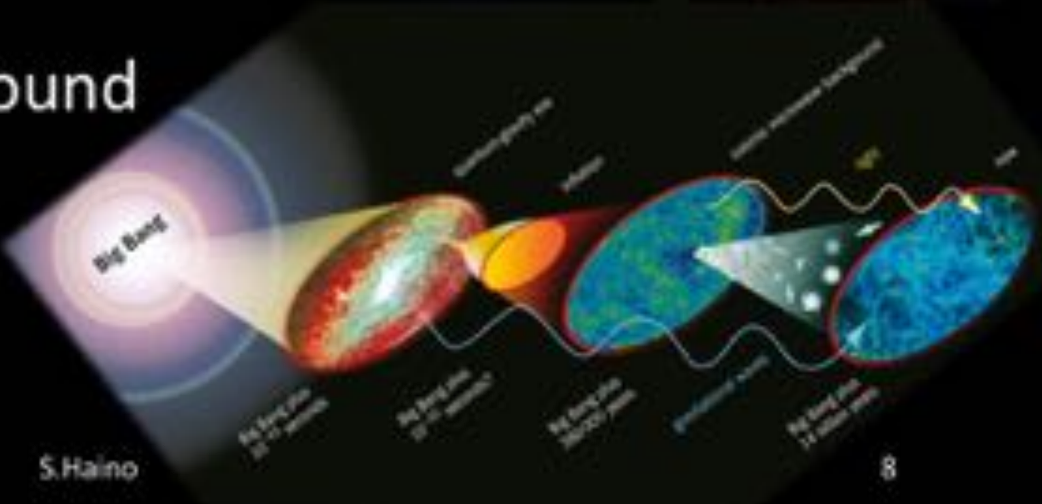


GW sources and physics

- Compact Binary Coalescences

- Continuous waves from pulsars

- Supernovae
- Stochastic GW background from Early Universe



Typical GW strain amplitude

$$h \sim \frac{2G}{c^4 R}\ddot{I} \sim \frac{2G}{c^4 R}\frac{Mr^2}{T^2} \sim \frac{2GM}{c^2}\frac{1}{R} = \frac{r_g}{R}$$

$\frac{Mr^2}{T^2}$: $\sim Mc^2$

$\frac{2GM}{c^2}$: r_g Schwarzschild radius

R: R Distance

Typical GW strain amplitude

$$h \sim \frac{2G}{c^4 R}\ddot{I} \sim \frac{2G}{c^4 R}\frac{Mr^2}{T^2} \sim \frac{2GM}{c^2}\frac{1}{R} = \frac{r_g}{R}$$

$\sim Mc^2$

r_g Schwarzschild radius

R Distance

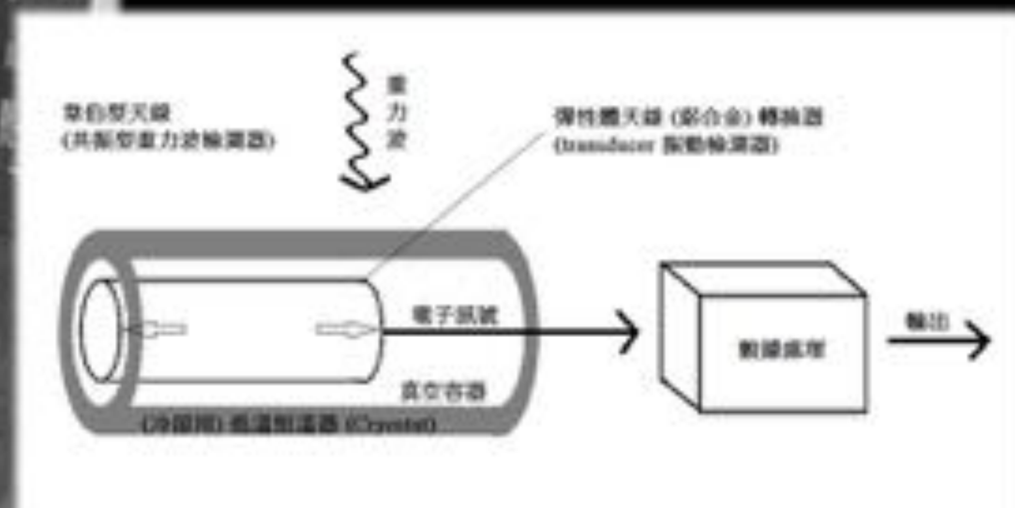
e.g. Solar mass (r_g~3km) NS-NS binary merging at ~speed of light located at 100 Mpc away

$$h \sim \frac{3\ \text{km}}{100\ \text{Mpc}} = 10^{-21}$$

GW signal is very tiny but propagate as 1/R (not $1/R^2$)

History of GW Detection

- 1916 Prediction of GW by A. Einstein
- 1960's Weber - Resonant-mass GW detectors



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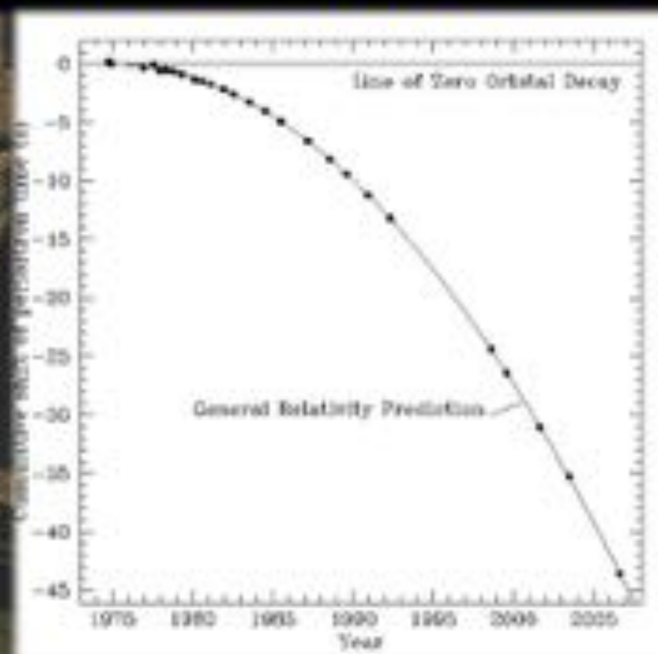

History of GW Detection

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- 1990's 1st. generation interferometric detectors
  - GEO (De), LIGO (US), Virgo (It), Tama (Jp), …

Interferometric GW detector

Prototype Michelson interferometer with Fabry–Perot cavities

1 August 1991 / Vol. 30, No. 22 / APPLIED OPTICS 3133

David Shoemaker, Peter Fritschel, Joseph Giaime, Nelson Christensen, and Rainer Weiss

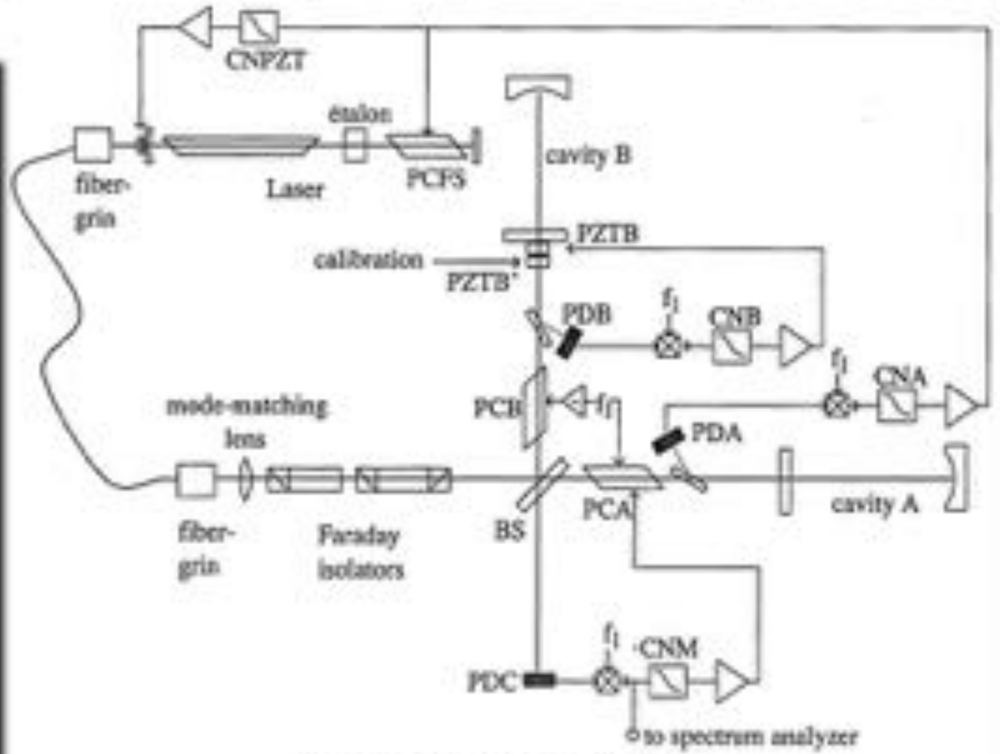
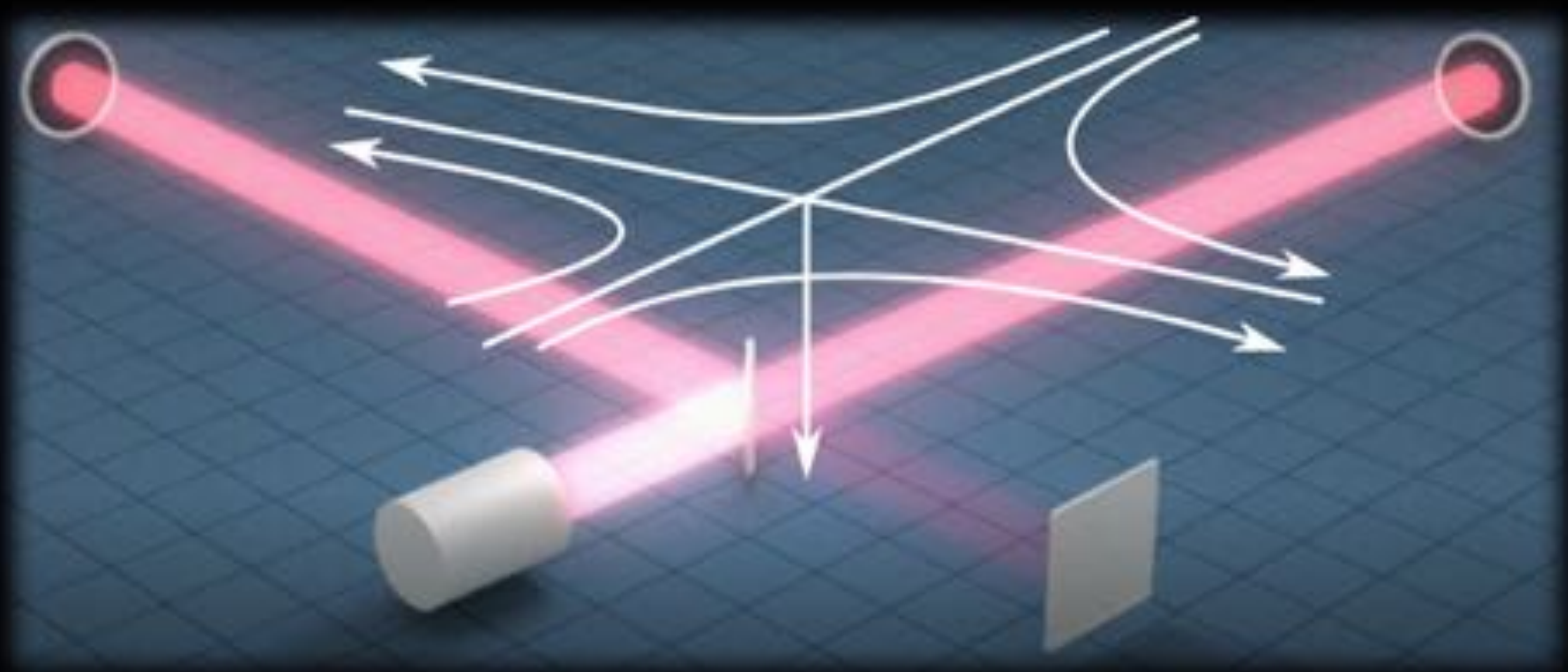
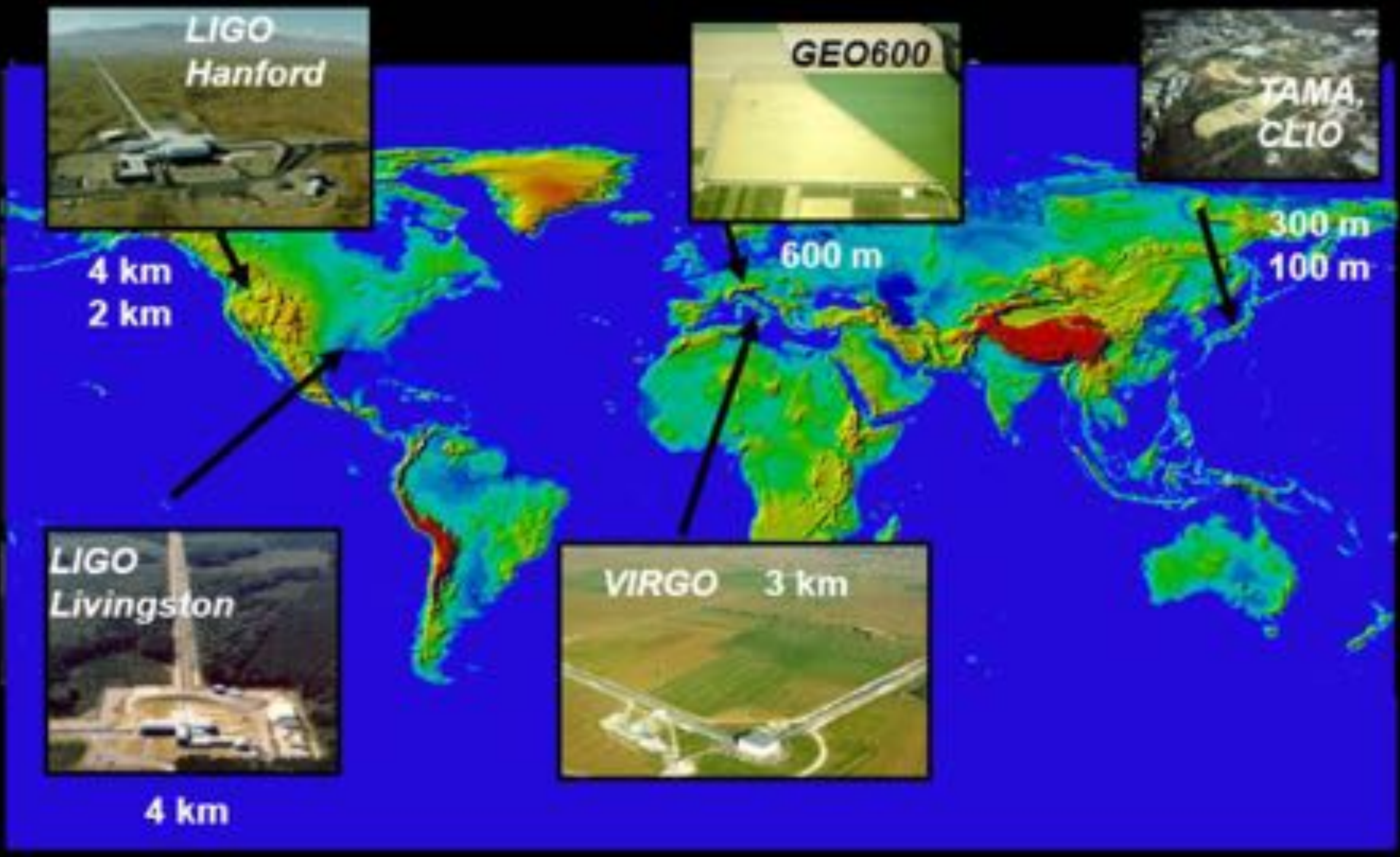


Fig. 1. Schematic diagram of the interferometer.

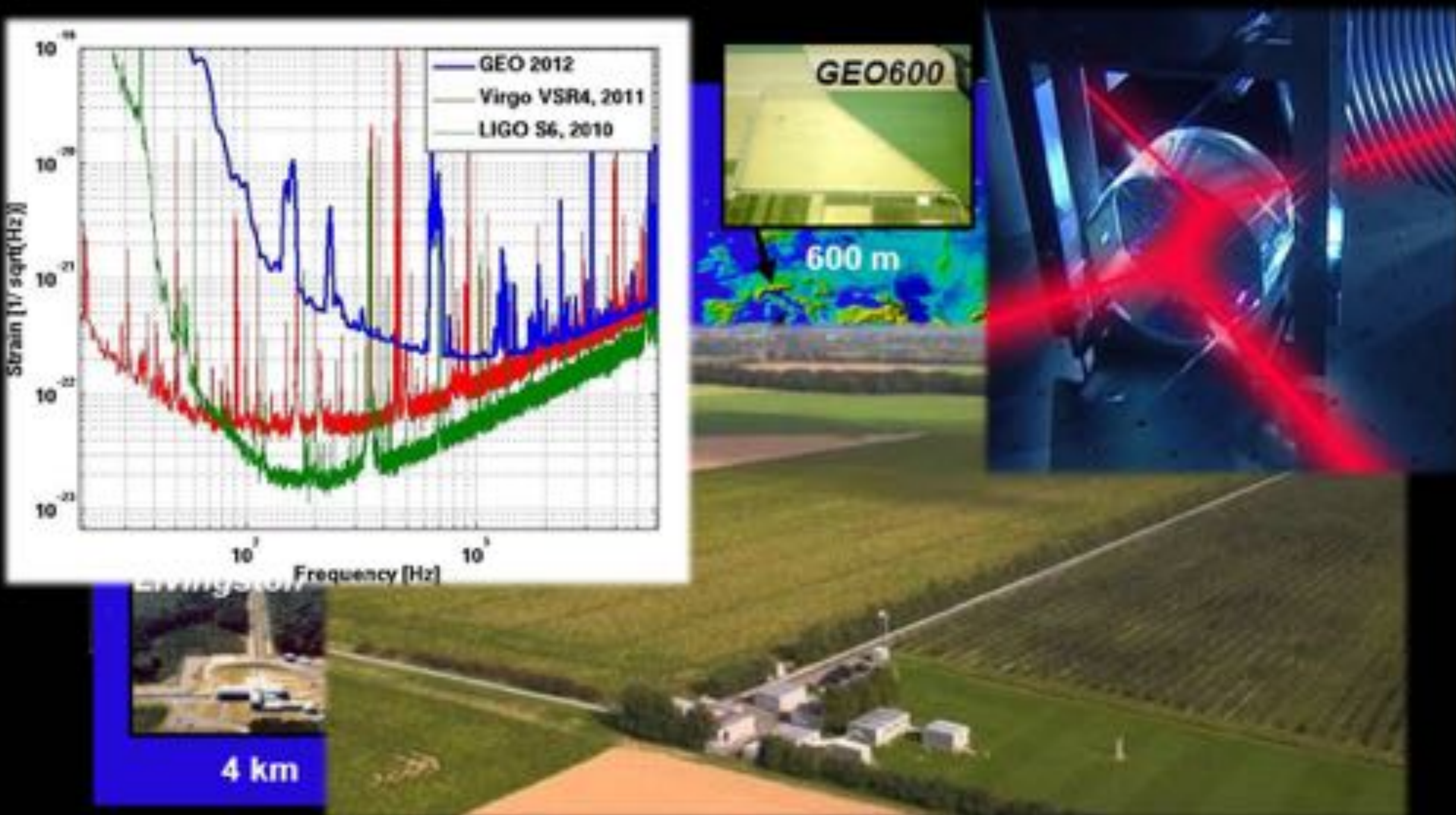
Interferometric GW detector



1st. generation detectors



GEO 600, as a 1.5 G detector



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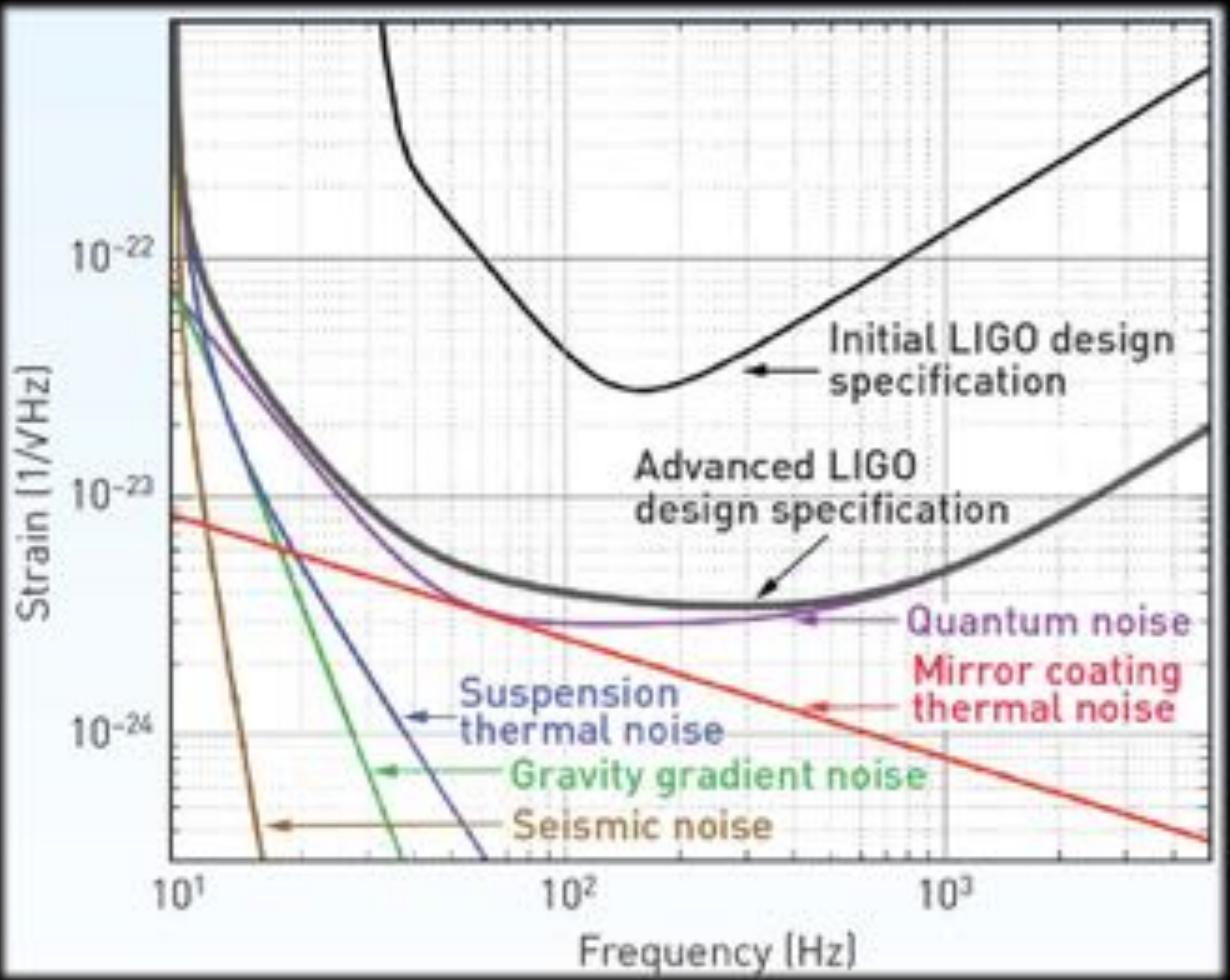
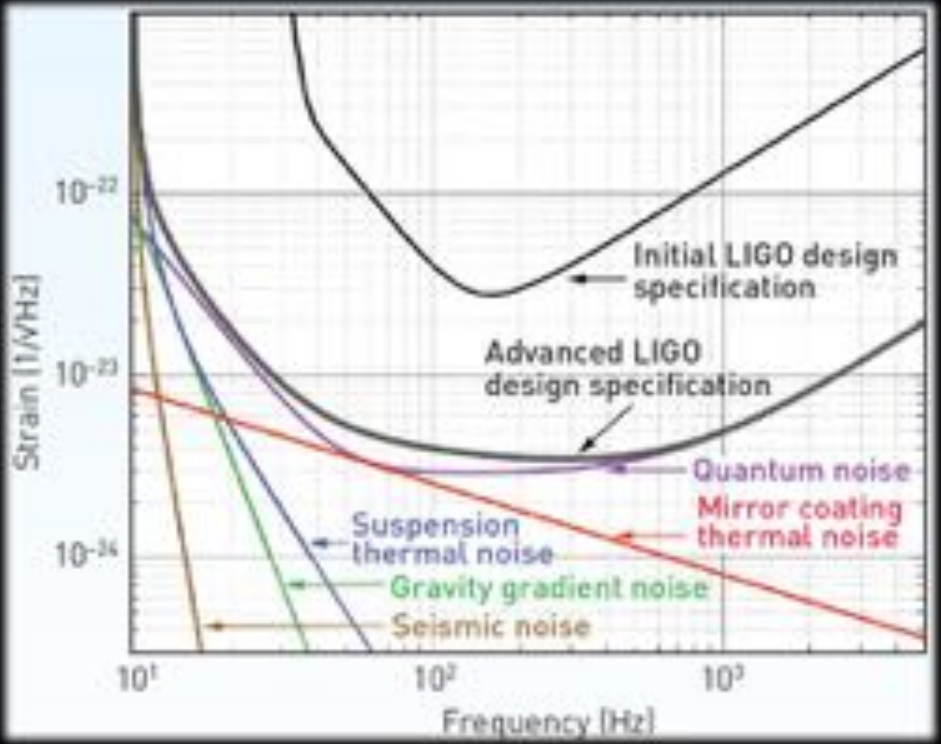
  - Adv. LIGO, Adv. Virgo, KAGRA

Advanced LIGO upgrades (2010-2015)



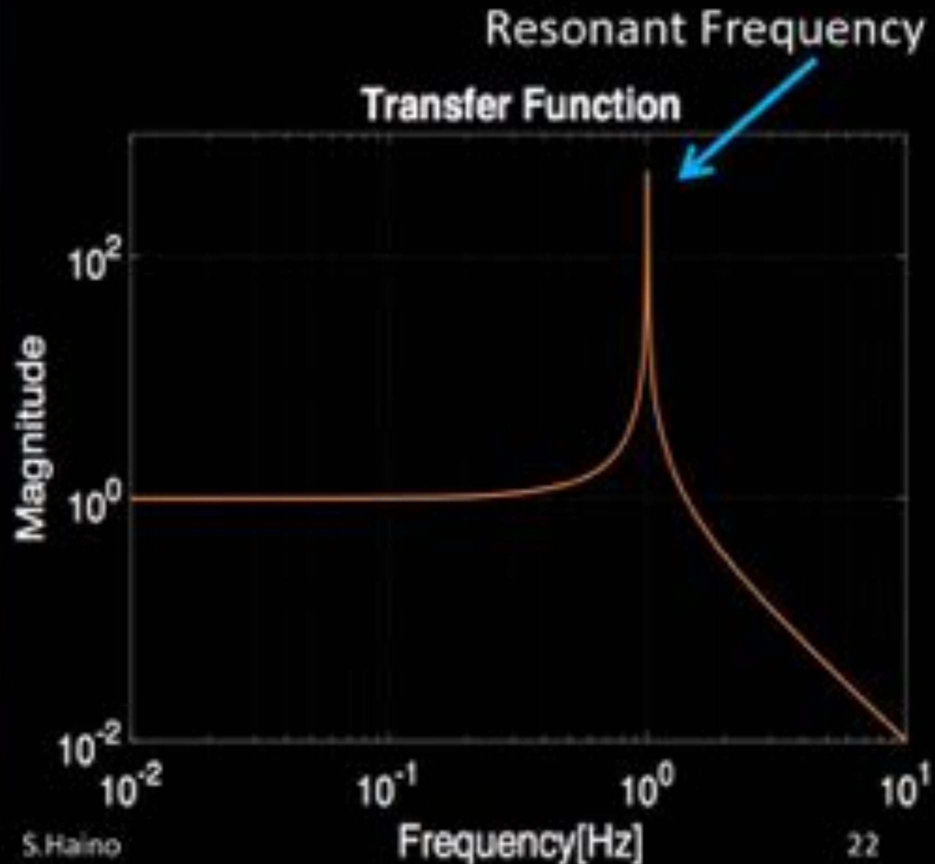
Dominant noise sources

- Seismic noise
- Quantum noise
  - Radiation pressure
  - LASER shot noise
- Mirror and suspension thermal noise

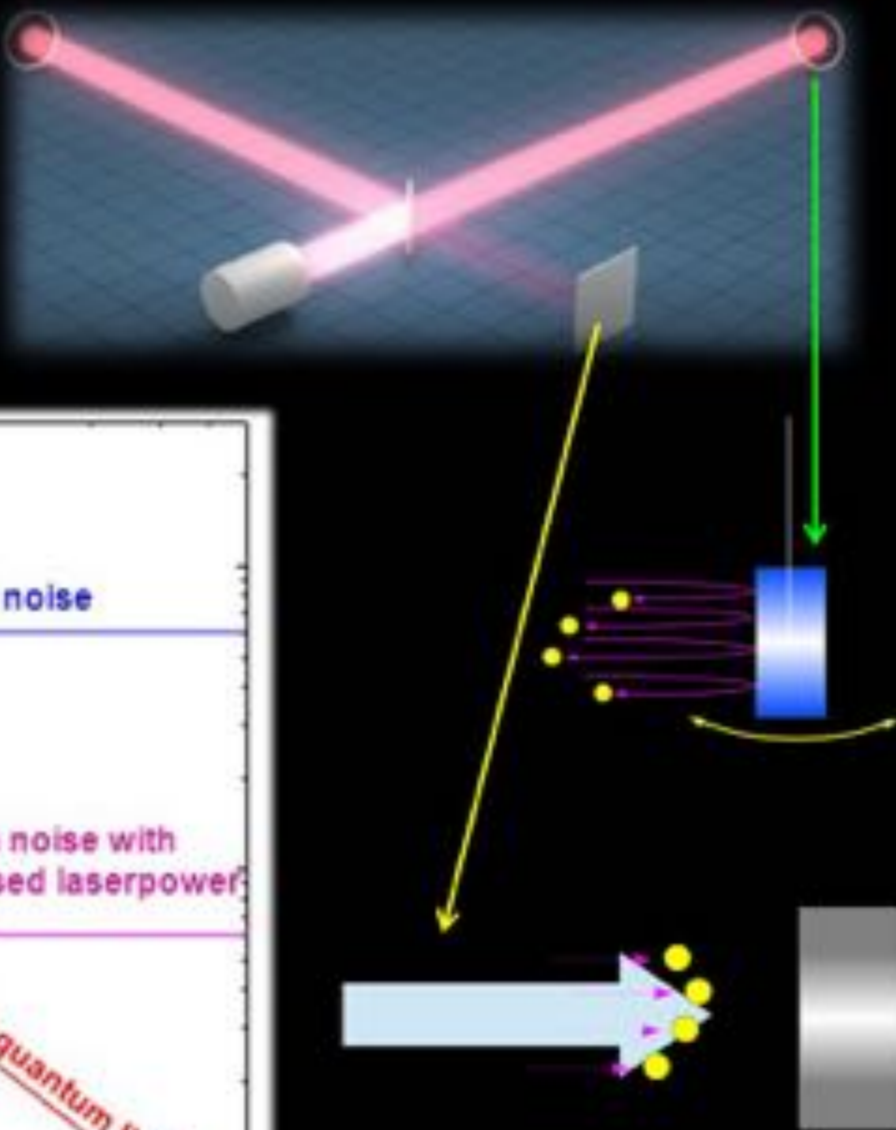


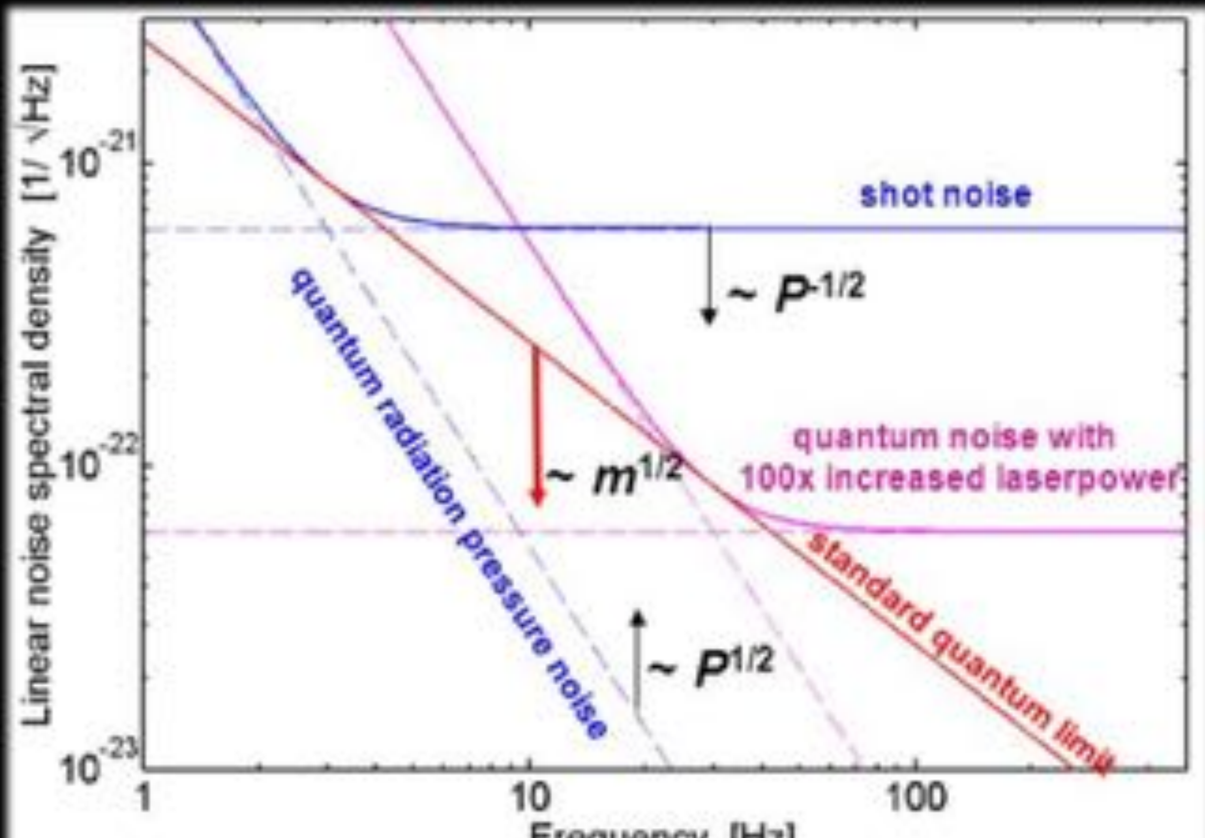
Seismic noise attenuation

$$\frac{x(\omega)}{y(\omega)} = \frac{\omega_0^2}{\omega_0^2 - \omega^2}$$



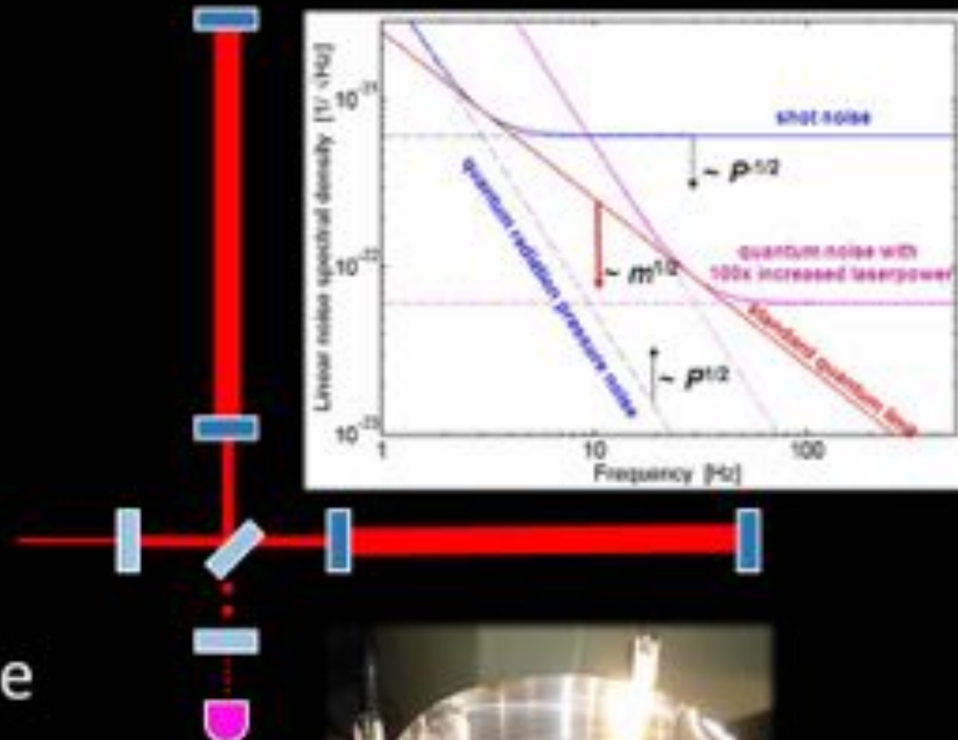
Quantum noise





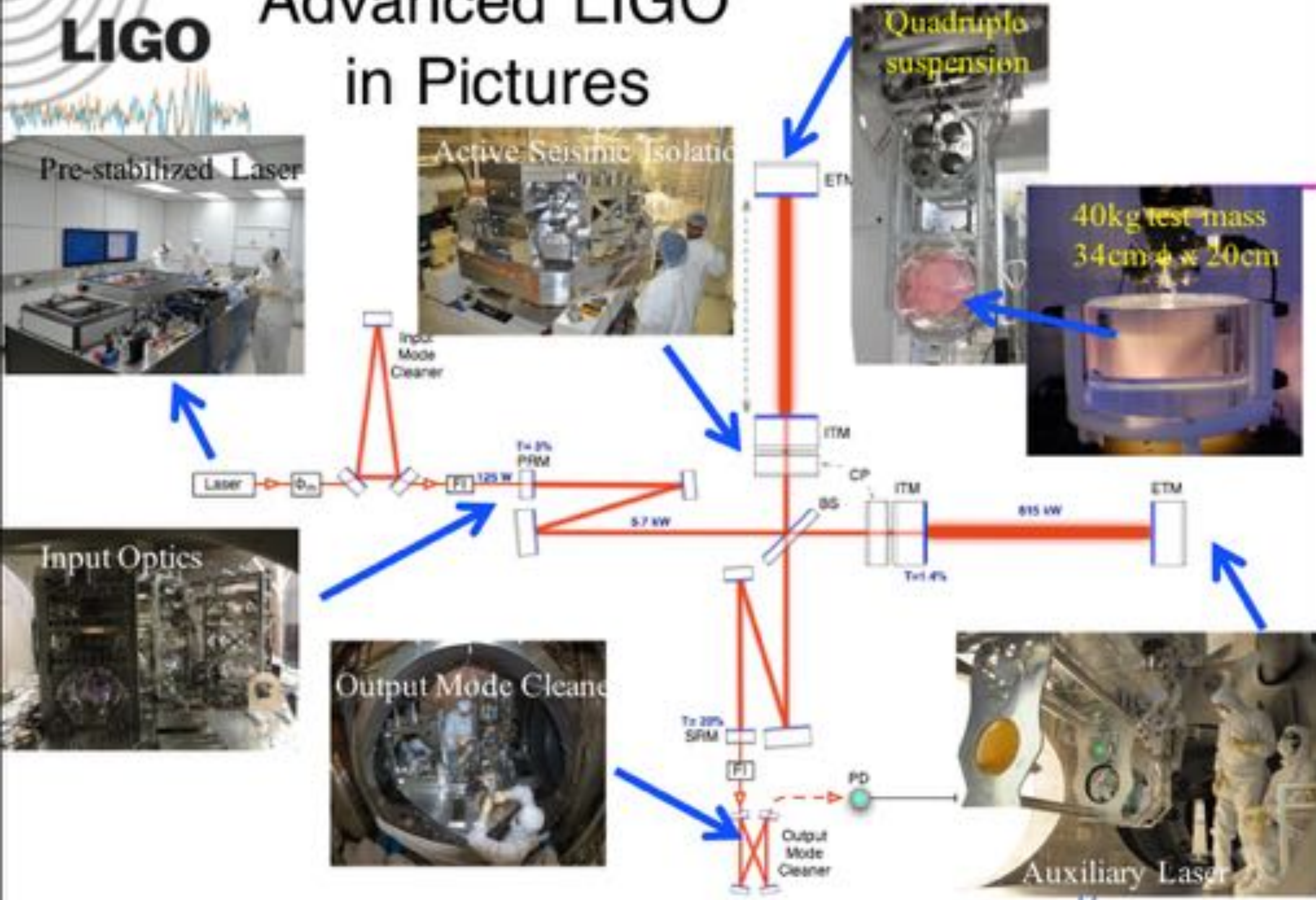
Quantum noise Reduction in 2G

- Shot noise
  - High power laser
  - Arm cavity
  - Dual recycling



- Radiation pressure noise
  - Heavier mirror

Advanced LIGO in Pictures



Advanced Virgo

Virgo is a European collaboration with about 280 members

Advanced Virgo (AdV): upgrade of the Virgo interferometric detector

Participation by scientists from France, Italy, The Netherlands, Poland, Hungary, Spain

- 20 laboratories, about 280 authors
  - APC Paris
  - ARTEMIS Nice
  - EGO Cascina
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma La Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - LAL Orsay – ESPCI Paris
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Nikhef Amsterdam
  - POLGRAW(Poland)
  - RADBOUD Uni. Nijmegen
  - RMKI Budapest
  - Univ. of Valencia

Funding approved in Dec 2009

- 21.8 ME CNRS and INFN
- 3.5 ME Nikhef in kind contribution

Goal: be part of the international network of 2nd generation detectors

Short-term goal: join the O2 run in 2017

6 European countries

Advanced Virgo design

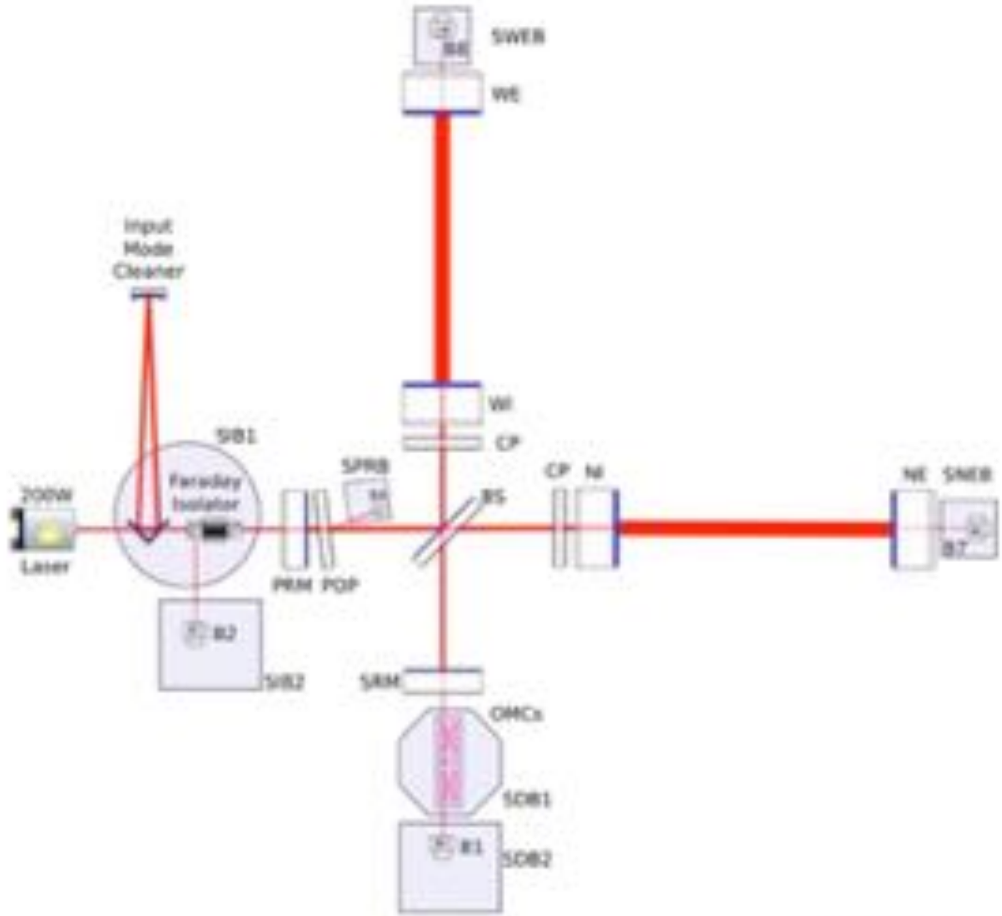
Advanced Virgo features many improvements with respect to Virgo and Virgo+

For 2017

- Larger beam
- Heavier mirrors
- Higher quality optics
- Thermal control of aberrations
- Stray light control
- Improved vacuum

For the period 2018 to 2019

- 200 W laser
- Squeezing
- Signal recycling
- Newtonian noise subtraction



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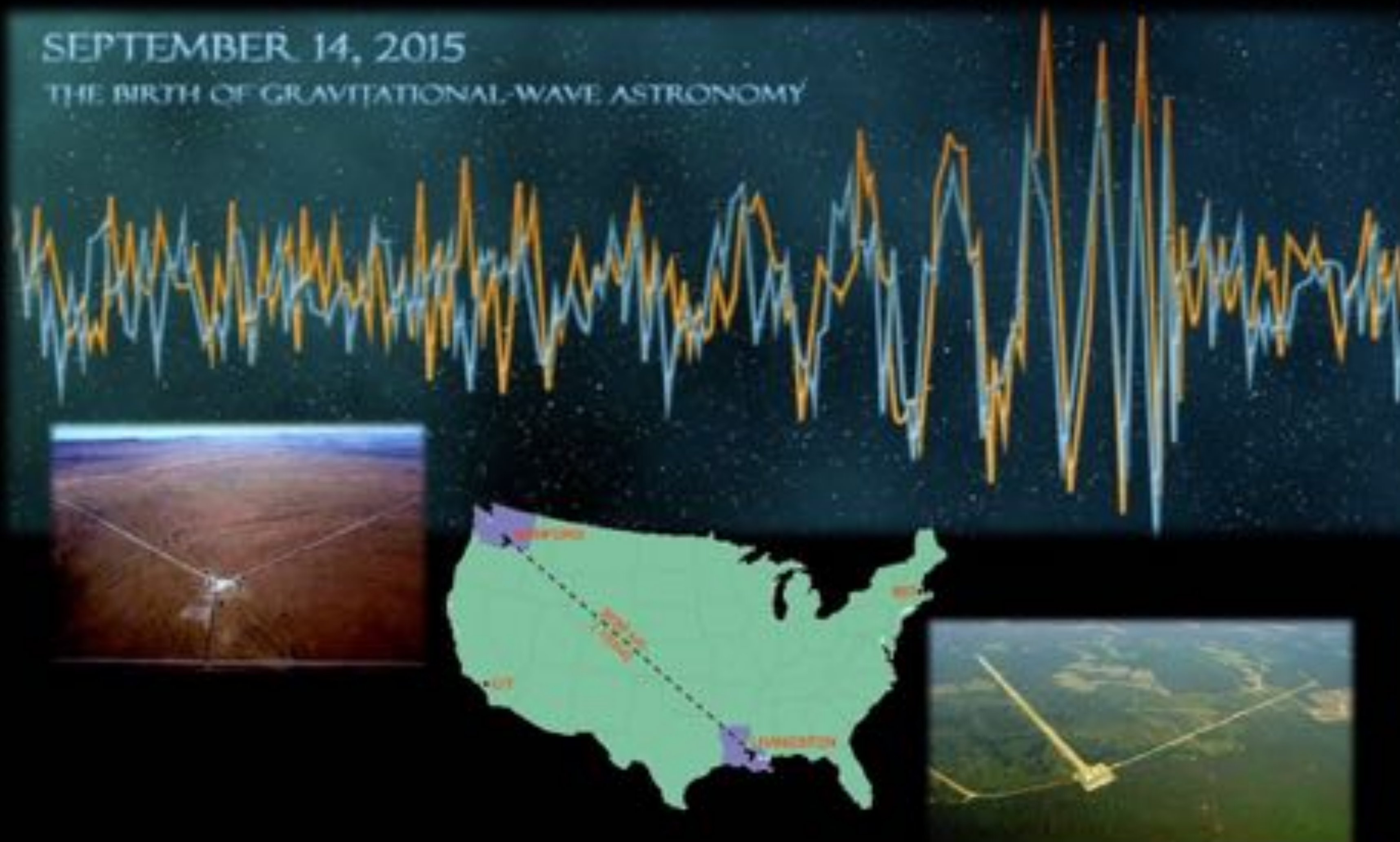
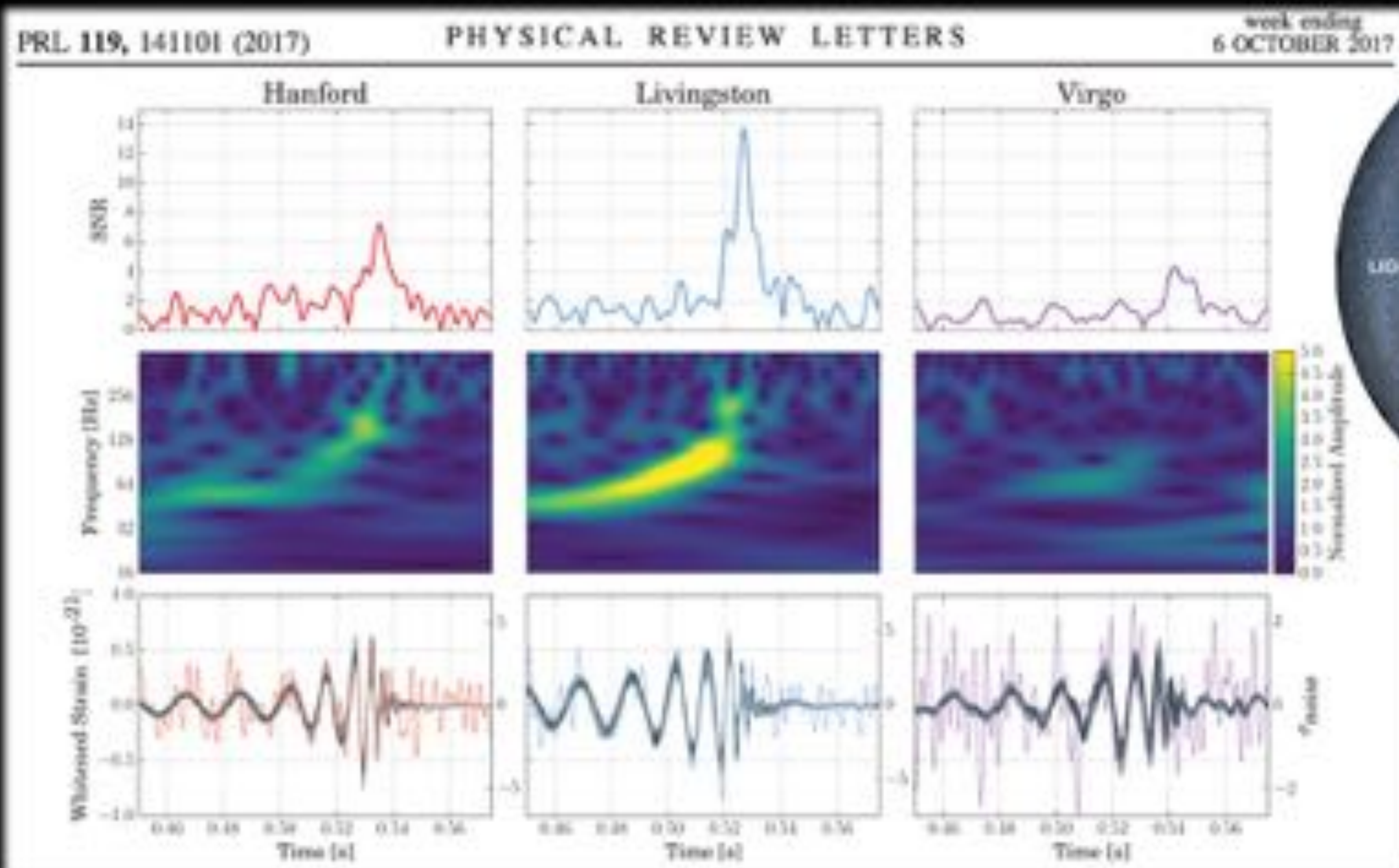
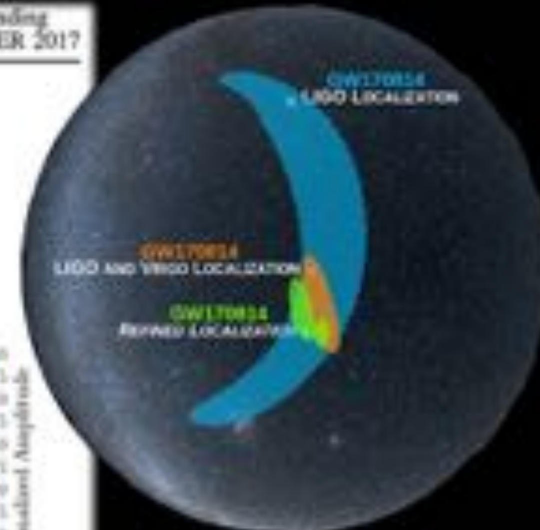
- 2010's 2nd. generation interferometric detectors
  - Adv. LIGO, Adv. Virgo, KAGRA
- 2015 First GW detection from Binary BH (O1 run)
- 2017 First GW detection from Binary NS (O2 run)

First GW detection (Sep.14, 2015)

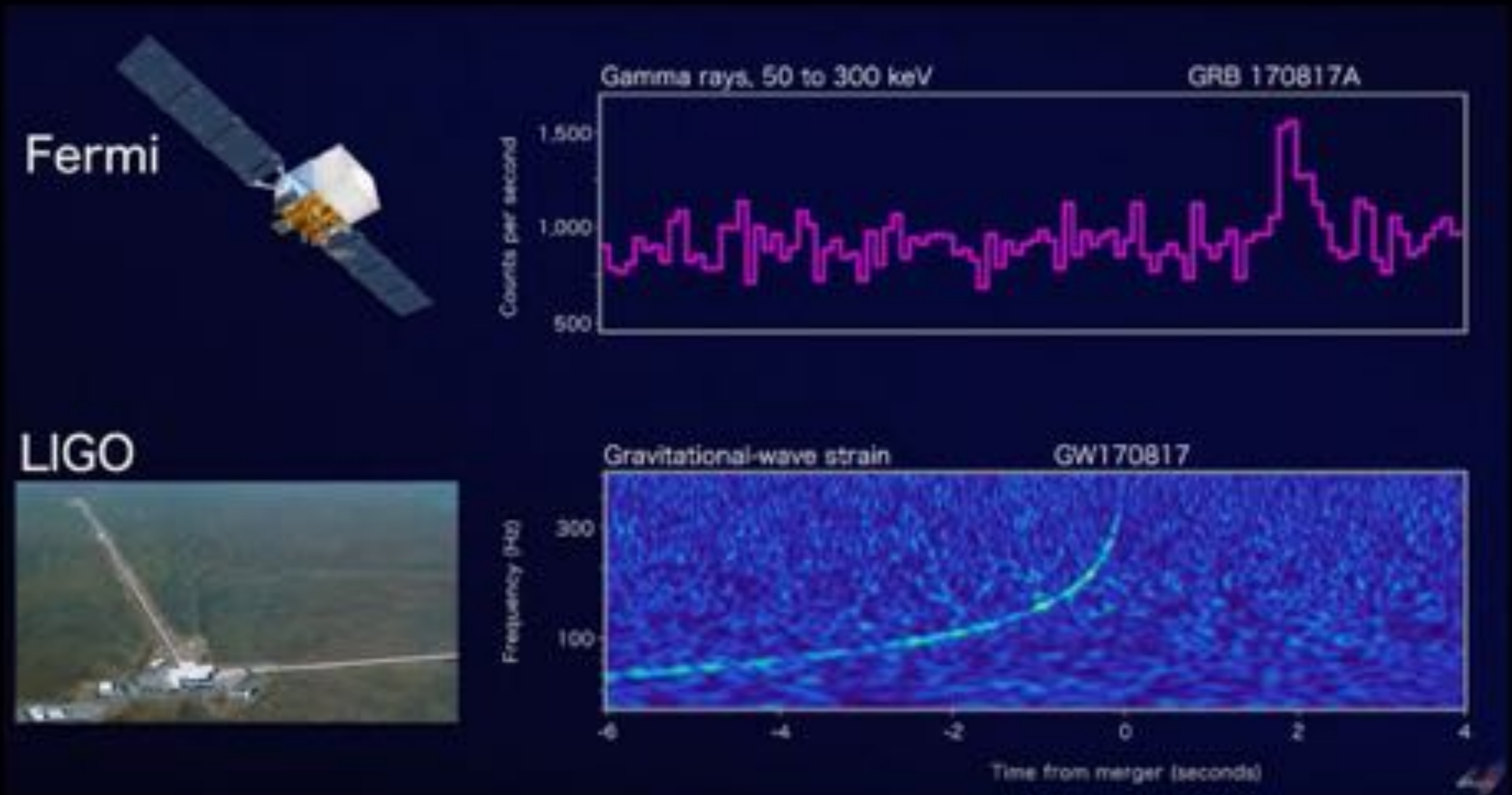


First GW detection with LIGO/Virgo – GW170814

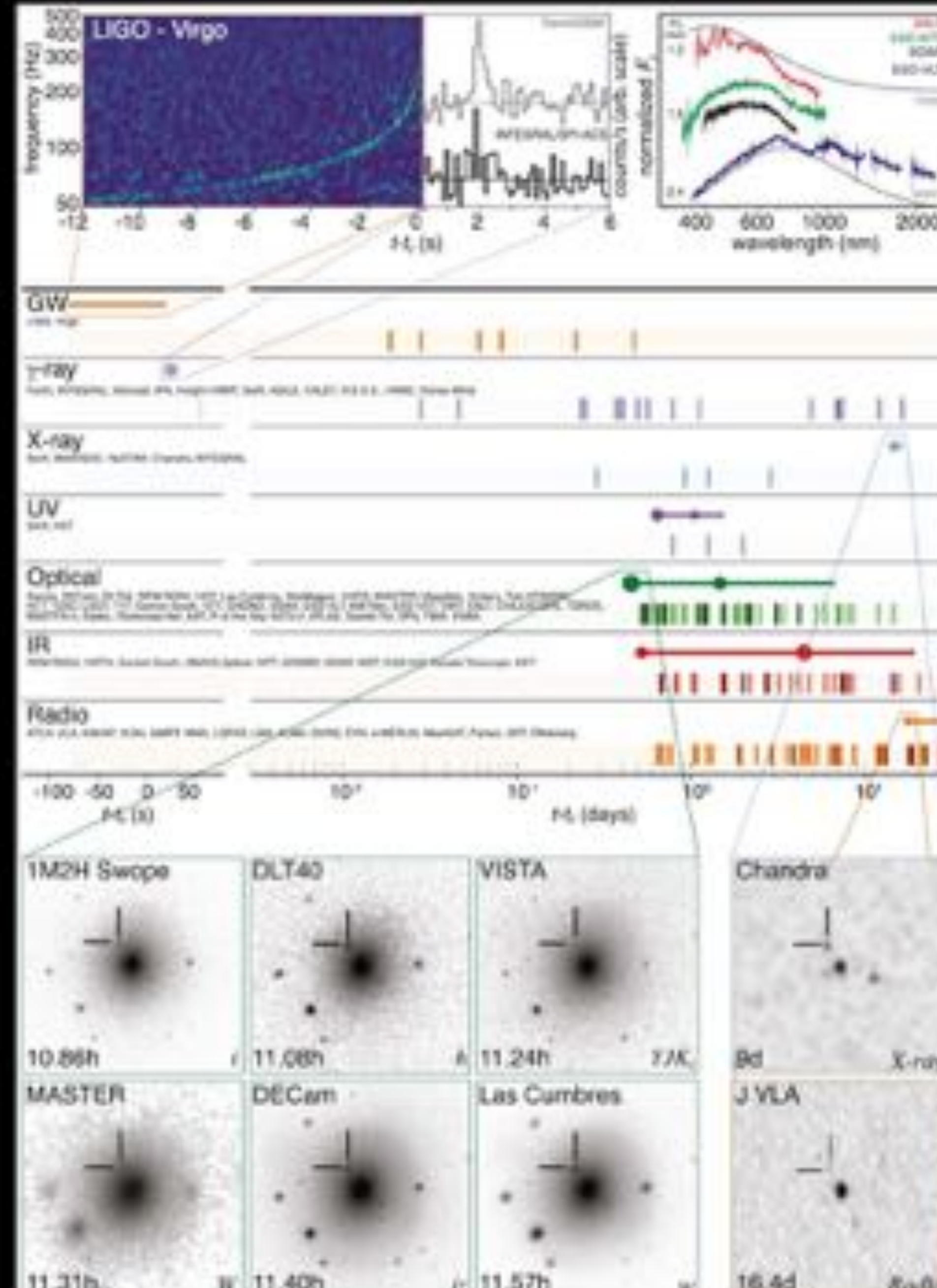




First GW detection from BNS

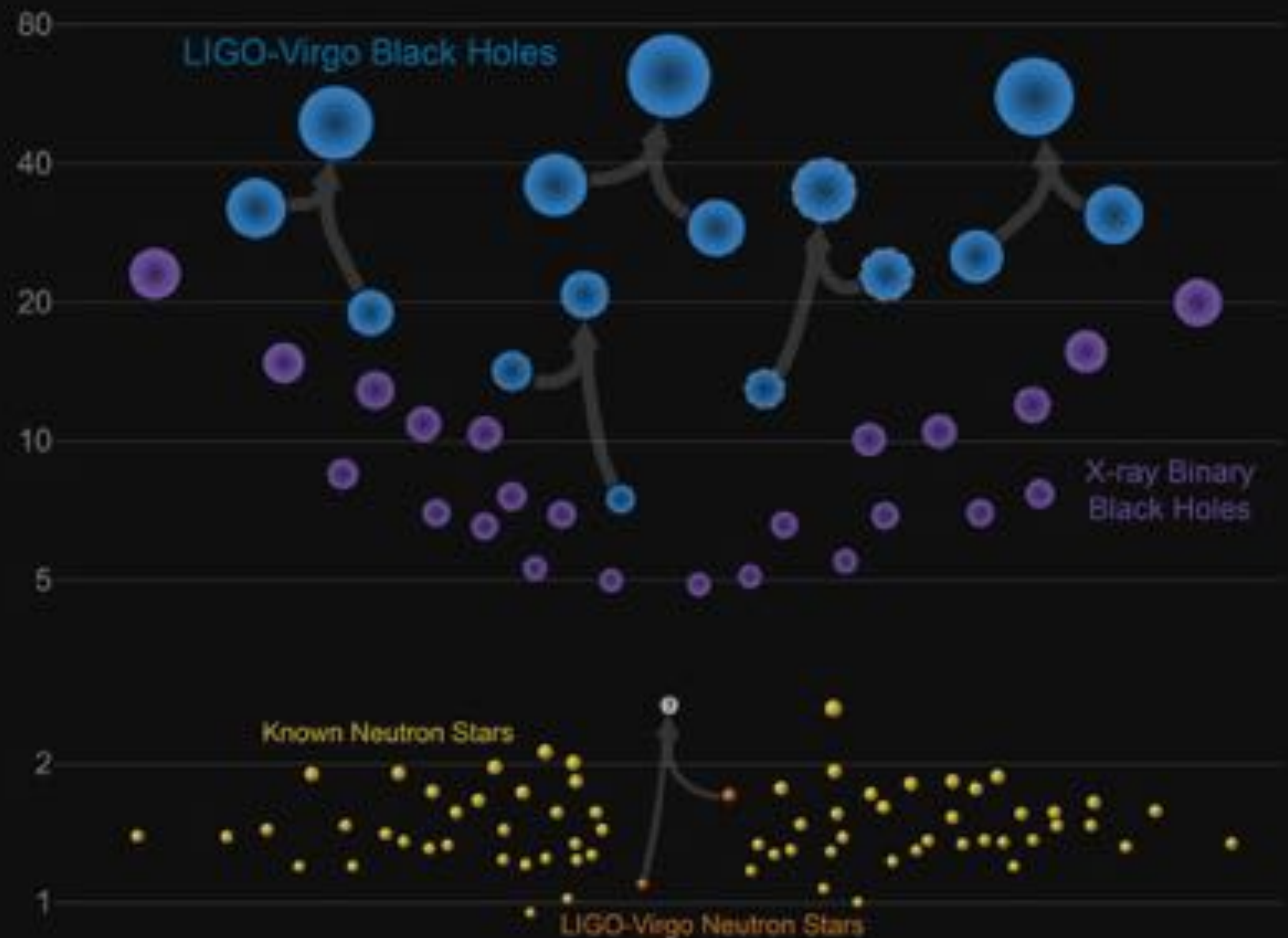



Earth
Space
LIGO Hanford
LIGO Livingston
Virgo


LIGO - Virgo
frequency (Hz)
wavelength (nm)
GW
γ-ray
X-ray
UV
Optical
IR
Radio
t-t$_c$ (days)
1M2H Swope
DLT40
VISTA
Chandra
10.86h
11.08h
11.24h
9d
X-ray
MASTER
DECam
Las Cumbres
J VLA
11.31h
11.40h
11.57h
16.4d
Radio

Masses in the Stellar Graveyard

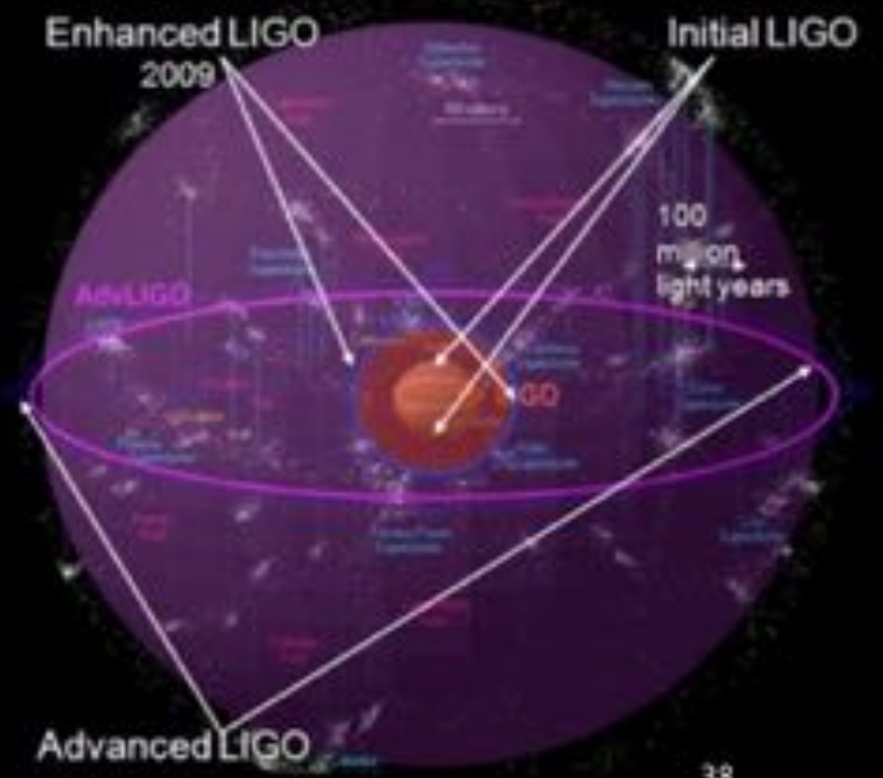
in Solar Masses



Opening of GW astronomy

- LIGO's GW detection opened a new era
- GW amplitude is proportional to 1/Distance

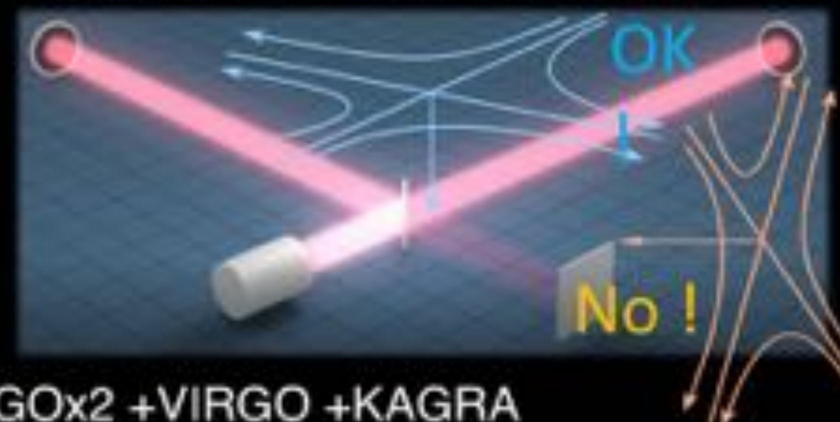
- 10 times improvement of sensitivity will increase number of sources by 1000 !



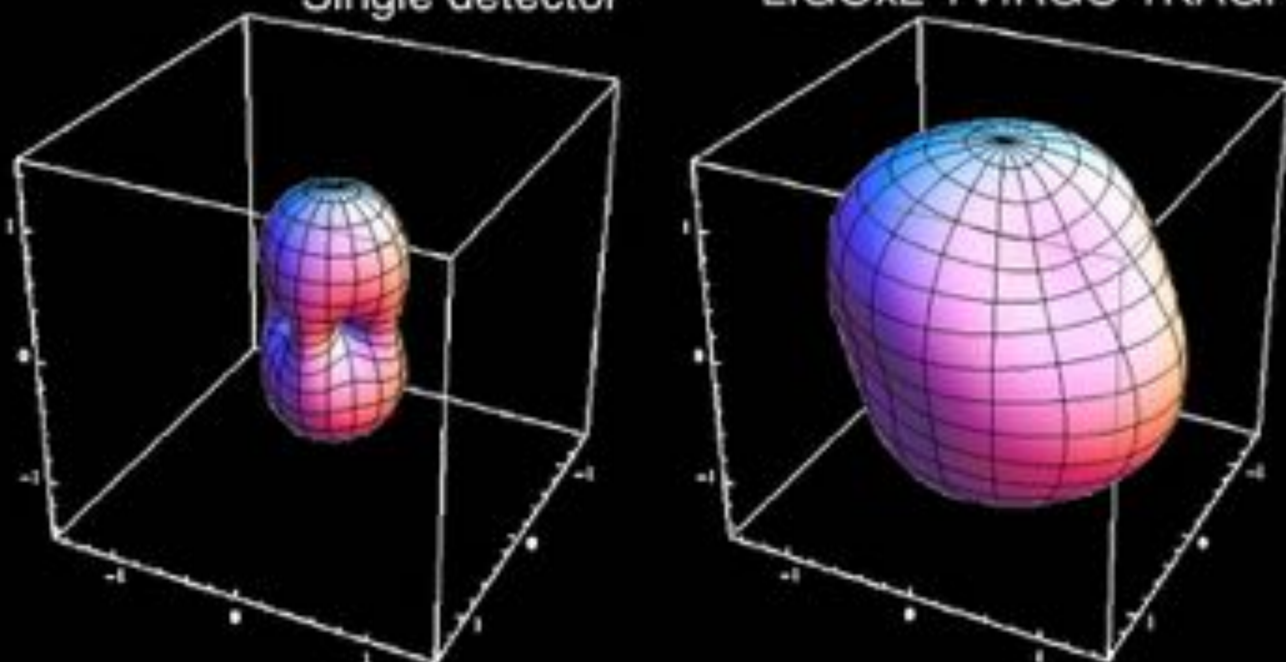
World-wide GW detector network

Advantages of detector network

- Increase the sky coverage



Single detector LIGOx2 +VIRGO +KAGRA

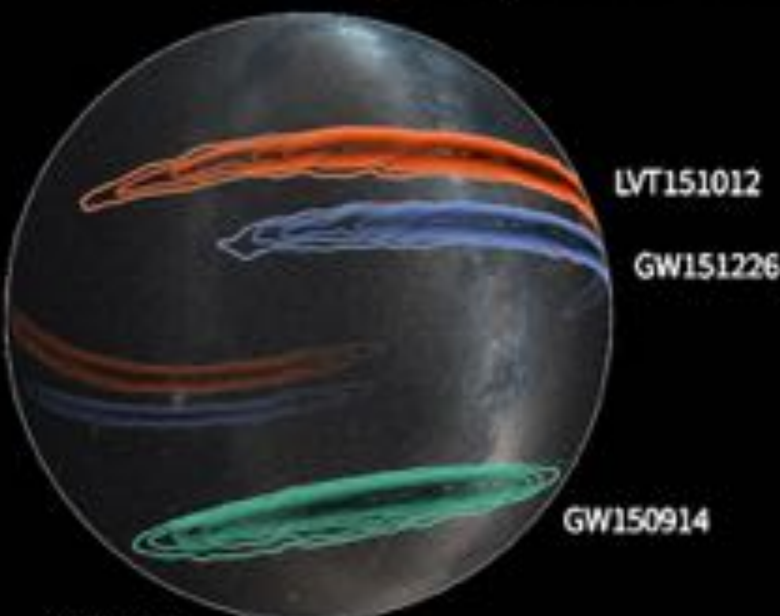


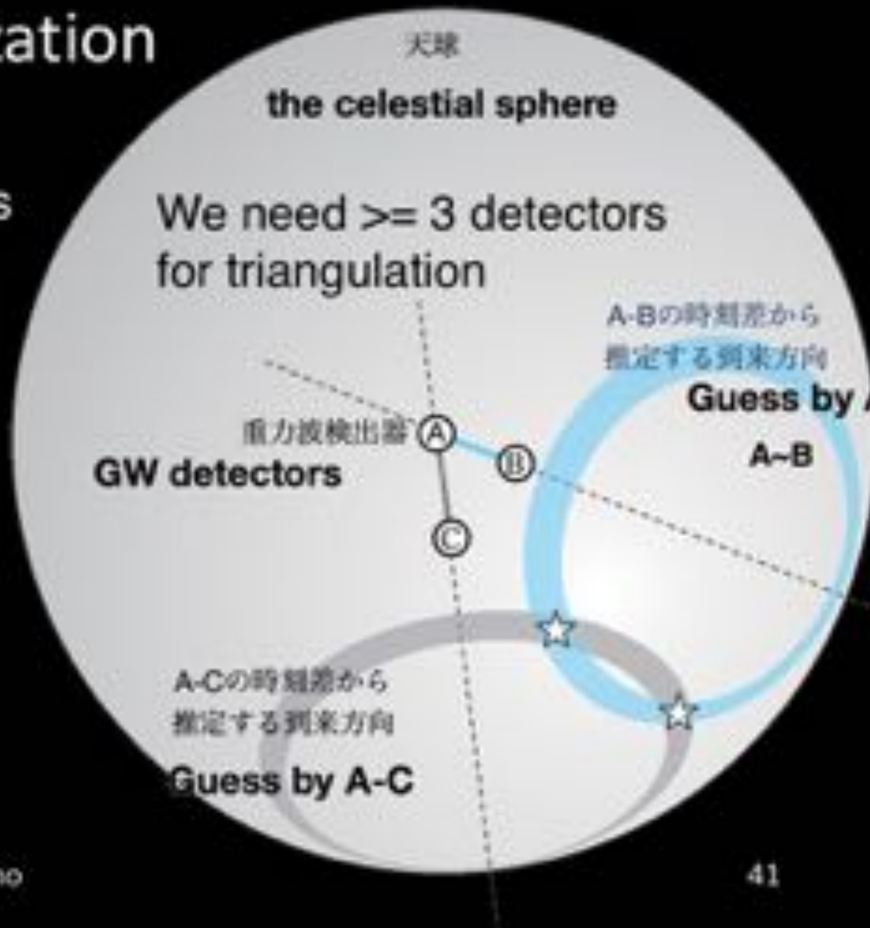
Antenna amplitude pattern (B.F. Schutz, N. Kanda)

Advantages of detector network

- Increase the sky coverage
- Improve the source localization

GW events locations
by only 2 LIGO detectors

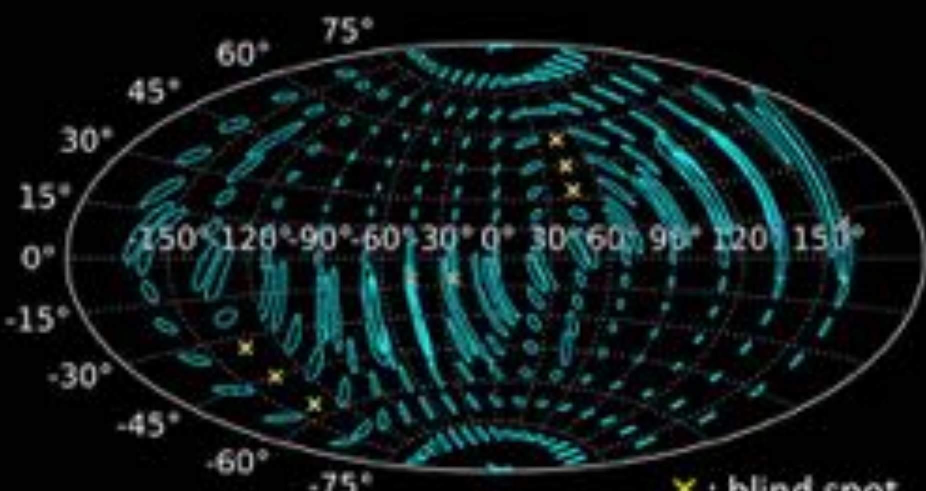




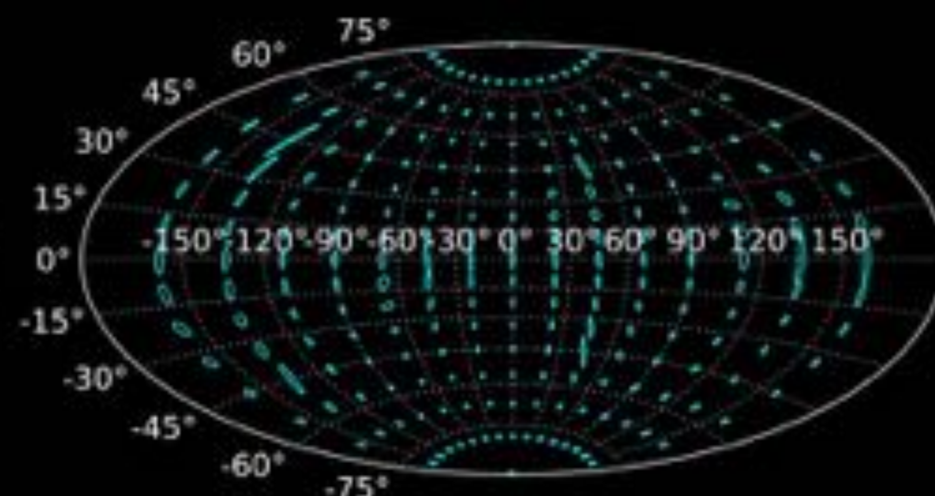
Advantages of detector network

- Increase the sky coverage
- Improve the source localization

2xLIGO + Virgo



2xLIGO + Virgo+ KAGRA



× : blind spot

S. Fairhurst, CQG 28, 105021 (2011)

KAGRA

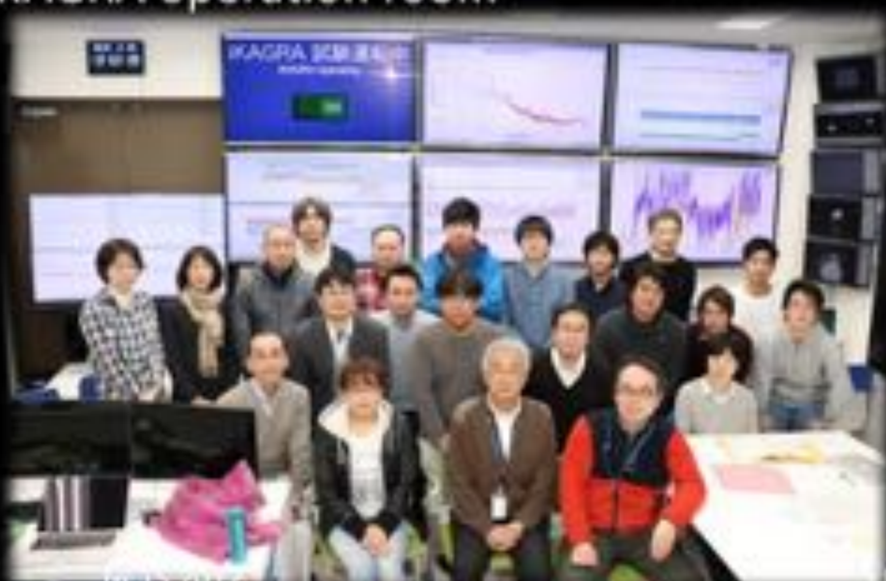

GEO 600m
LIGO (Livingston) 4km
advanced LIGO
Virgo 3km
advanced Virgo
LIGO (Hanford) 4km
LIGO-India
Japan
Kamioka
1000km

KAGRA collaboration

~300 researchers from Japan and Asia

KAGRA meeting in Korea

KAGRA operation room



KAGRA Taiwan team

Taipei Gravitational Wave Group (TGWG)

FACULTY

Chian Shu Chen

Ting Wai Chiu

Sadakazu Haino

Chun Yu Lin

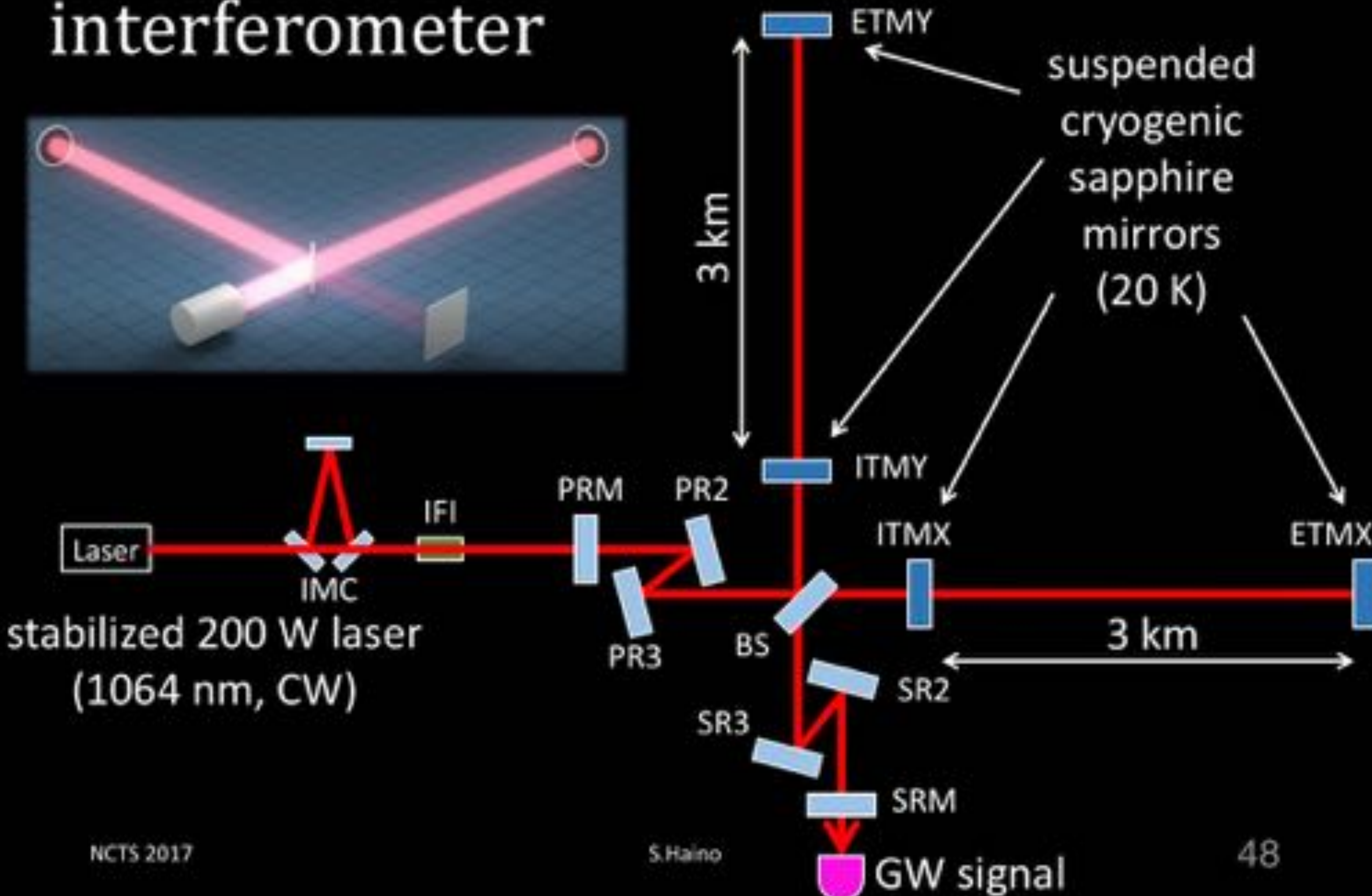
Feng Li Lin

Guo Qing Liu

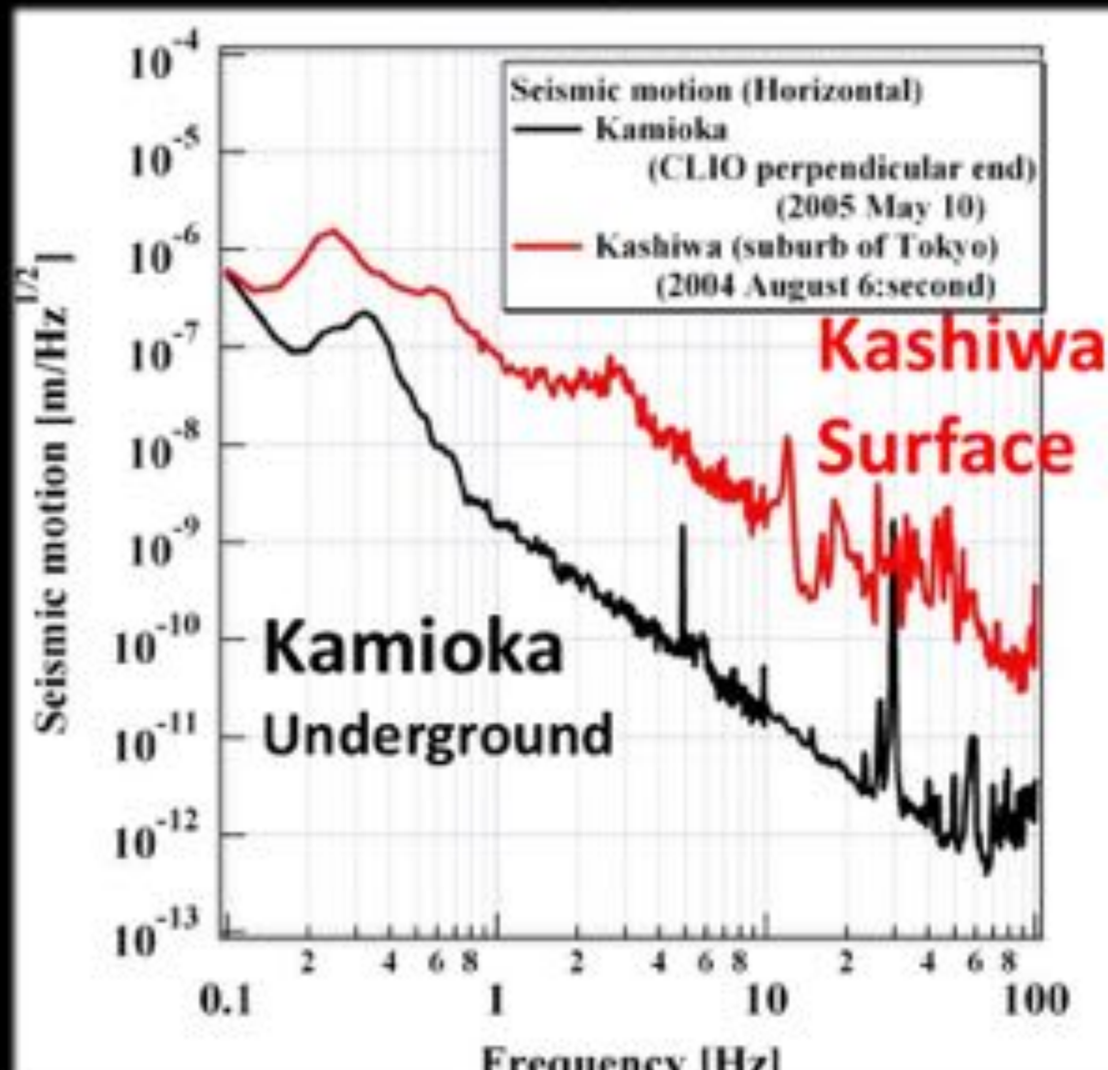
國立臺灣師範大學 (NTNU)
淡江大學 (TKU)
國家高速網路與計算中心 (NCHC)
中央研究院 物理研究所 (ASIoP)

Kamioka underground site

Dual-recycling Fabry-Perot interferometer



KAGRA – The first km-scale detector at underground




Tunnel excavation was
done in 2014


Vacuum tubes
installed in 2015


Tunnel entrance

Vacuum System

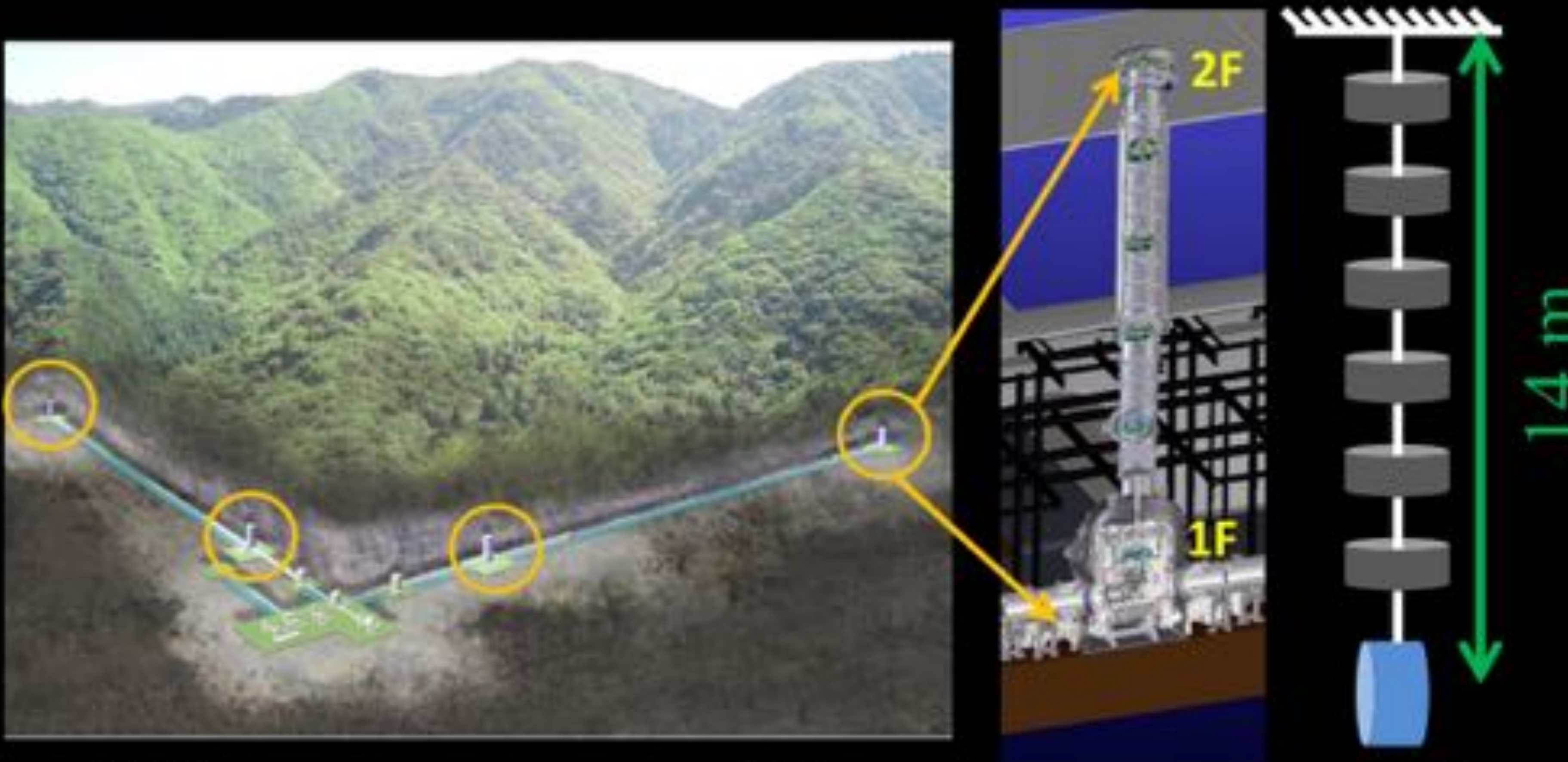
- In order to minimize the laser scattering noise ultra-high vacuum (10^{-7} Pa) is required

- GW detectors are the three world largest vacuum system

- LIGO	1.2mϕ x4km x2 = 10,000 m^3 (each)
- Virgo	1.2mϕ x3km x2 = 6,800 m^3
- KAGRA	0.8mϕ x4km x2 = 3,000 m^3
- LHC	110 m^3

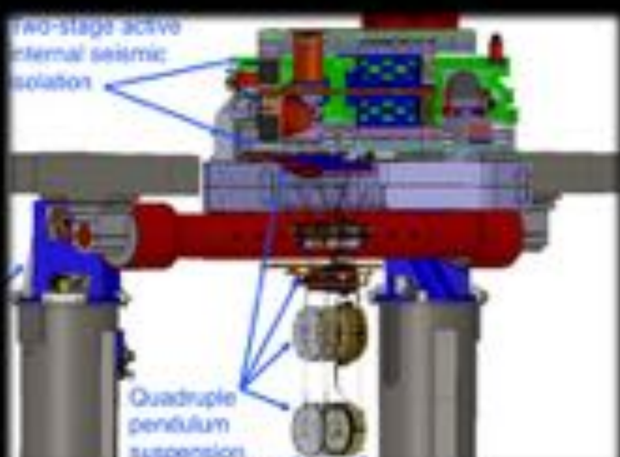
Vibration Isolation System (VIS)

Two-floor structure to avoid the resonances of the tall structure.

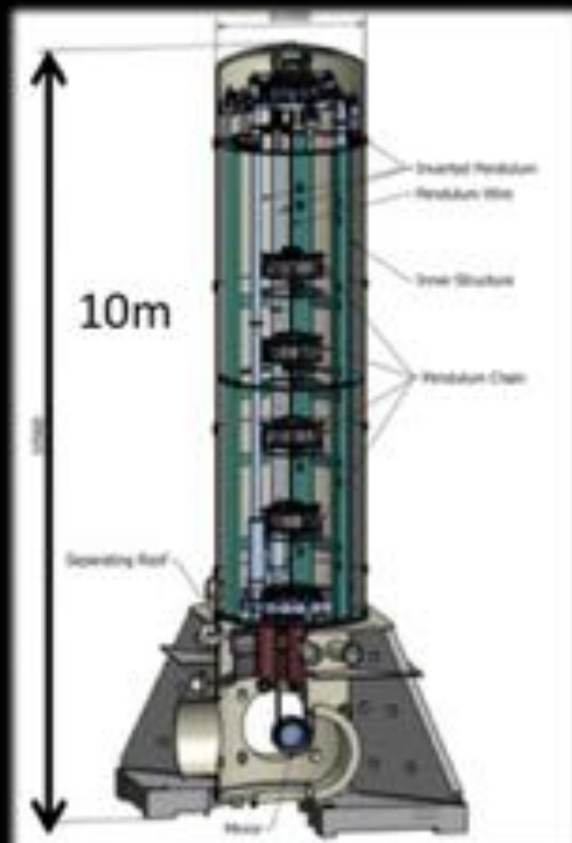


Comparison of Vibration Isolation System

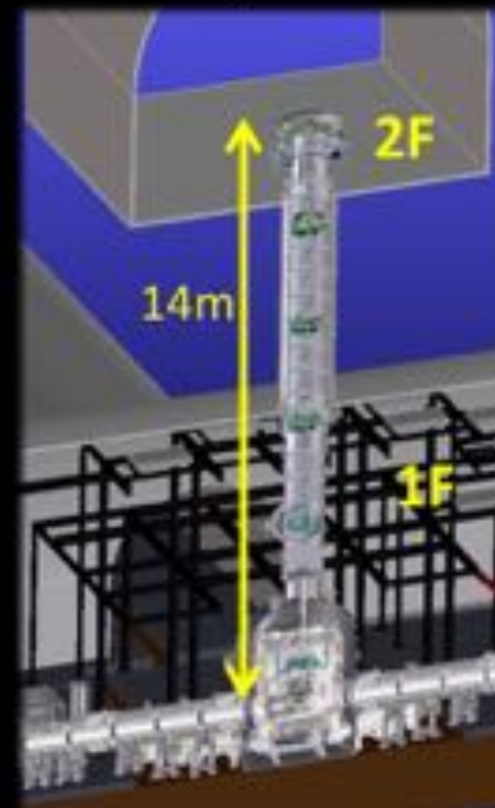
LIGO
Active system



VIRGO
Tall tower



KAGRA
2-story tunnel



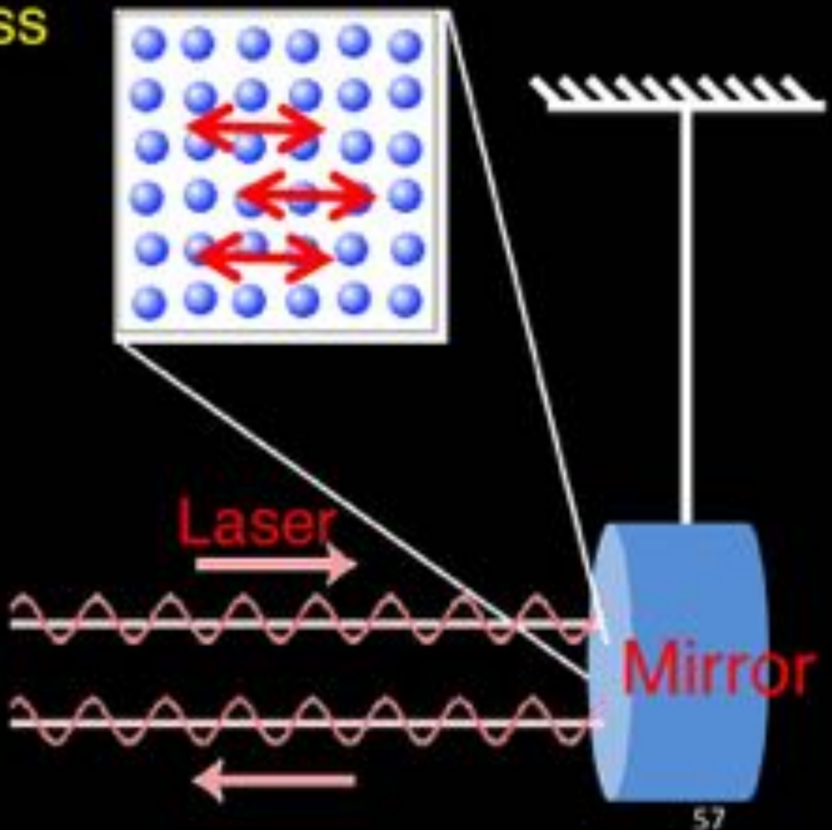
KAGRA – The first km-scale cryogenic detector

Thermal noise — Temperature — Mechanical loss

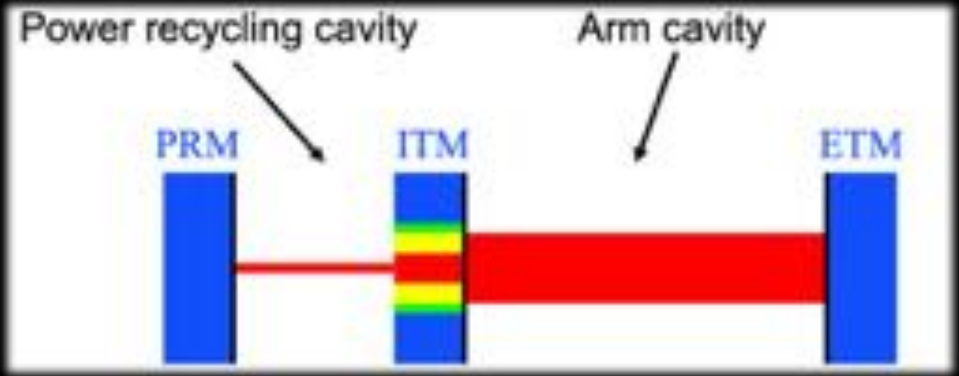
$$\sqrt{x(\omega)^2} \propto \sqrt{T\,\phi}$$

Sapphire @ 20K

$$\phi = 5 \times 10^{-9} \text{ (bulk)}$$
$$\phi = 1 \times 10^{-7} \text{ (fiber)}$$



Thermal lensing comparison

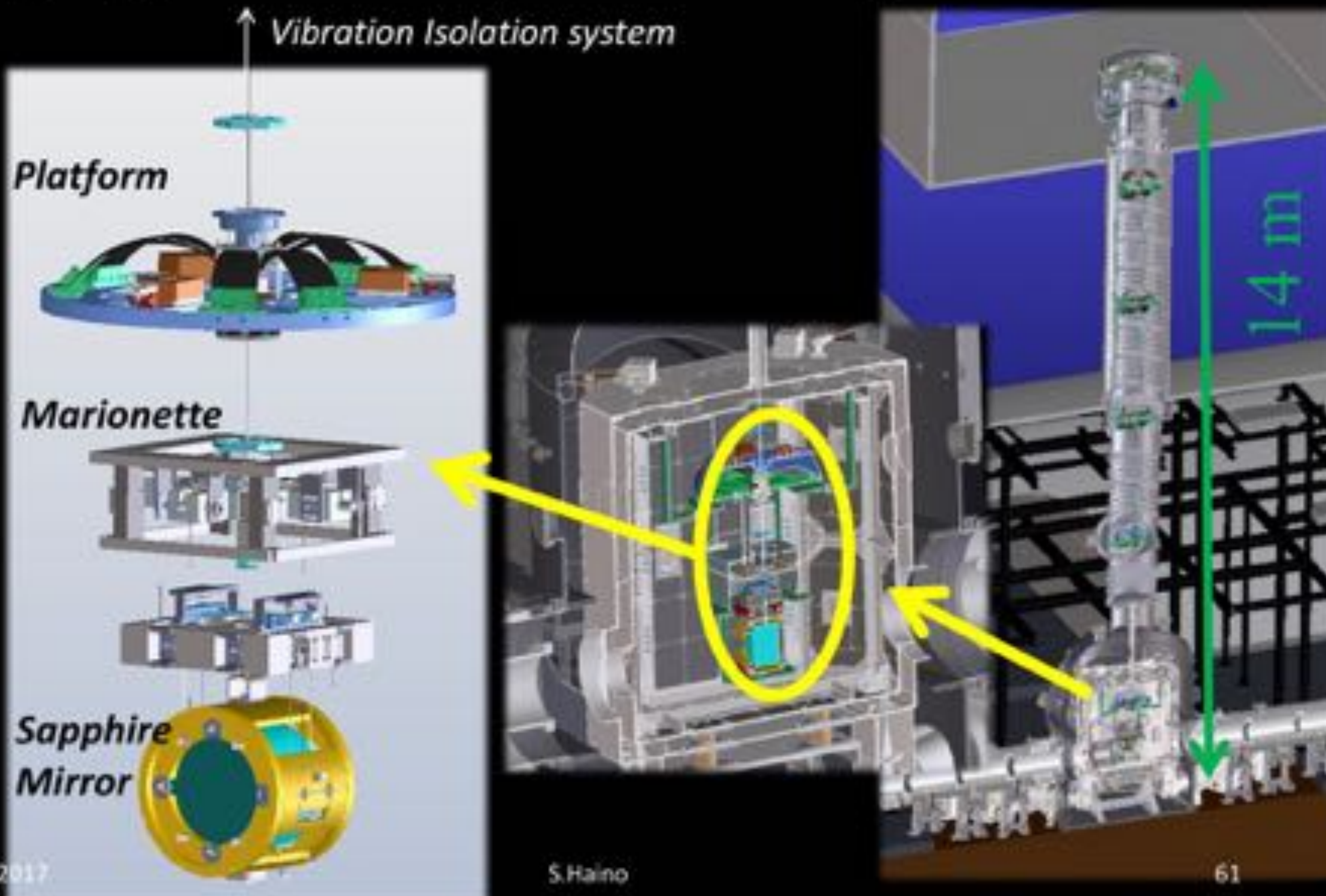


Thermal lensing effect is significantly reduced with cryogenic sapphire mirror

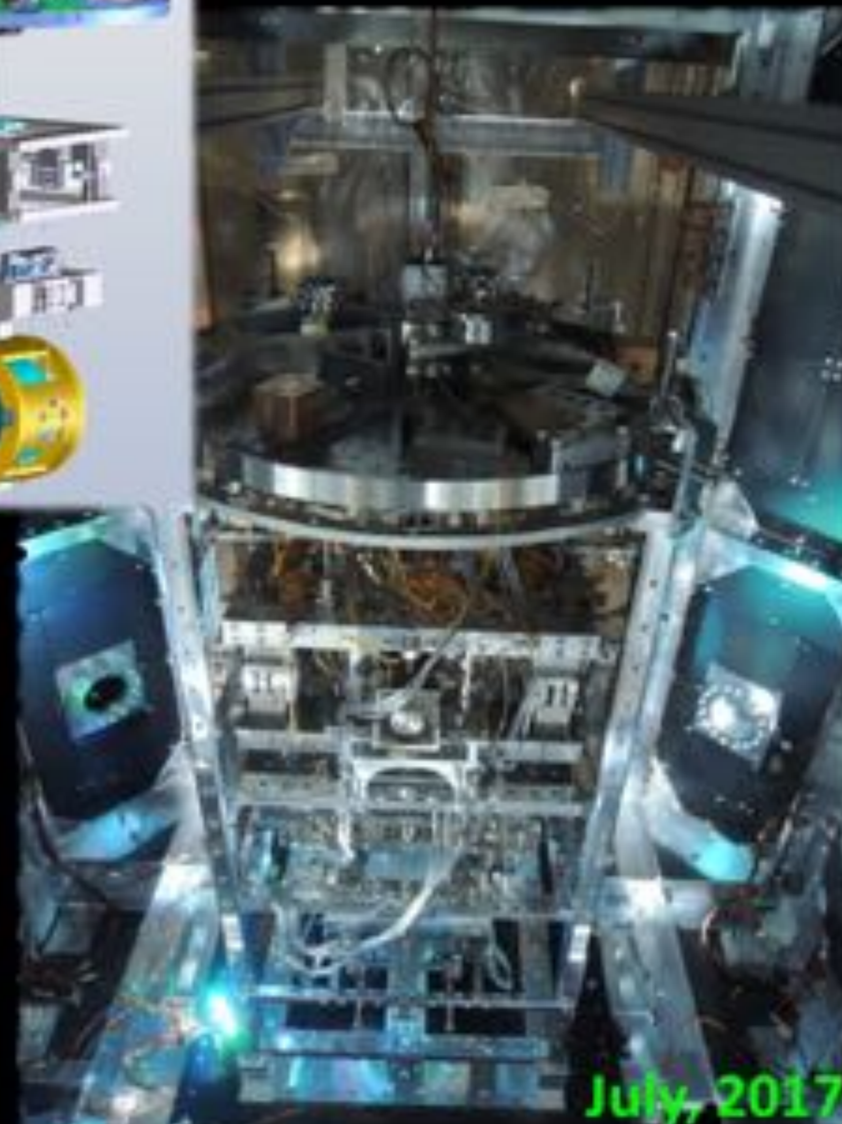
		Fused silica (300 K)	Sapphire (300 K)	Sapphire (20 K)
Abs. coeff.	α (ppm cm^{-1})	2–20	40–100	90
Th. conductivity	κ(Wm^{-1}K^{-1})	1.4	46	4.3×10^3
dn/dT	β(K^{-1})	1.4×10^{-5}	1.3×10^{-5}	$\leqslant (9 \times 10^{-8})$
Wave front distortion	$\alpha\beta/\kappa$(W^{-1}) $\times 10^{-9}$	2–20	1–3	$\leqslant (2 \times 10^{-4})$

T. Tomaru et al., Class. Quantum Grav. 19 (2002) 1

Cryogenic suspension system

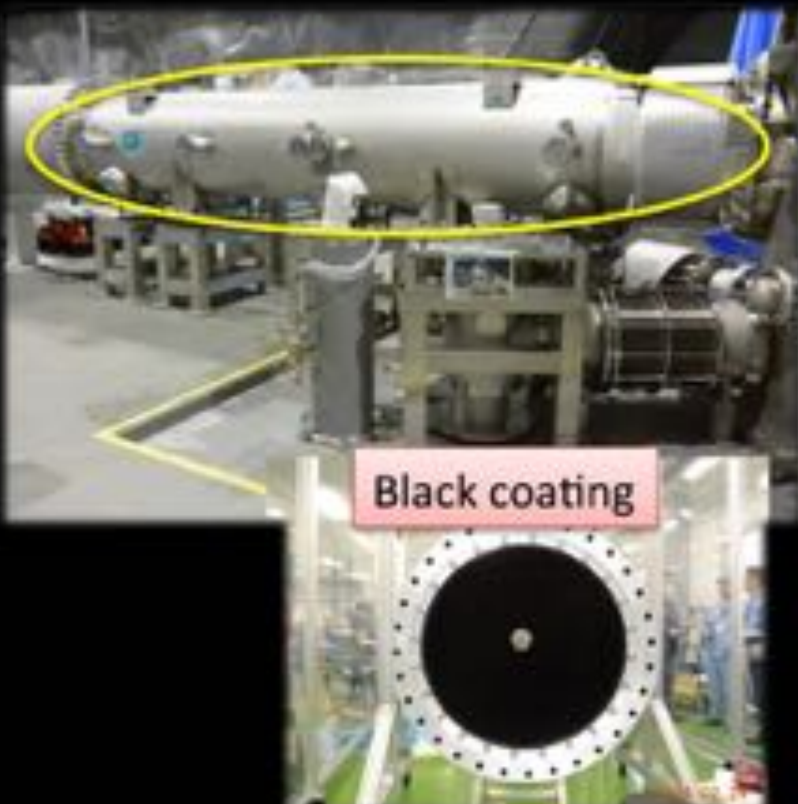


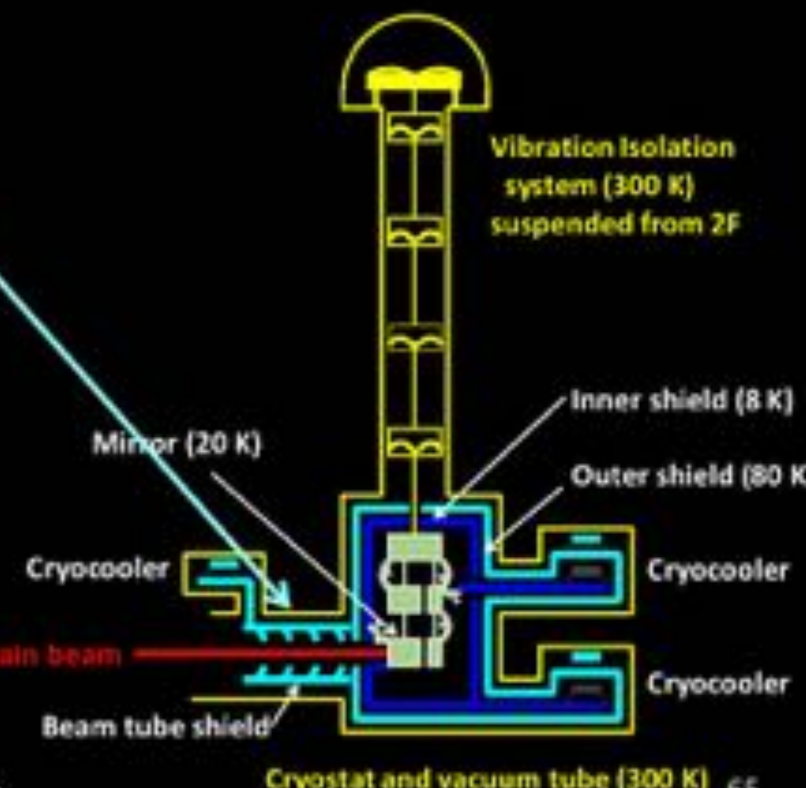

July, 2017


July, 2017

Key cryogenic developments

Black coated baffles at ~100 K can reduce the thermal radiation by 1/1000





T. Tomaru et. al., J.J. A. P. 47 (2008) 1771

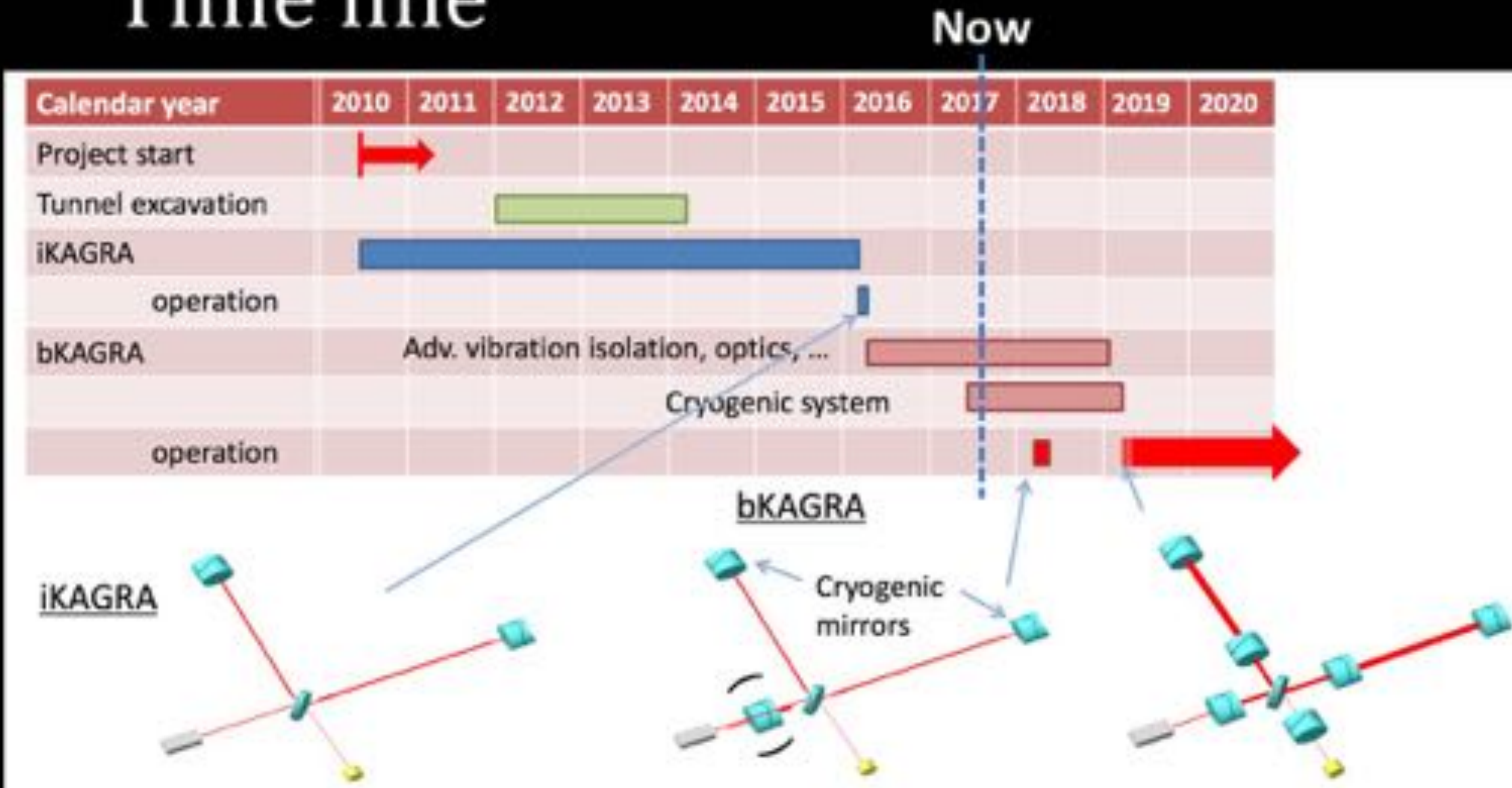
Application of Accelerator technologies to KAGRA

J-PARC neutrino super-conducting beam line

KEK cryogenic center is leading the development of KAGRA cryogenic system

Cryogenic suspension system was just installed at Y-end

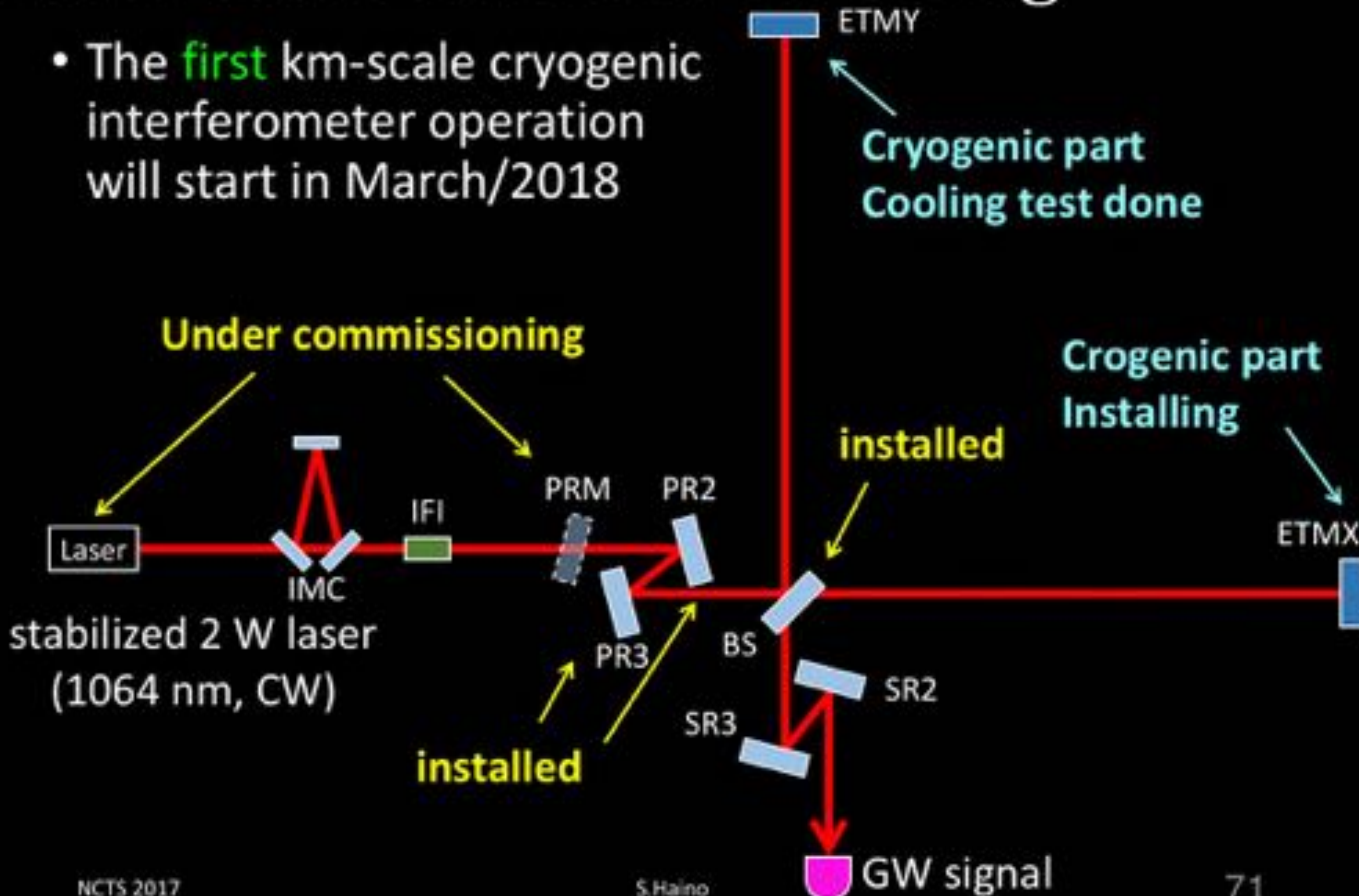
Time line



Room temperature Cryogenic Final configuration

Phase 1 Installation On Going

- The first km-scale cryogenic interferometer operation will start in March/2018

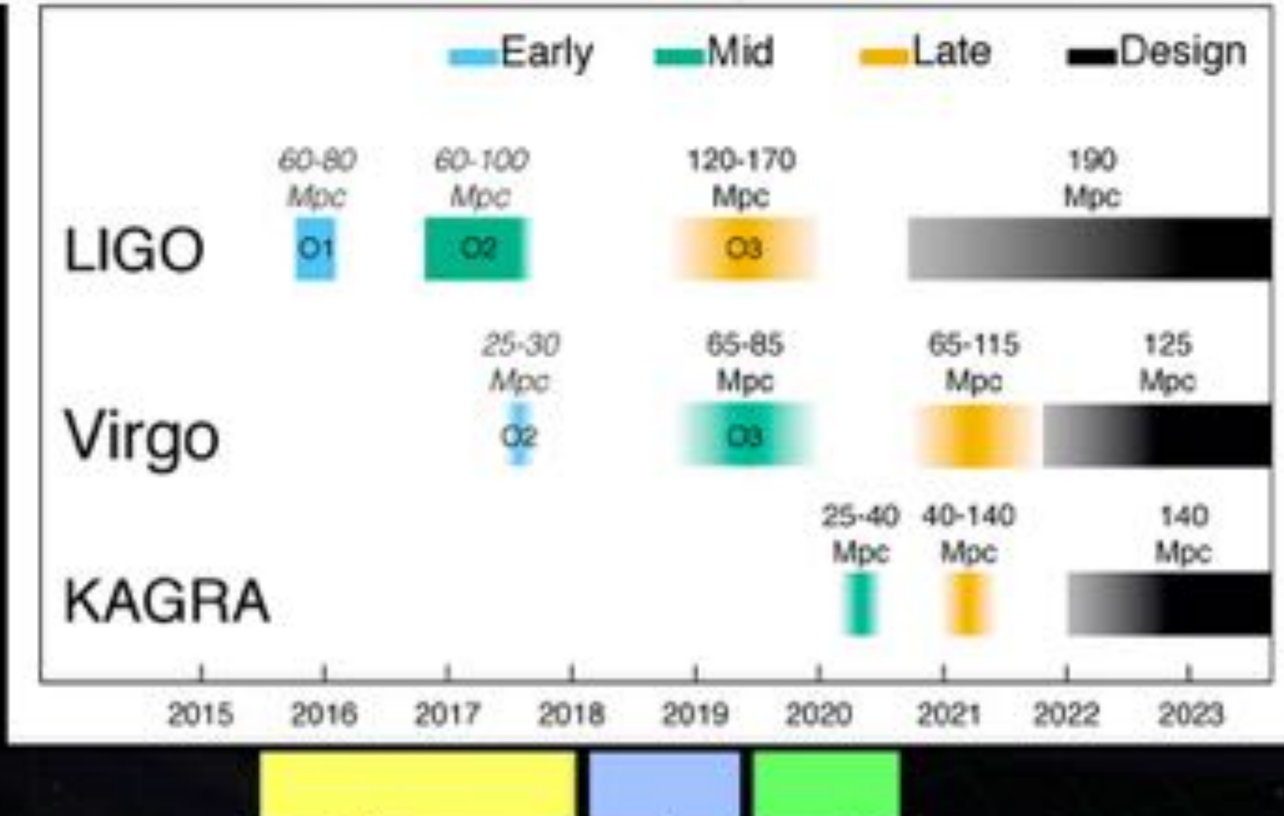


arXiv.org > gr-qc > arXiv:1304.0670

General Relativity and Quantum Cosmology

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA

The KAGRA Collaboration, the LIGO Scientific Collaboration, the Virgo Collaboration: B. P. Abbott, R. Abbott, T. D.



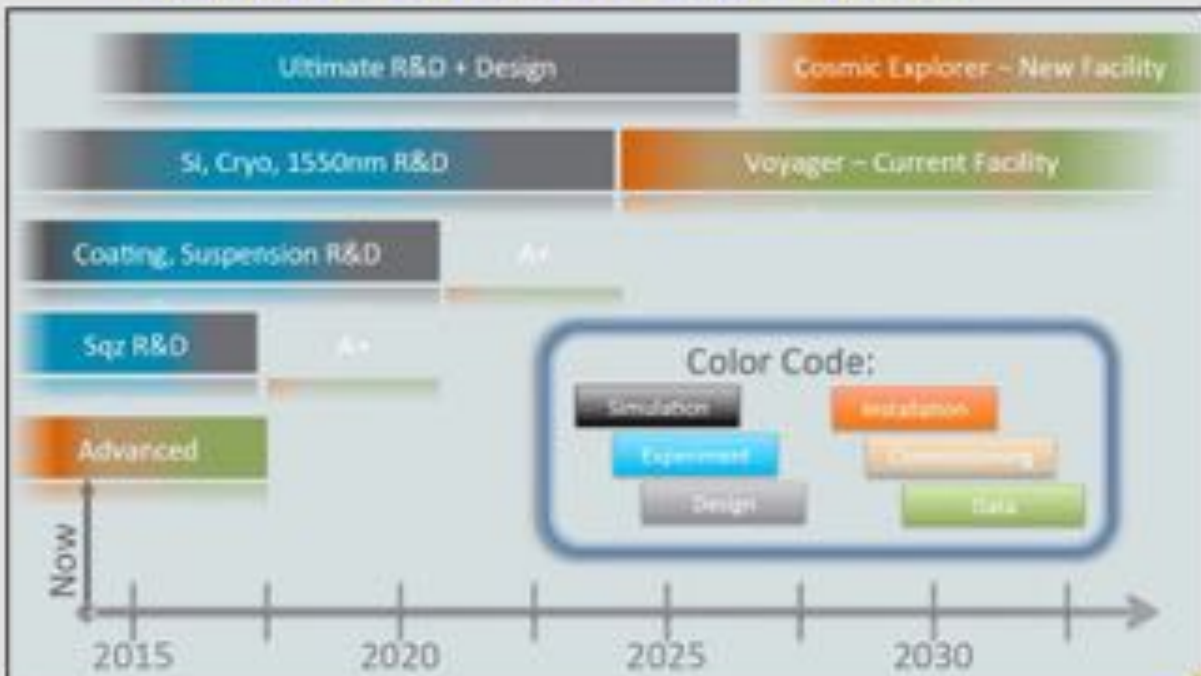
Phase-1
Cryogenic (PR)MI
No sensitivity goal

Phase-2
Cryogenic RSE
No sensitivity goal

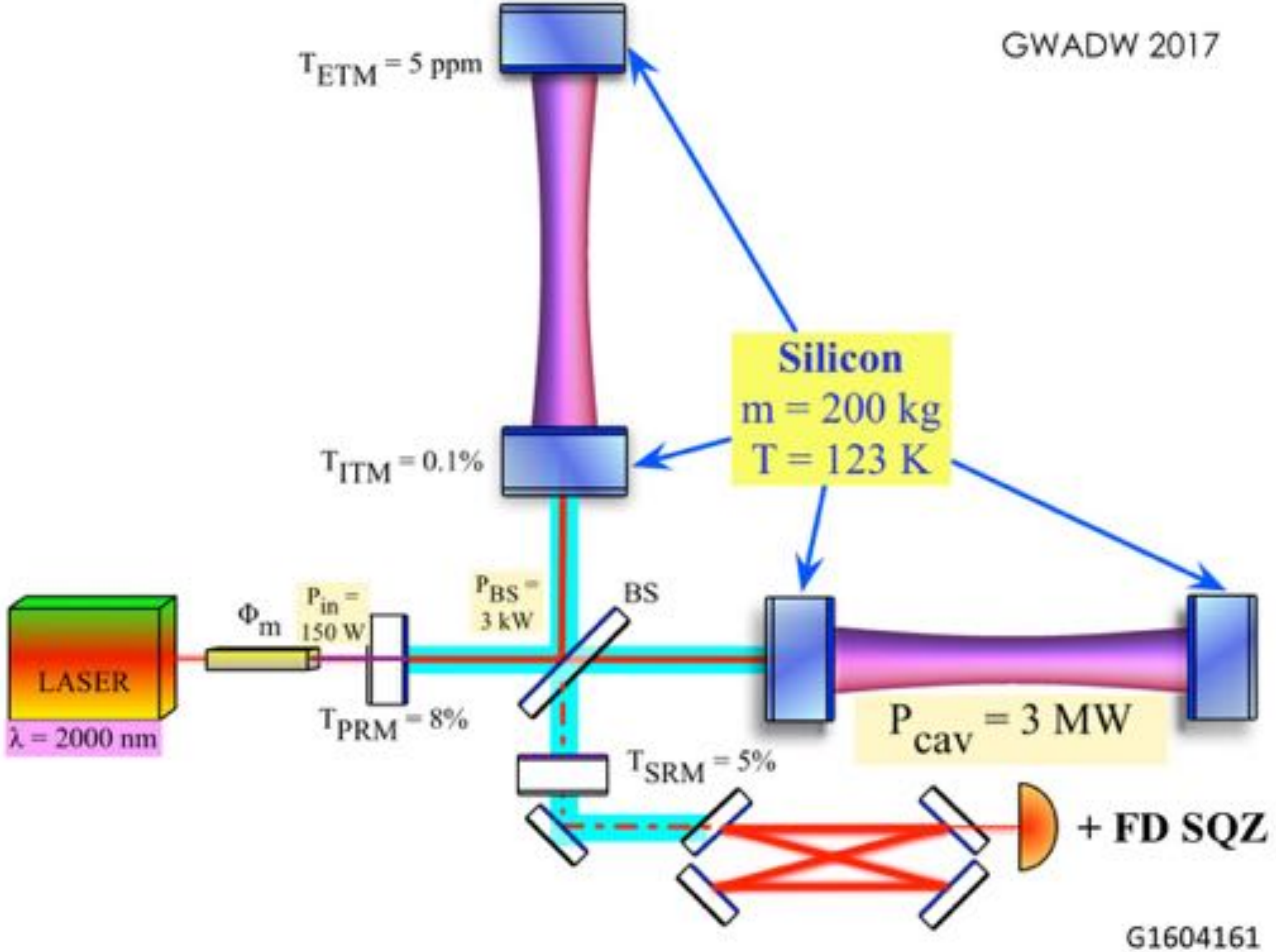
Phase-3
Cryogenic RSE, 1-yr commissioning after the first full operation

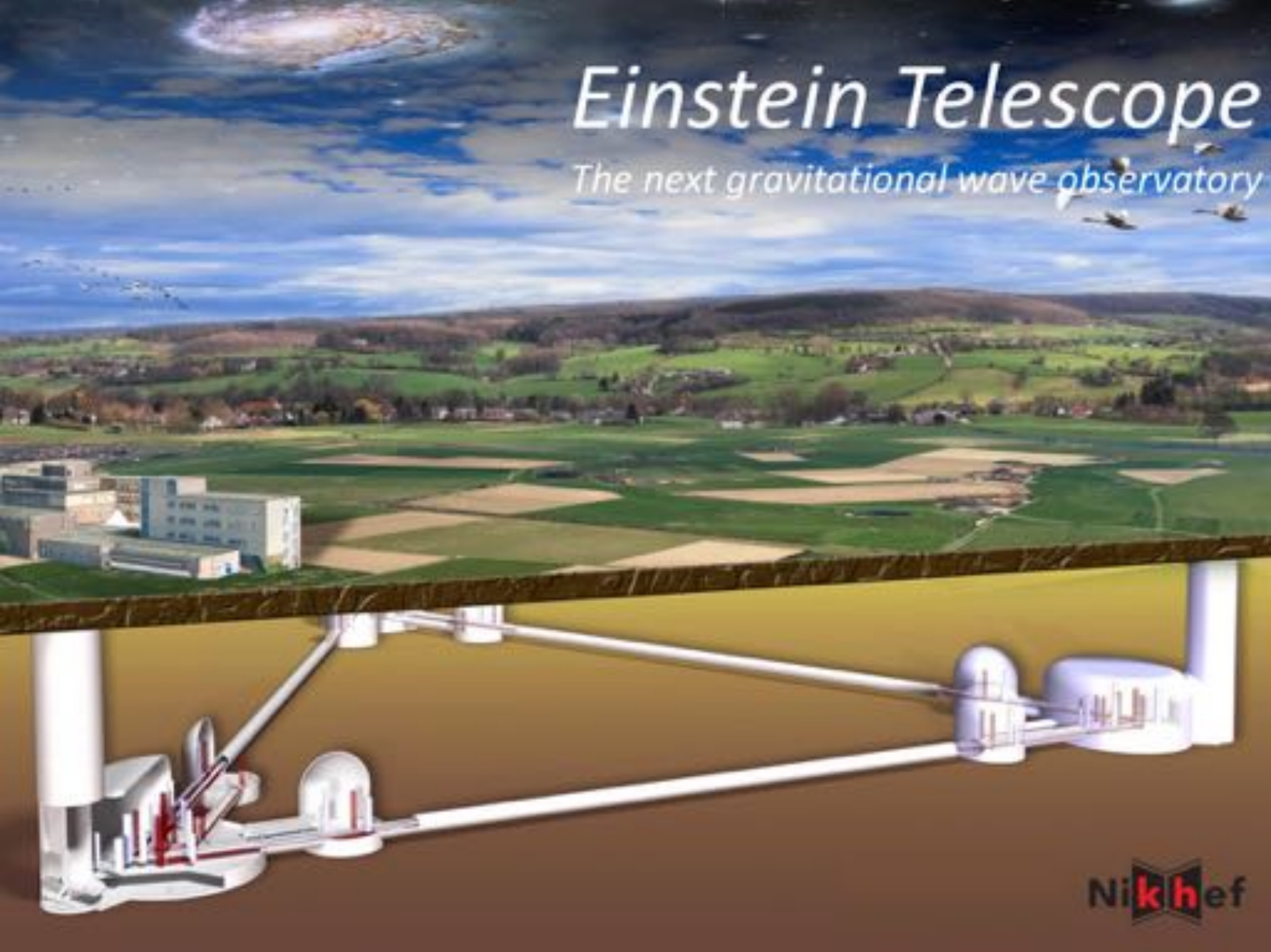
Improvements and upgrades - Roadmap 2016-2040

- Experience shows that concept to operation takes about 15 years.
  - Detector cycle includes: simulation, experimental tests, conceptual design, prototyping, engineering, construction, installation and commissioning
- Three detector upgrade epochs over next 25 years
  - A+, LIGO Voyager, LIGO Cosmic Explorer



LIGO-T1600119
Instrument Science
White Paper


GWADW 2017
T_ETM = 5 ppm
Silicon
m = 200 kg
T = 123 K
T_ITM = 0.1%
P_BS = 3 kW
BS
Φ_m
P_in = 150 W
LASER
λ = 2000 nm
T_PRM = 8%
P_cav = 3 MW
T_SRM = 5%
+ FD SQZ
G1604161


Einstein Telescope
The next gravitational wave observatory
Nikhef

Summary

- GW will allow us to explore new physics at extreme condition and/or from early Universe
- GW detections (BBH, BNS) in 2015~2017 !!
- The next milestone is to build world wide network LIGO/Virgo/KAGRA network will start in 2019~2020
- 3rd Generation (3G) detector under planning