KAGRA
Underground Cryogenic Gravitational Wave Telescope

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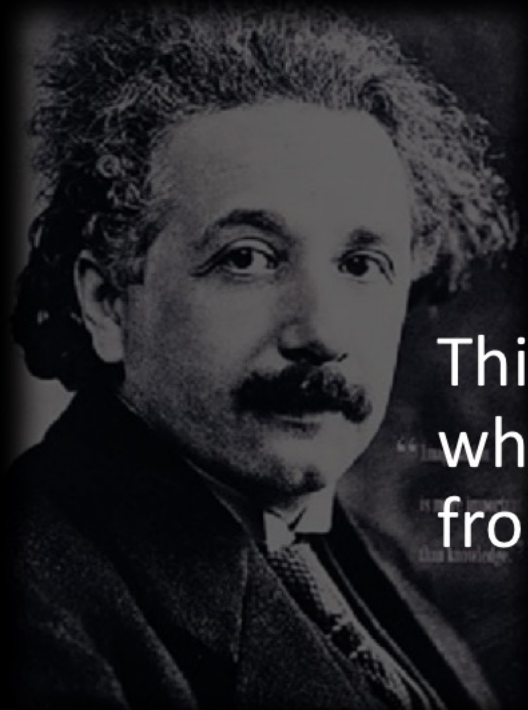
KAGRA collaboration

Gravitational waves (GW)

- Predicted by A. Einstein in 1916

Ripple of space-time propagating in speed of light

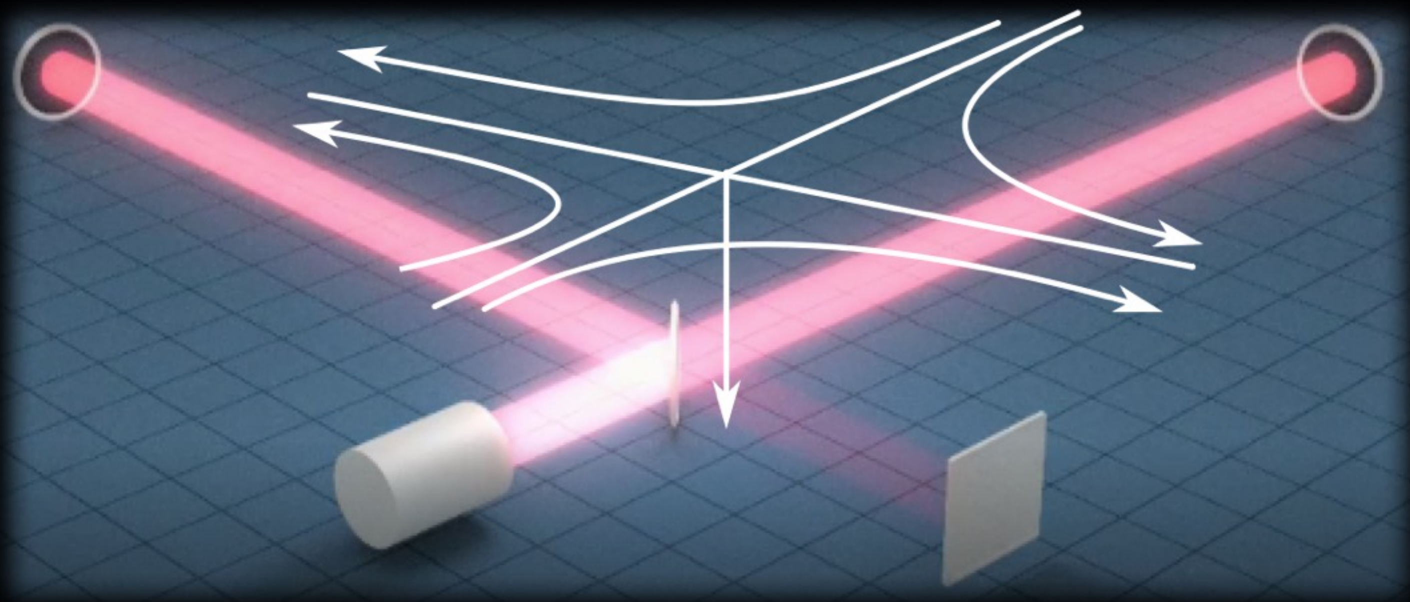


GW is transparent for any material, except gravity sources.

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

Gravitational waves (GW)

- Predicted by A. Einstein in 1915
- Laser interferometer was developed to detect GW



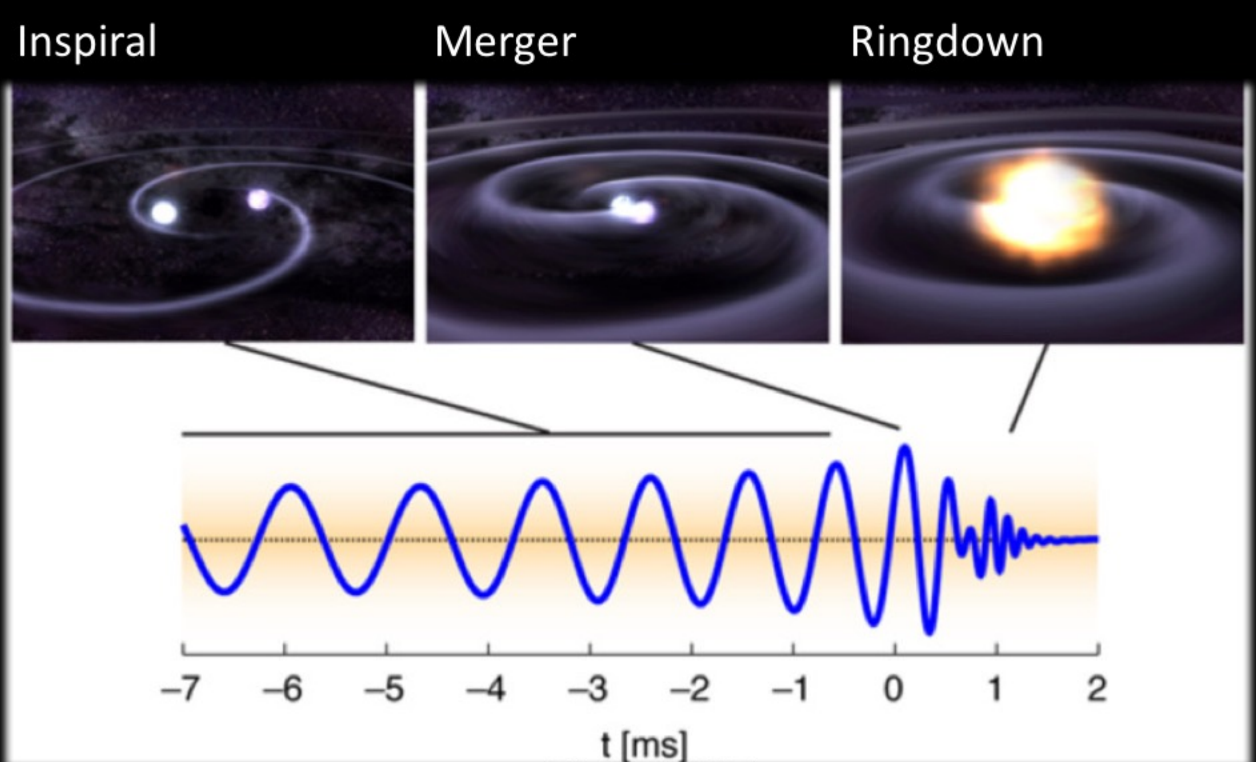
Gravitational waves (GW)

- Predicted by A. Einstein in 1915
- First detection by LIGO in 2015 !!

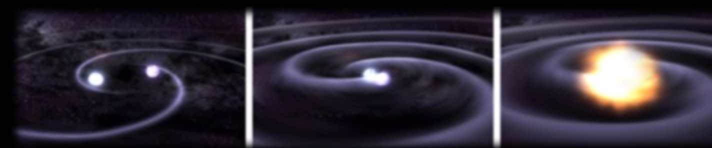
LIGO collaboration

GW sources and physics

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

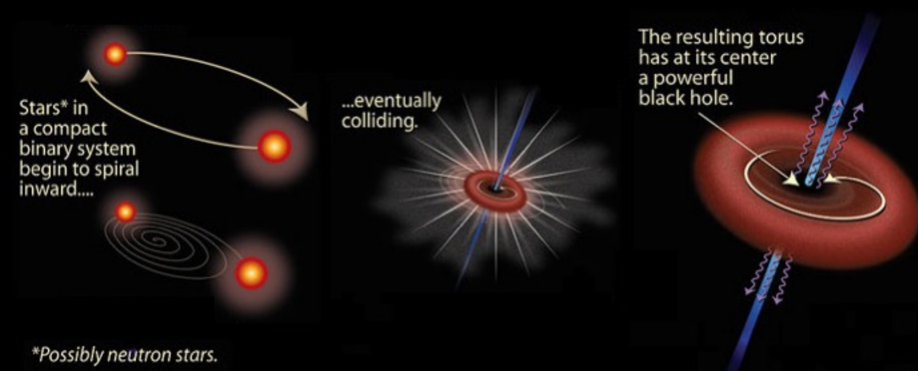


GW sources and physics



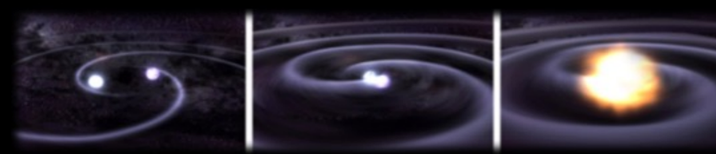
- Compact Binary Coalescences
  Physics examples

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

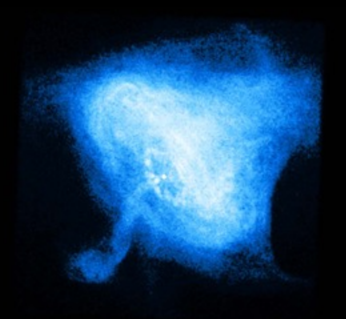


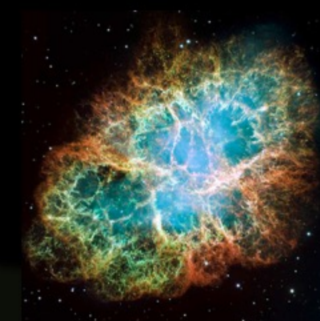
GW sources and physics

- Compact Binary Coalescences

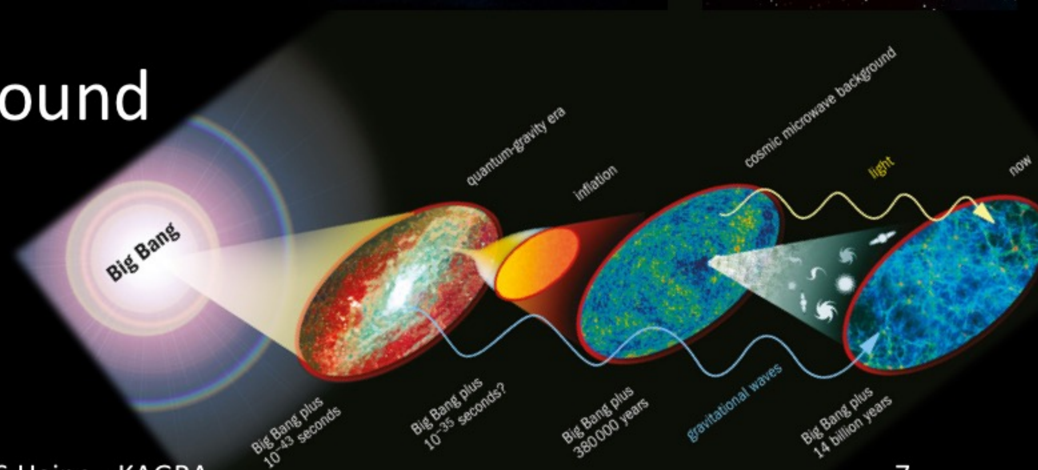


- Continuous waves from pulsars



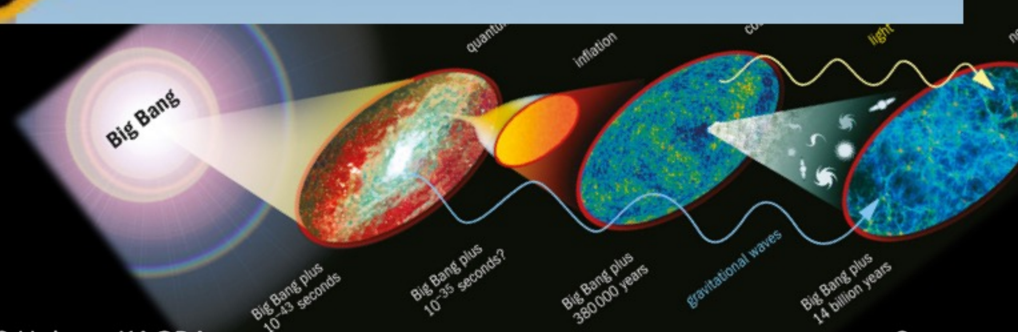


- Supernovae
- Stochastic GW background from Early Universe



GW sources and physics

- C
- C
- S
- S
  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 ($r_g \sim 3\mathrm{km}$) NS-NS binary merging at ~speed of light located at 100 Mpc away

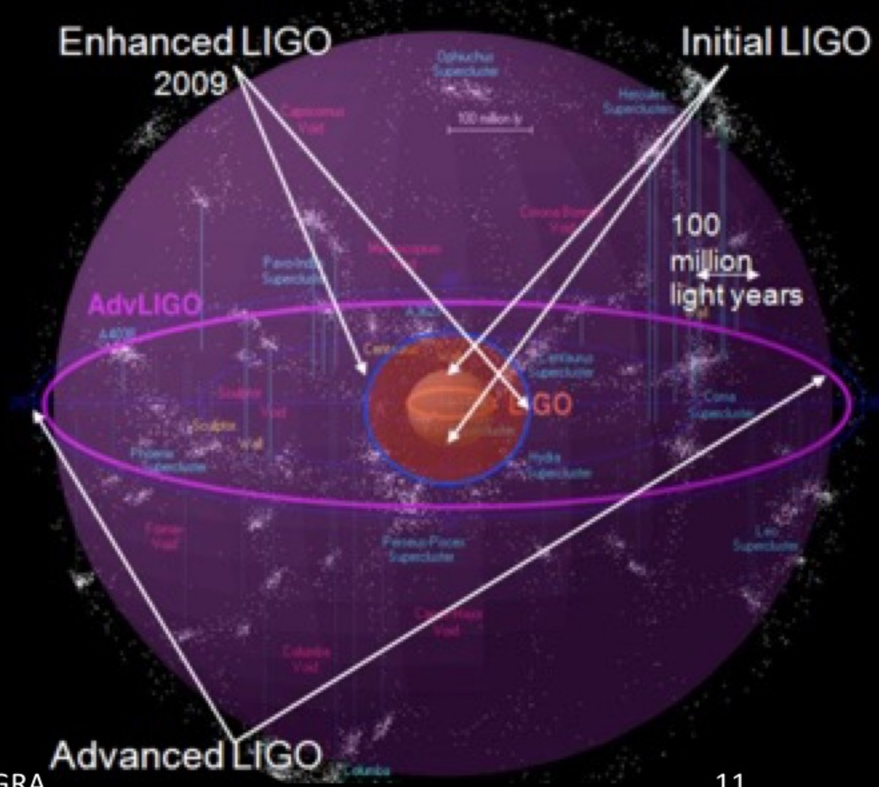
$$h \sim \frac{3\ \mathrm{km}}{100\ \mathrm{Mpc}} = 10^{-21}$$

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

Opening of GW astronomy

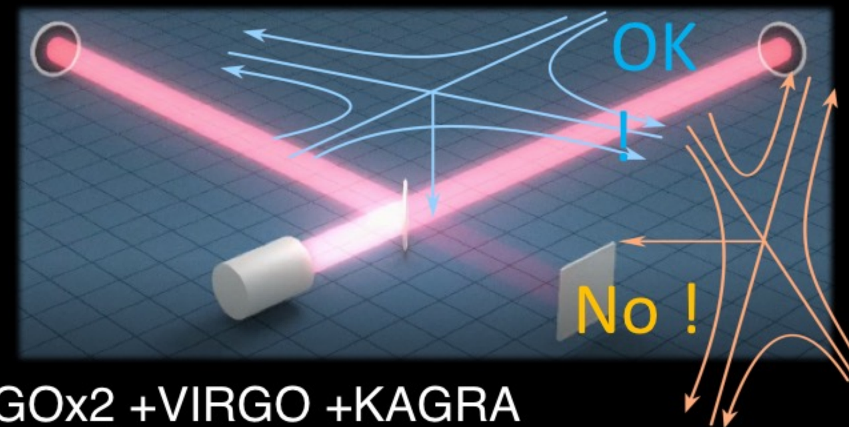
- LIGO's GW detection opened a new era
- GW amplitude is proportional to 1/Distance

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

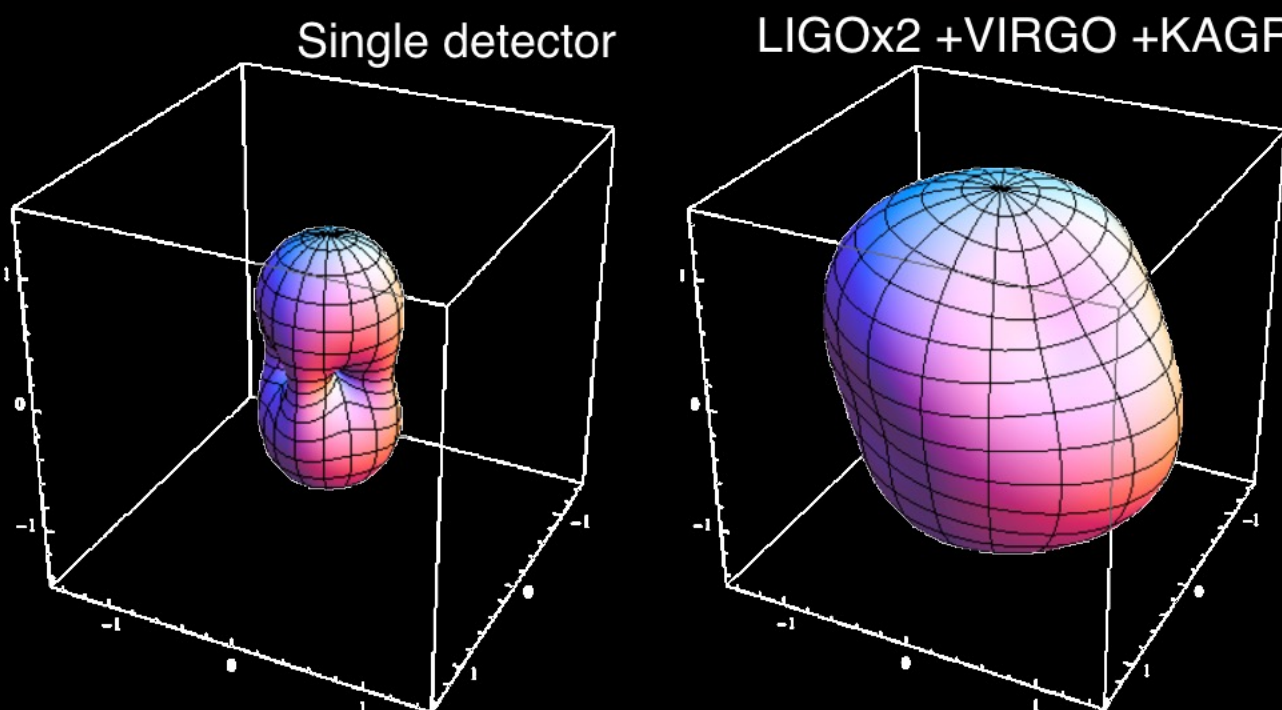


World-wide GW detector network

Advantages of detector network



- Increase the sky coverage

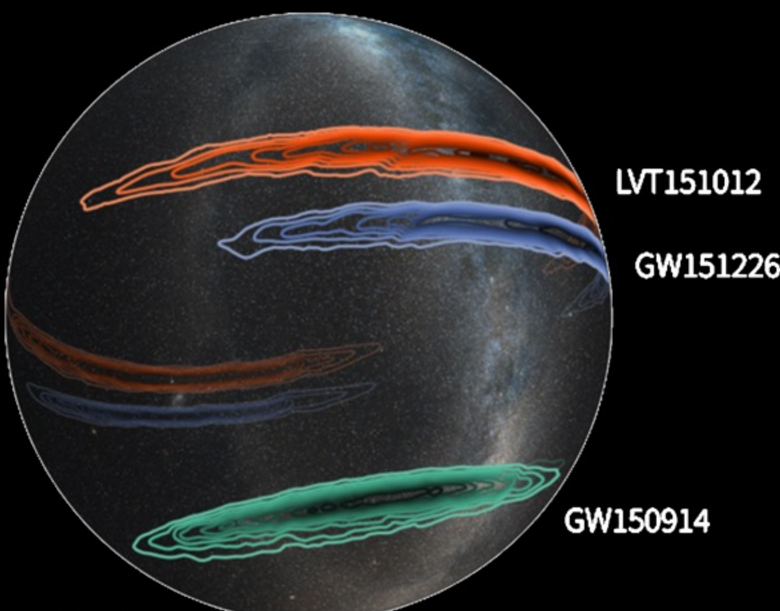


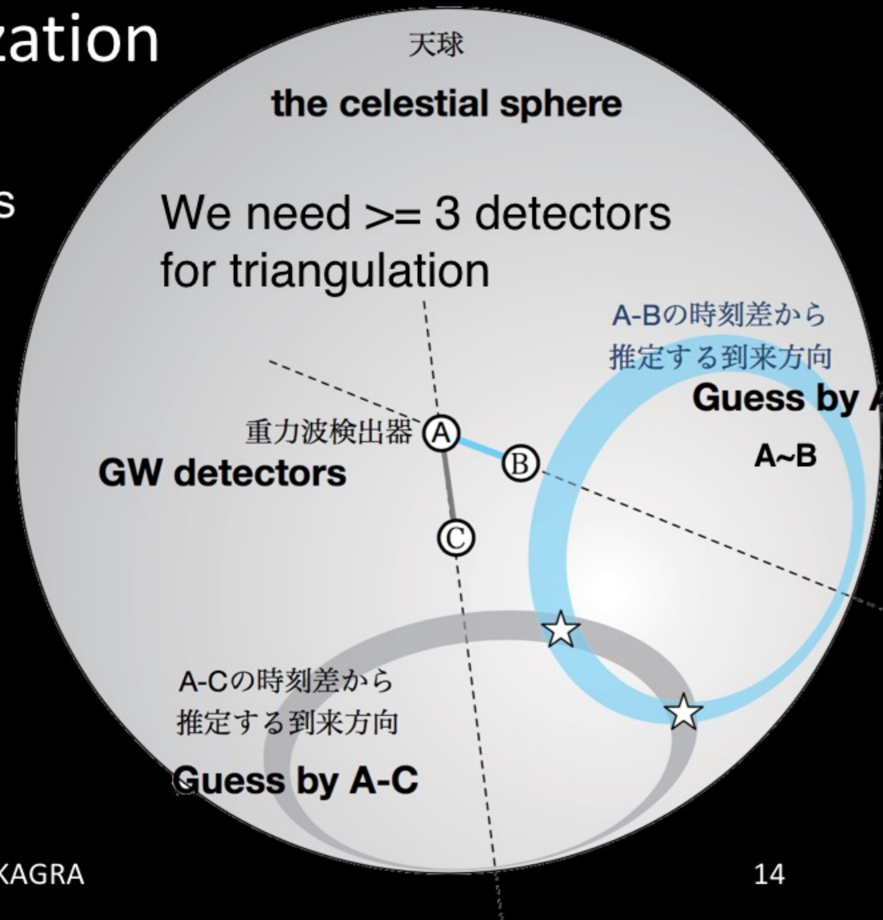
Antenna amplitude pattern (B.F. Schutz, N. Kanda)

Advantages of detector network

- Increase the sky coverage
- Improve the source localization

GW events locations
by only 2 LIGO detectors

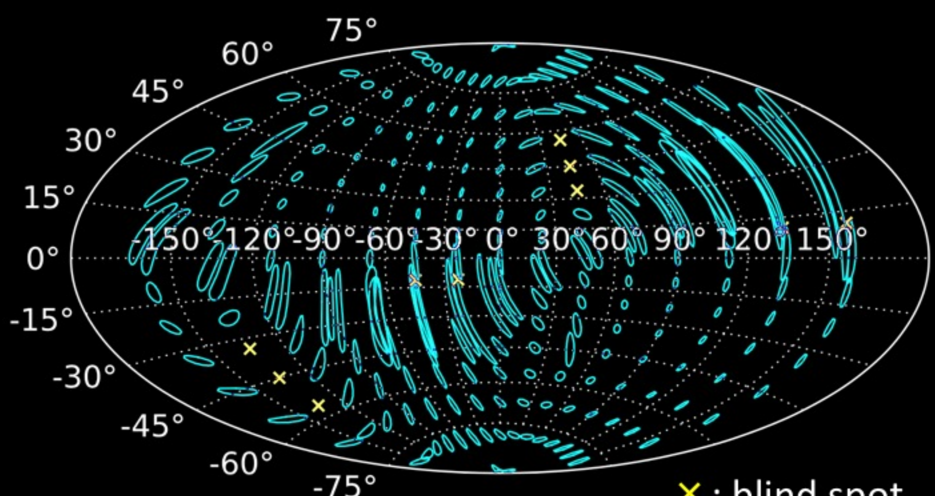




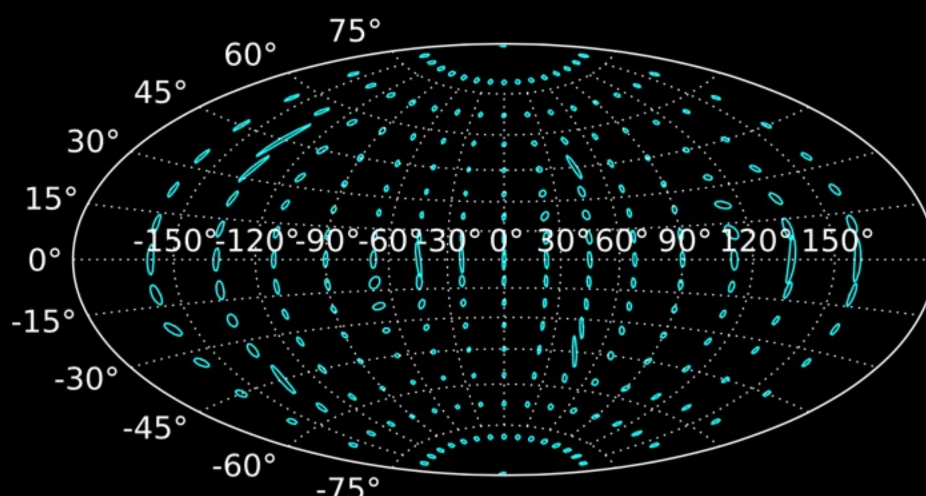
Advantages of detector network

- Increase the sky coverage
- Improve the source localization

2xLIGO + Virgo



2xLIGO + Virgo+ KAGRA

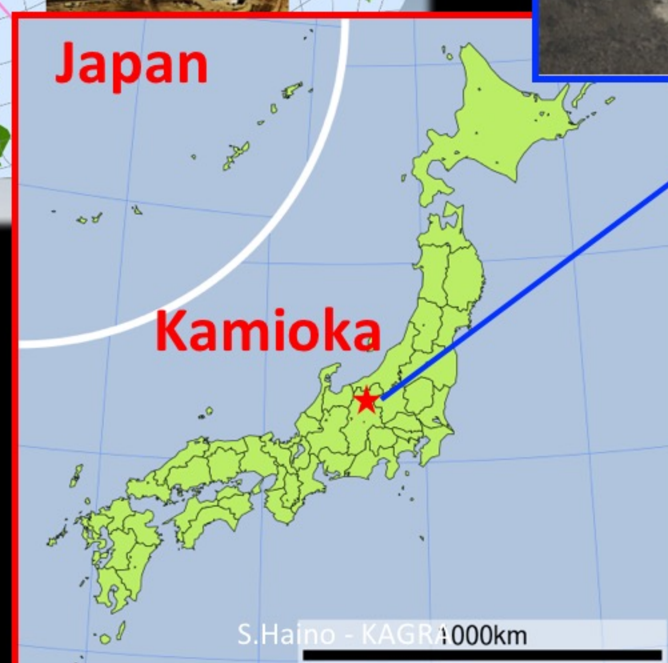


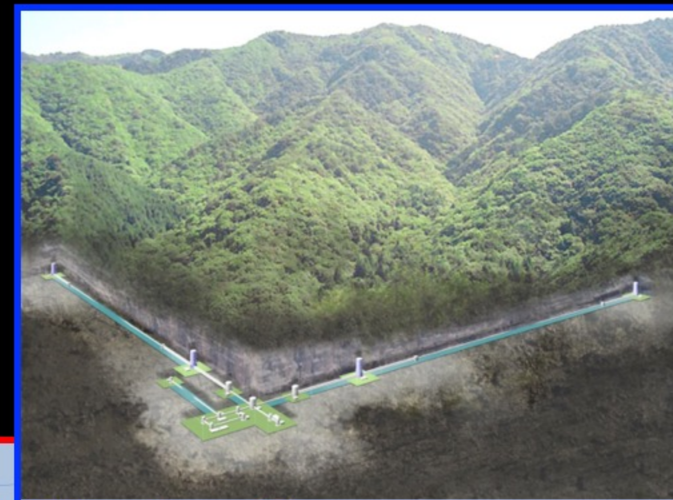
LP2017

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



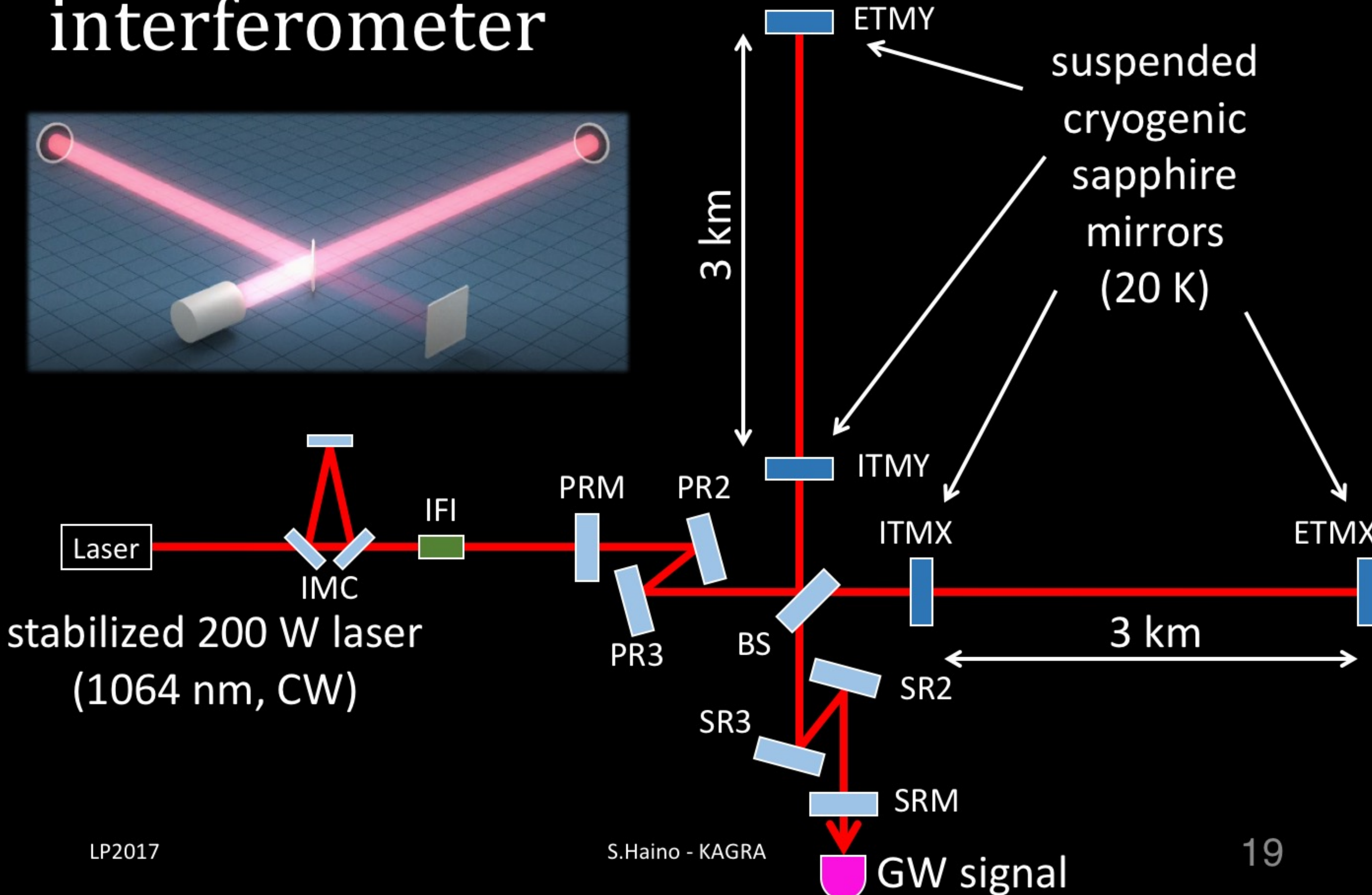
Kamioka underground site

Comparison LIGO/Virgo/KAGRA

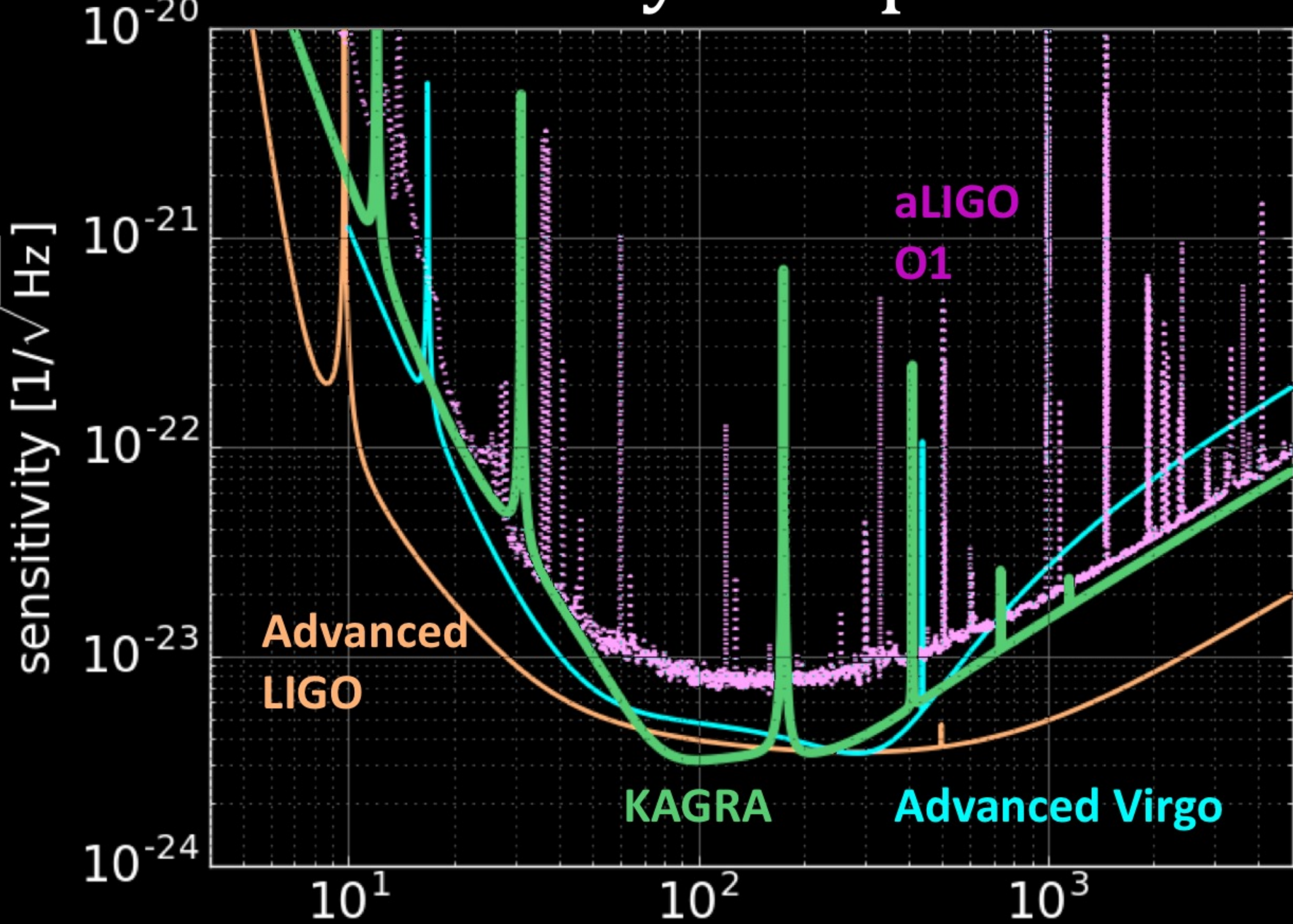
	LIGO (each)	**Virgo**	**KAGRA**
Host country	U.S.	Italy	Japan
Type	Dual-recycling Fabry-Perot interferometer		
Arm length	4 km	3 km	3 km
Location	Surface	Surface	Underground
Test Mass Mirror	Silica 40 kg 295 K	Silica 42 kg 295 K	Sapphire 23 kg @ 20 K
Arm power	710 kW	700 kW	280 kW

Parameters from LIGO-T1600119, JPCS 610, 01201 (2015), KAGRA: v201609

Dual-recycling Fabry-Perot interferometer



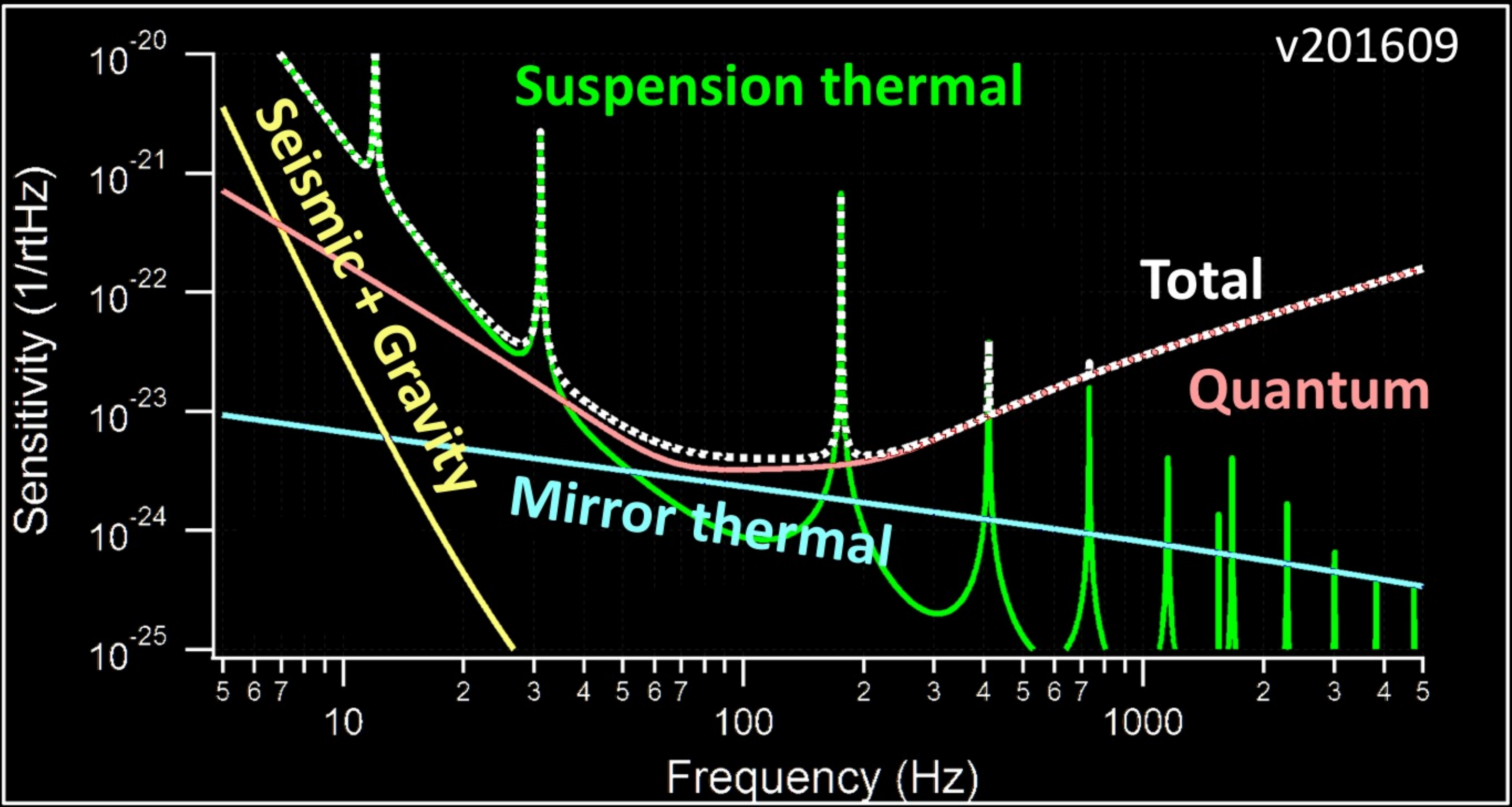
Sensitivity comparison



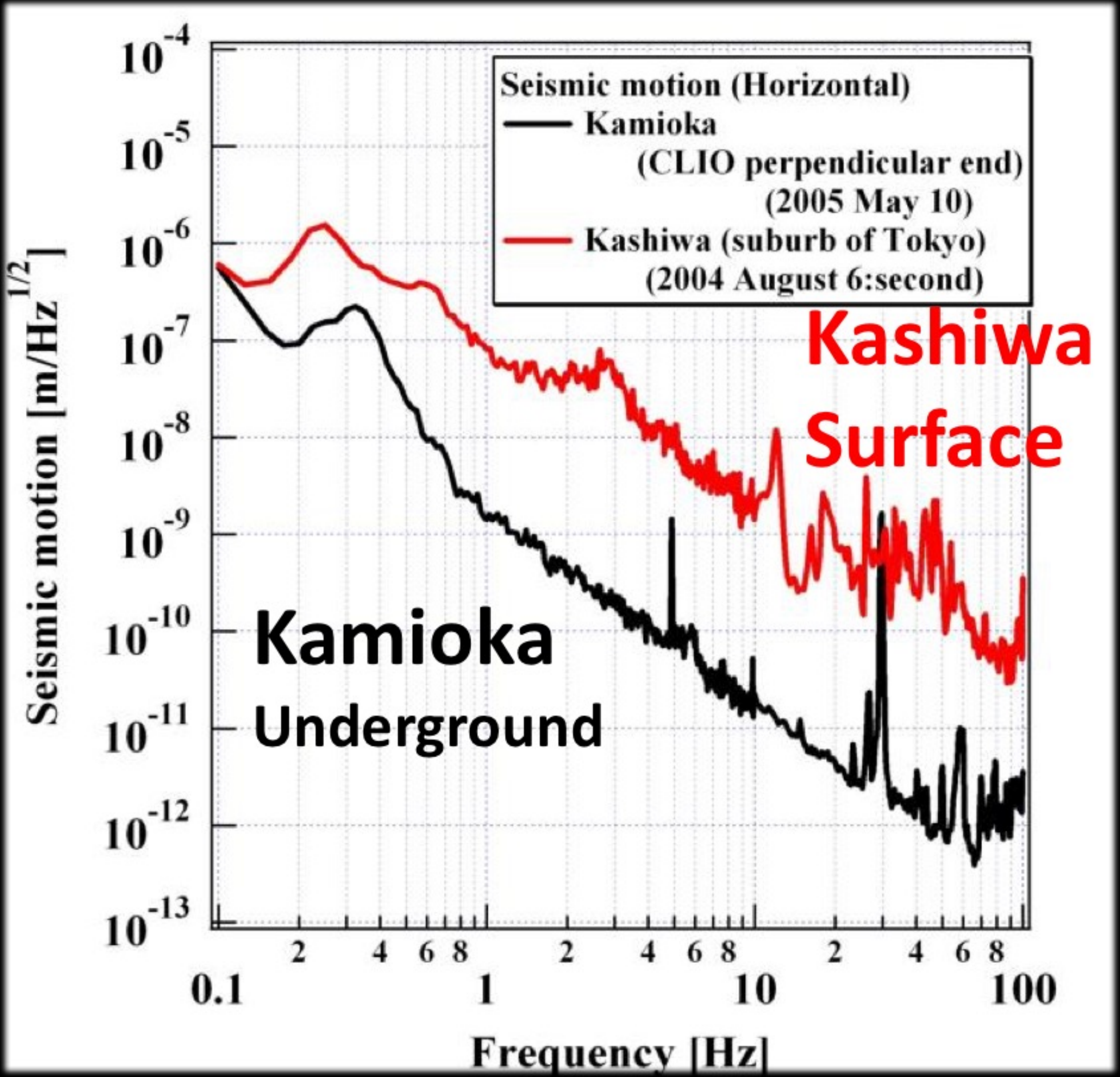
Spectra data from LIGO-T1500293

KAGRA Estimated Sensitivity

NS-NS 140 Mpc (1.4-1.4 Msun)



KAGRA – The first km-scale detector at underground



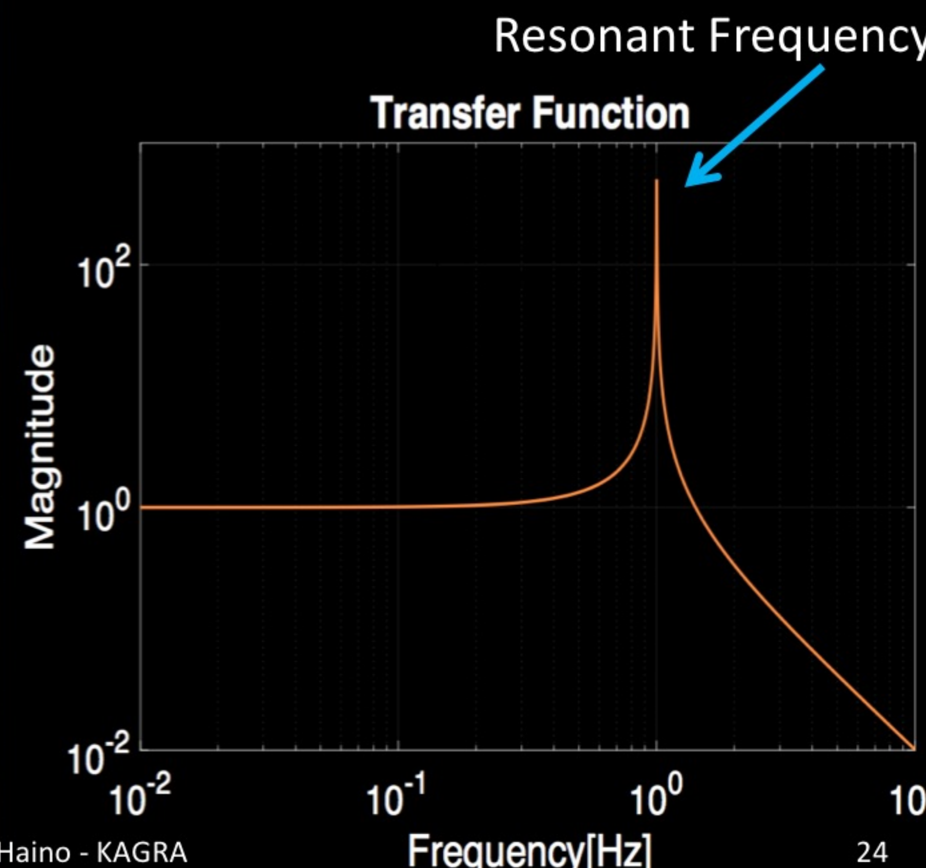

Tunnel excavation was done in 2014


Tunnel entrance
かぐらトンネル


Vacuum tubes installed in 2015

Seismic noise attenuation

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



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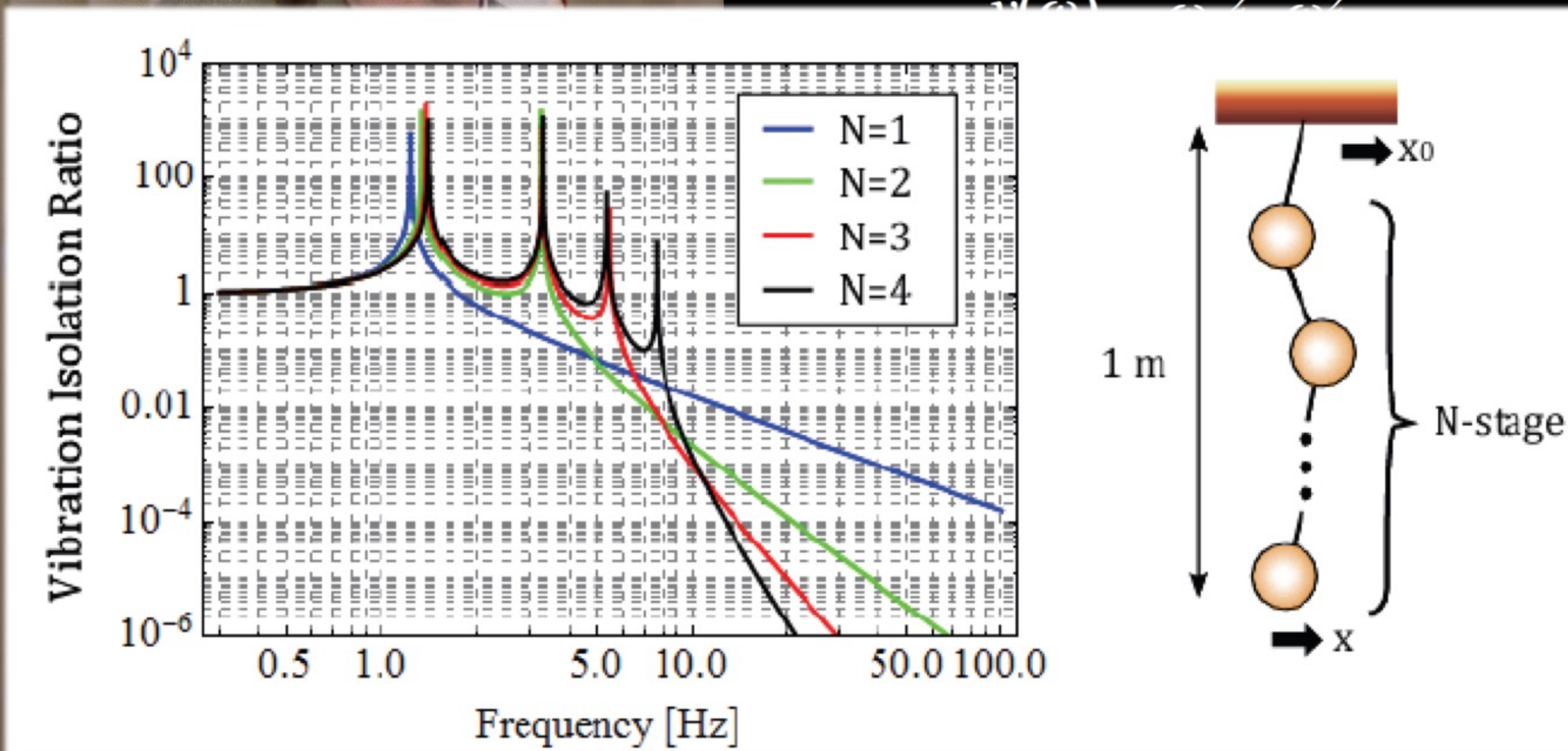
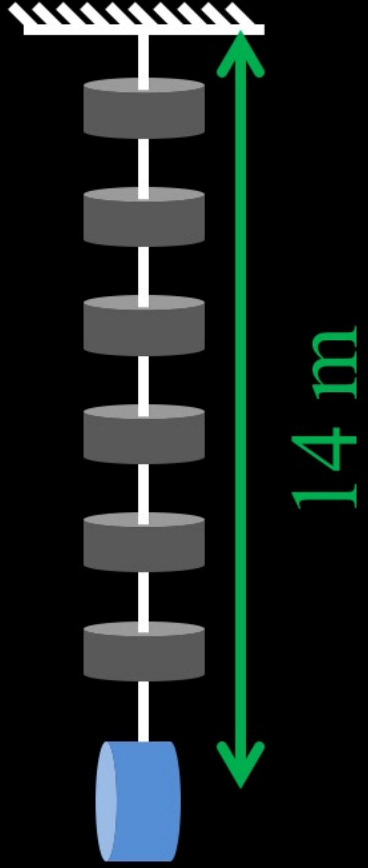


Frequency[Hz]

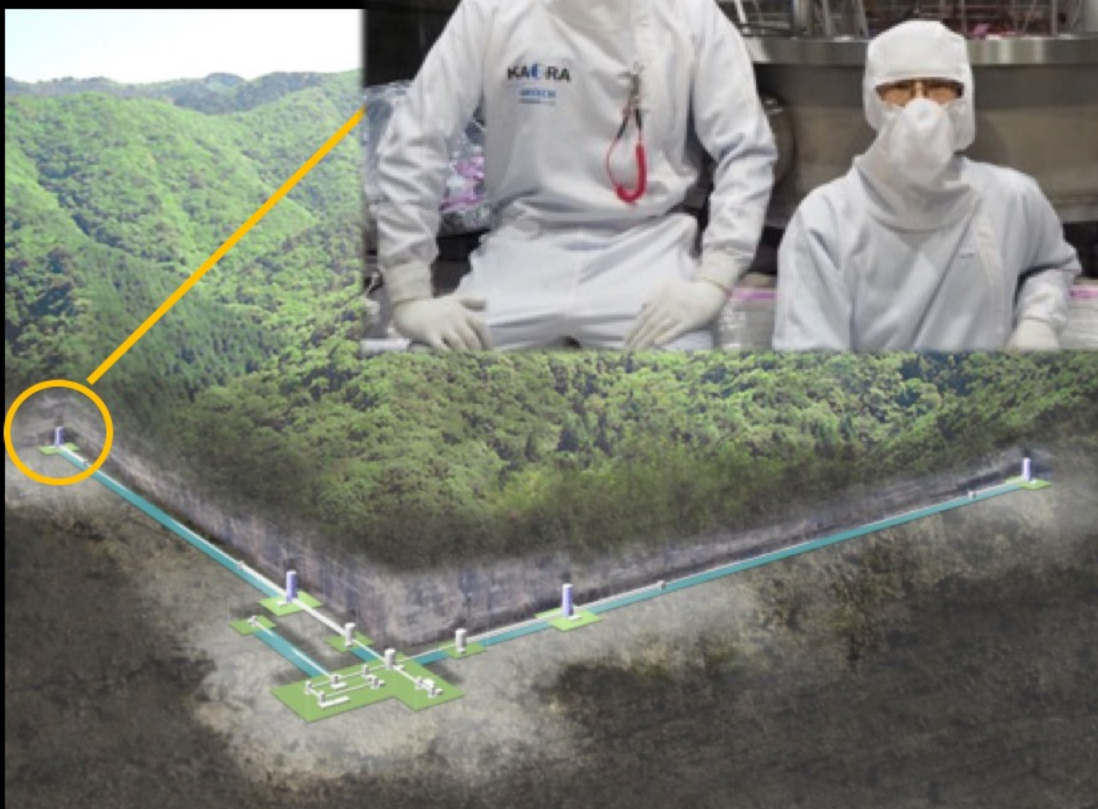
Vibration Isolation System (VIS)

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



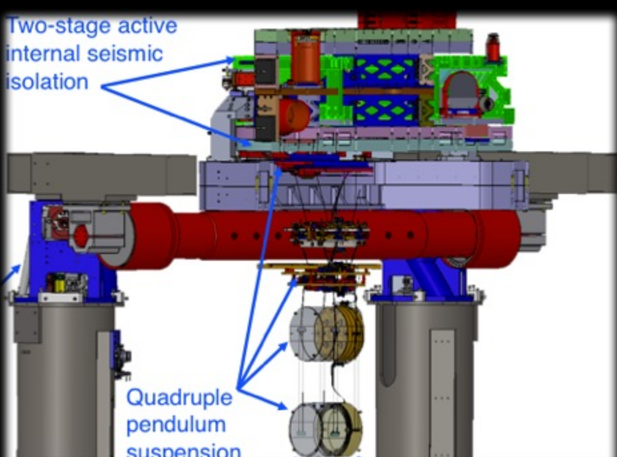
Vibra … VIS)

Two-layer str … structure.

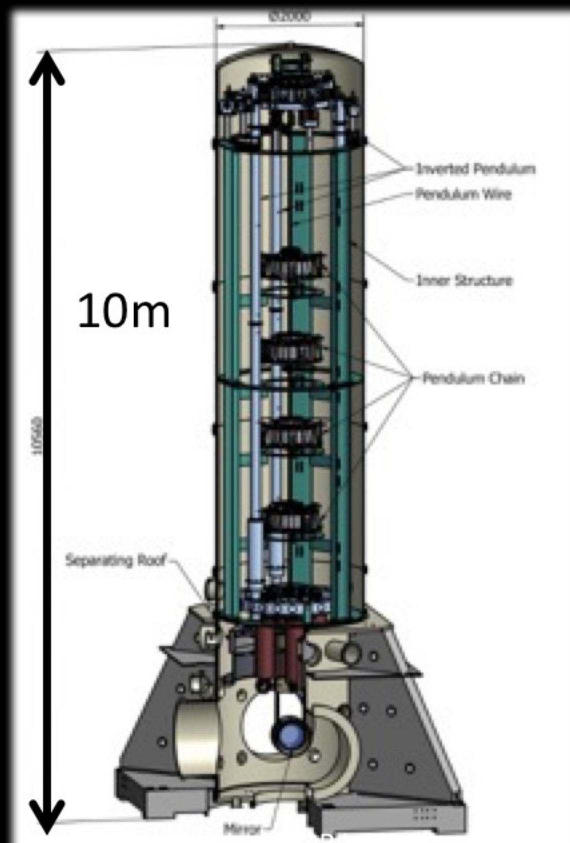


Comparison of Vibration Isolation System

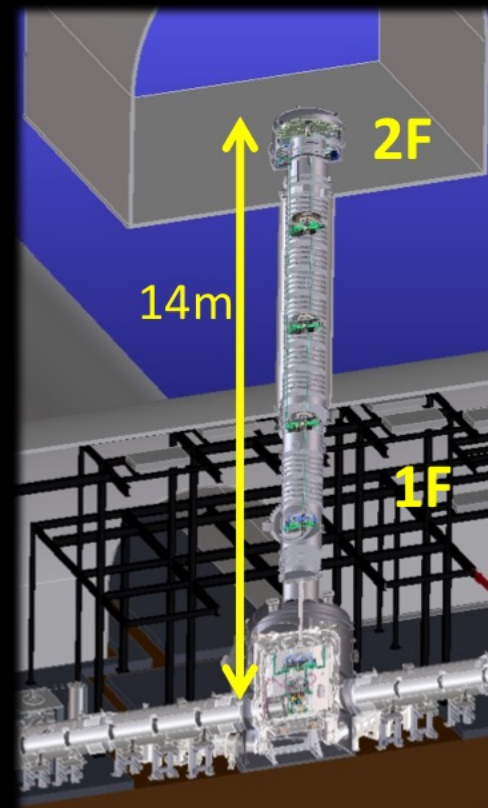
LIGO
Active system



VIRGO
Tall tower



KAGRA
2-story tunnel



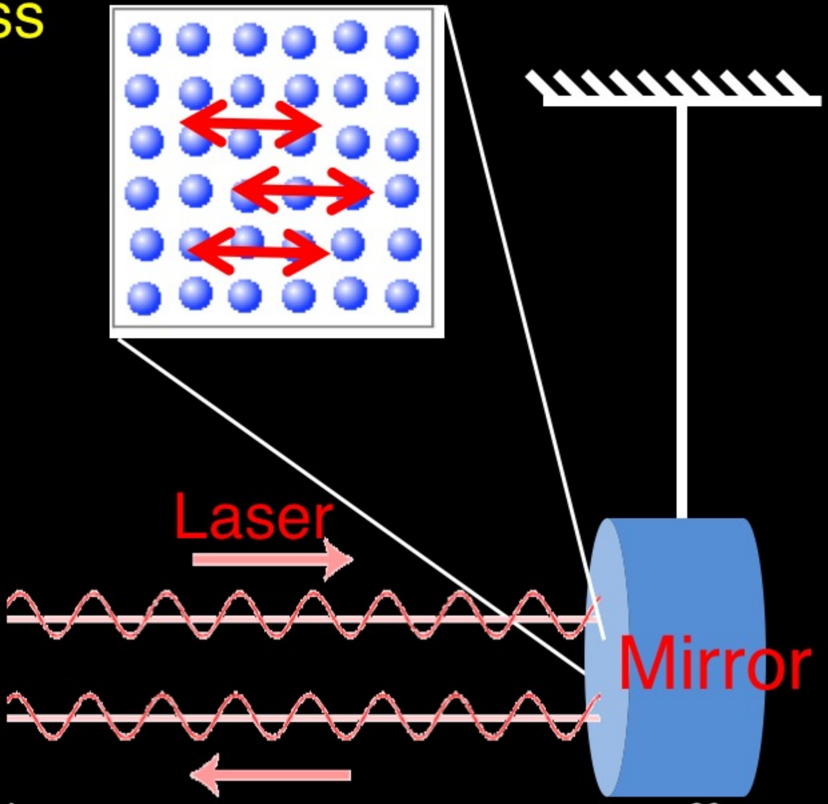
KAGRA – The first km-scale cryogenic detector

Thermal noise | Temperature | Mechanical loss

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

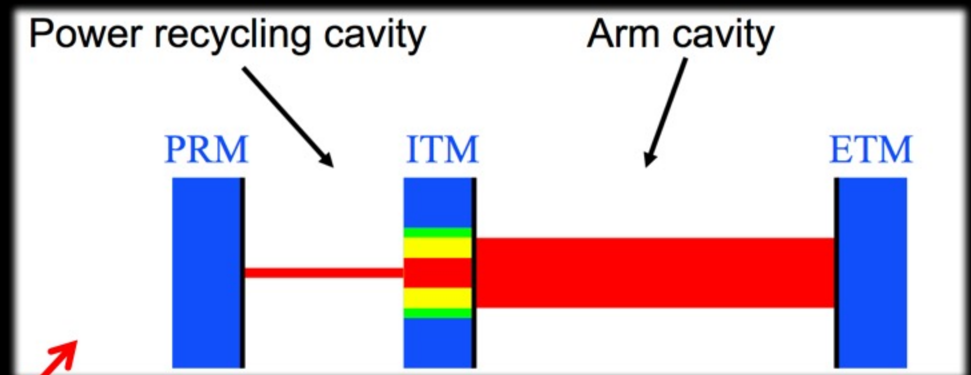
Sapphire @ 20K $\phi = 5 \times 10^{-9}$ (bulk)

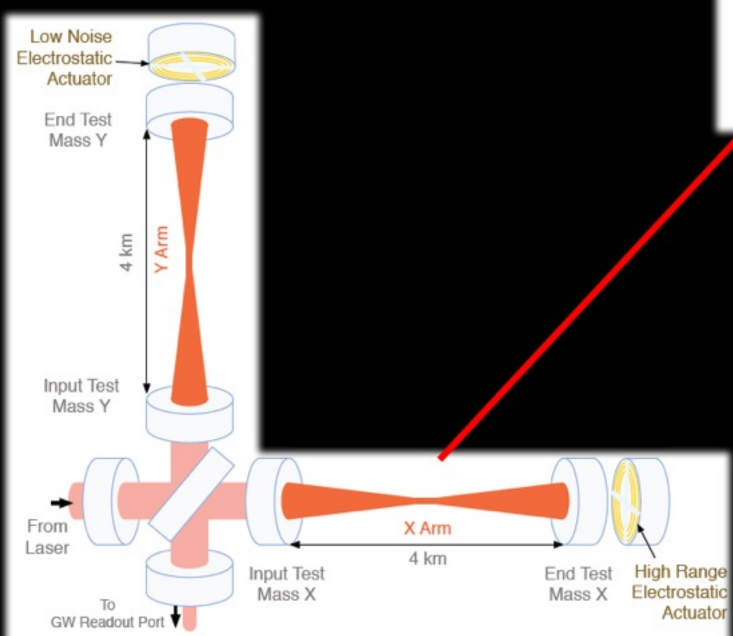
$\phi = 1 \times 10^{-7}$ (fiber)

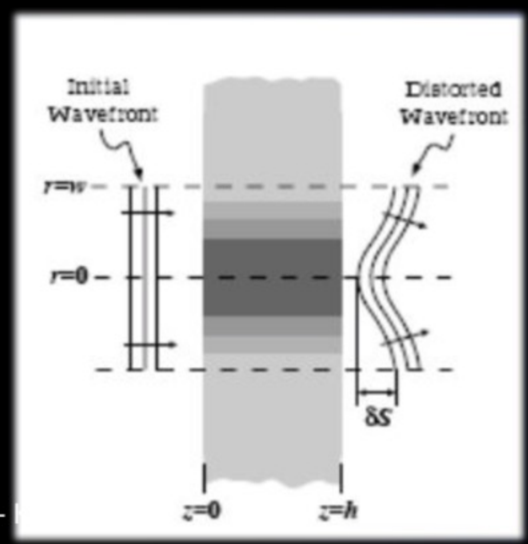


Thermal lensing effect

LIGO and Virgo : Silica mirrors at room temperature

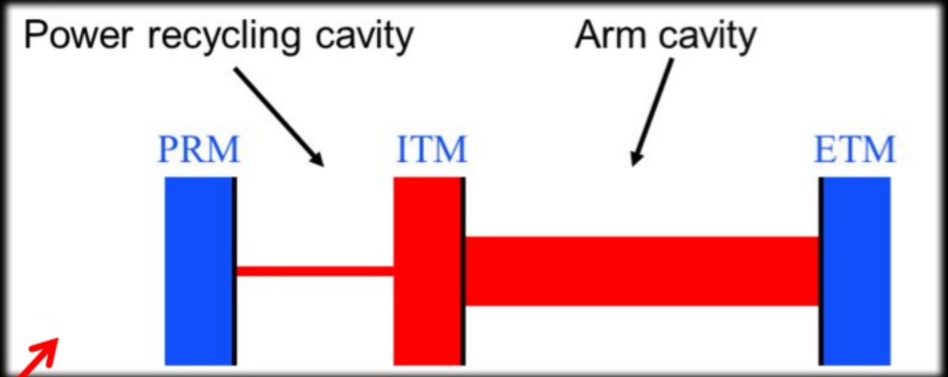


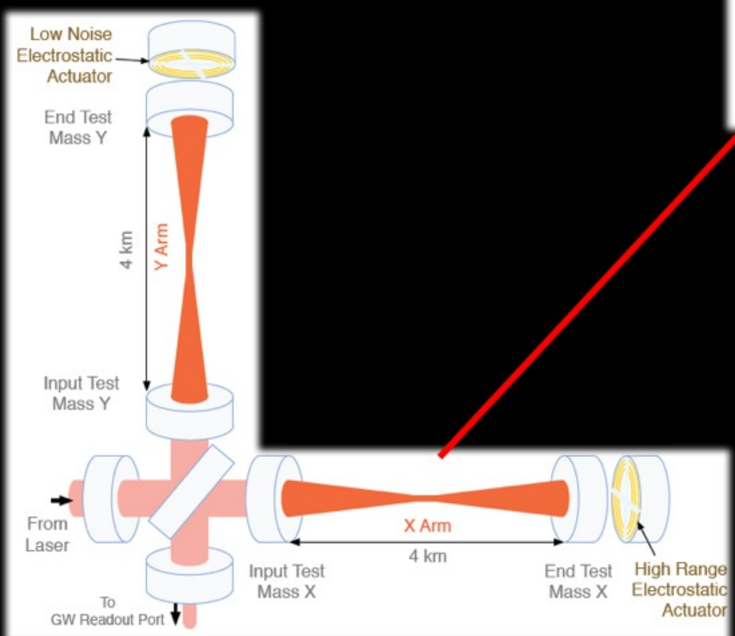


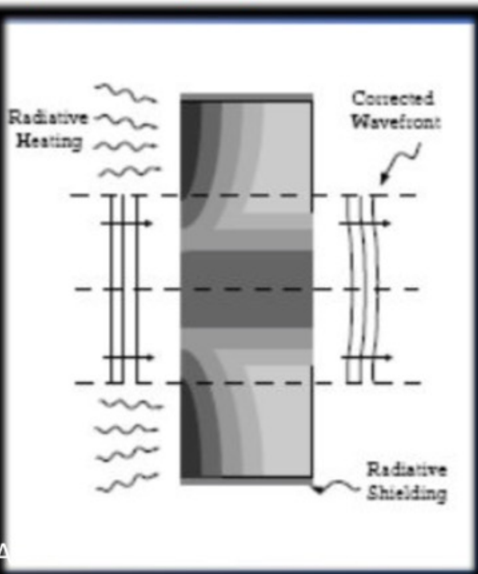


Thermal lensing effect

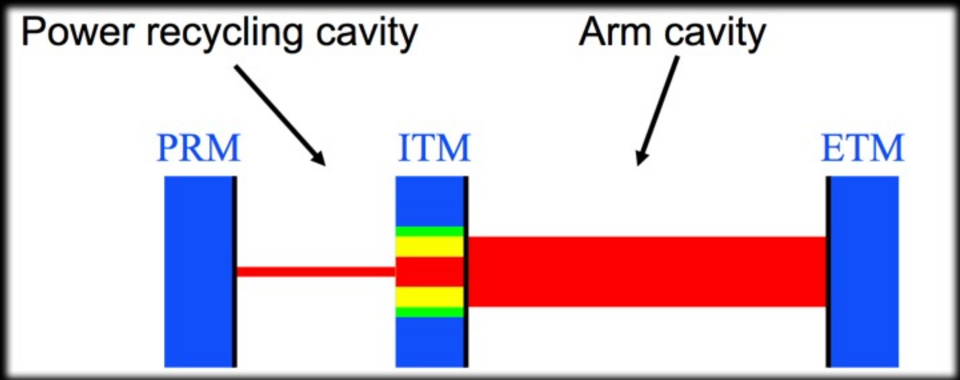
LIGO and Virgo : Thermal compensation system







Thermal lensing comparison

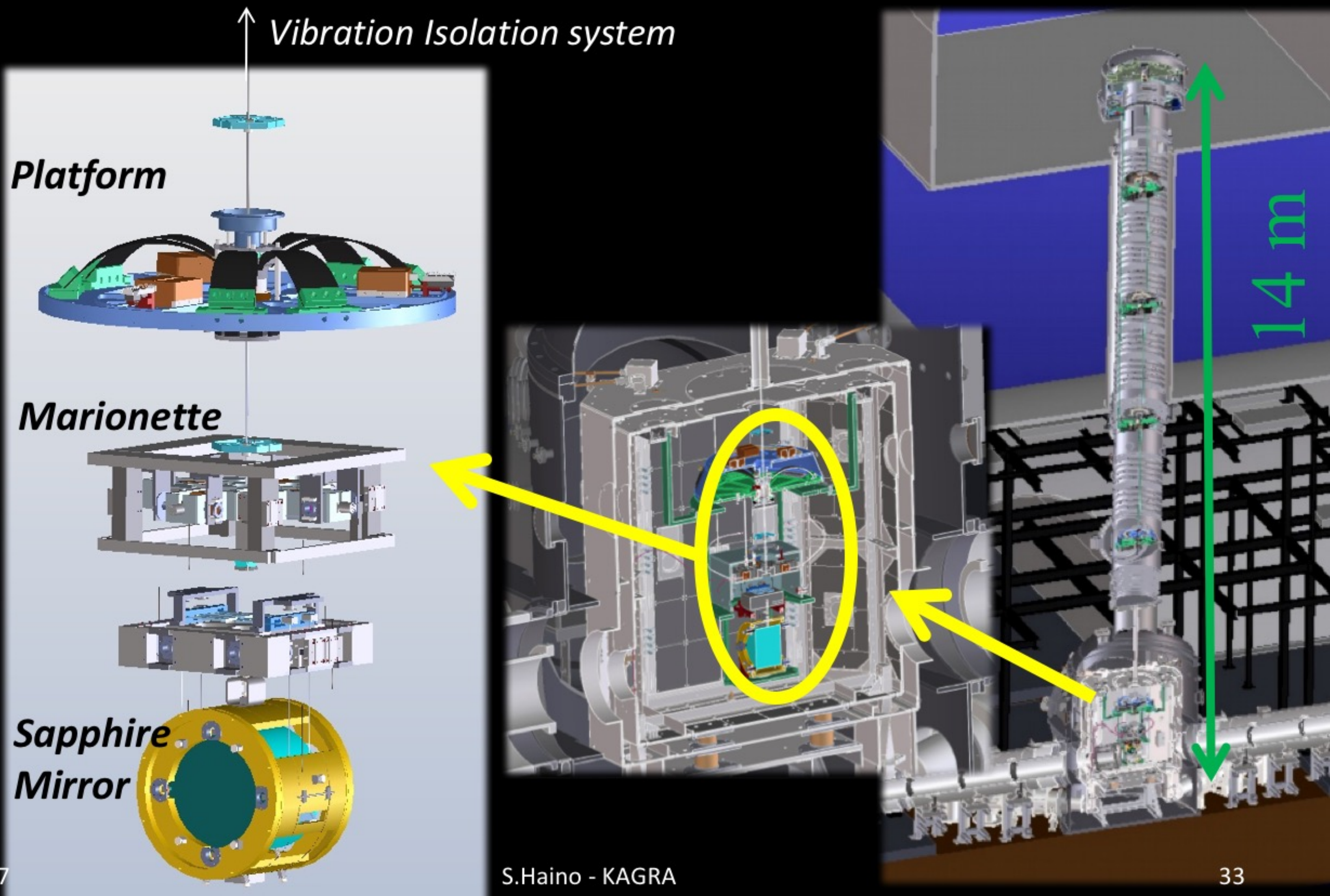


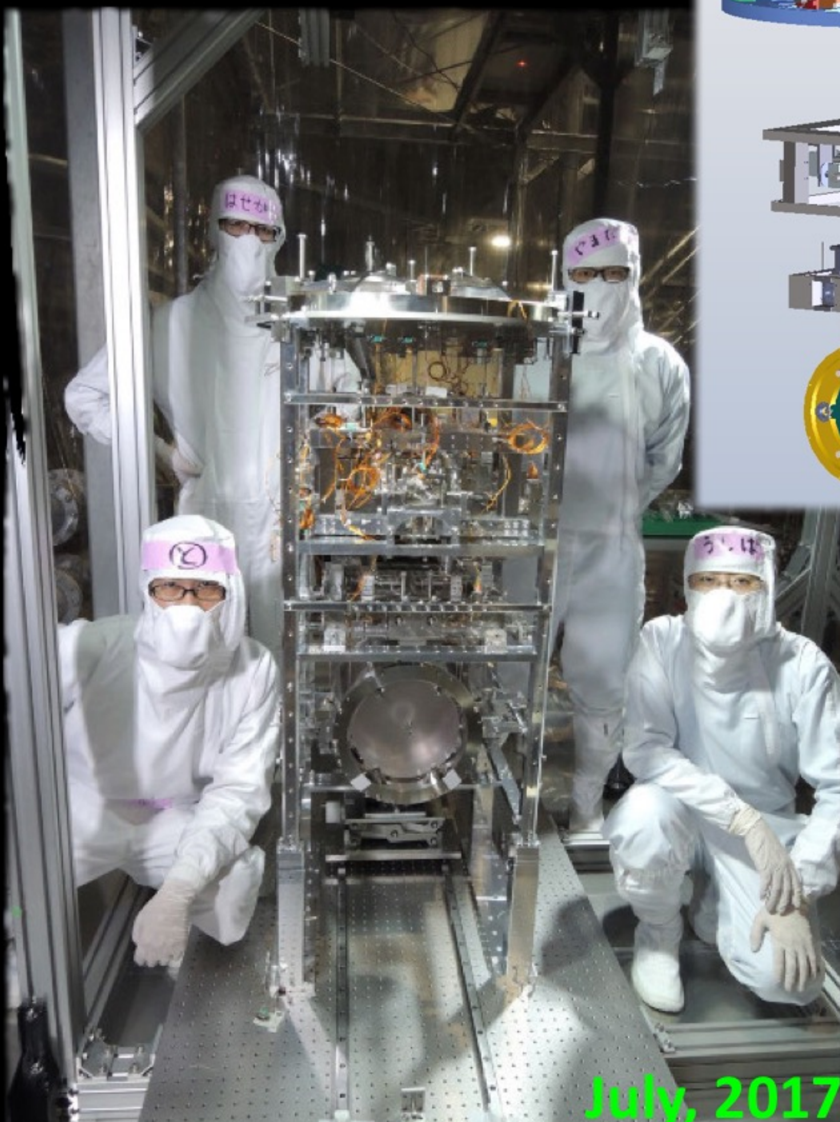
Thermal lensing effect is significantly reduced with cryogenic sapphire mirror

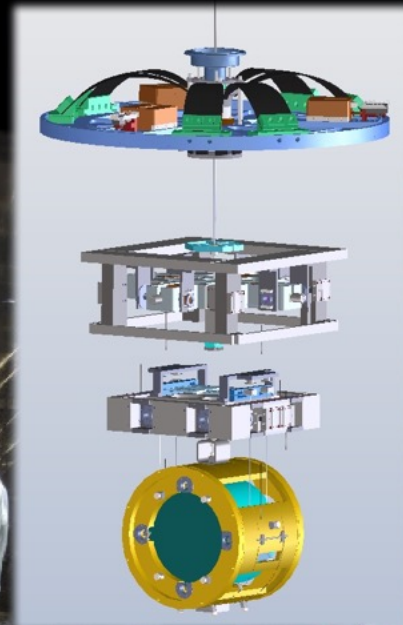
		Fused silica (300 K)	Sapphire (300 K)	Sapphire (20 K)
Abs. coeff.	α (ppm cm^{-1})	2–20	40–100	90
Th. conductivity	κ (Wm^{-1}K^{-1})	1.4	46	4.3×10^3
dn/dT	β (K^{-1})	1.4×10^{-5}	1.3×10^{-5}	$\leqslant (9 \times 10^{-8})$
Wave front distortion	$\alpha\beta/\kappa$ (W^{-1}) $\times 10^{-9}$	2–20	1–3	$\leqslant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

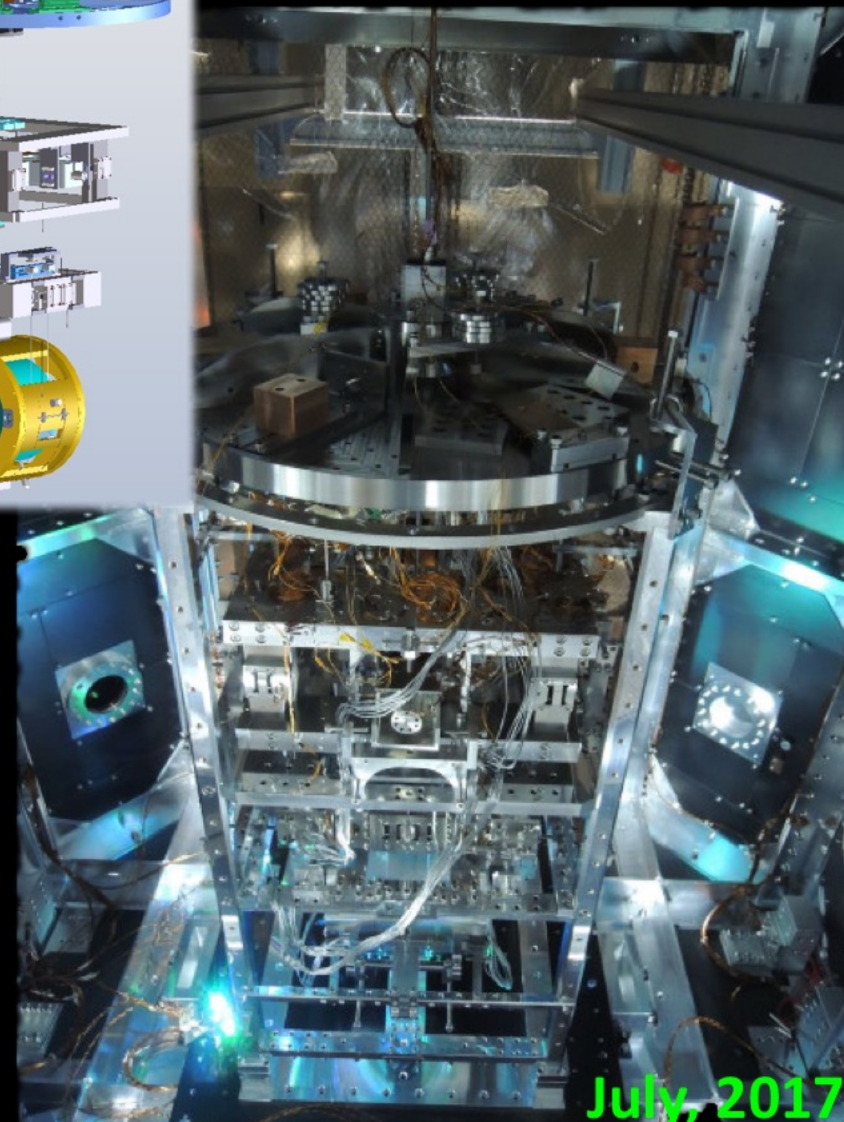
T. Tomaru et al., Class. Quantum Grav. 19 (2002) 1

Cryogenic suspension system

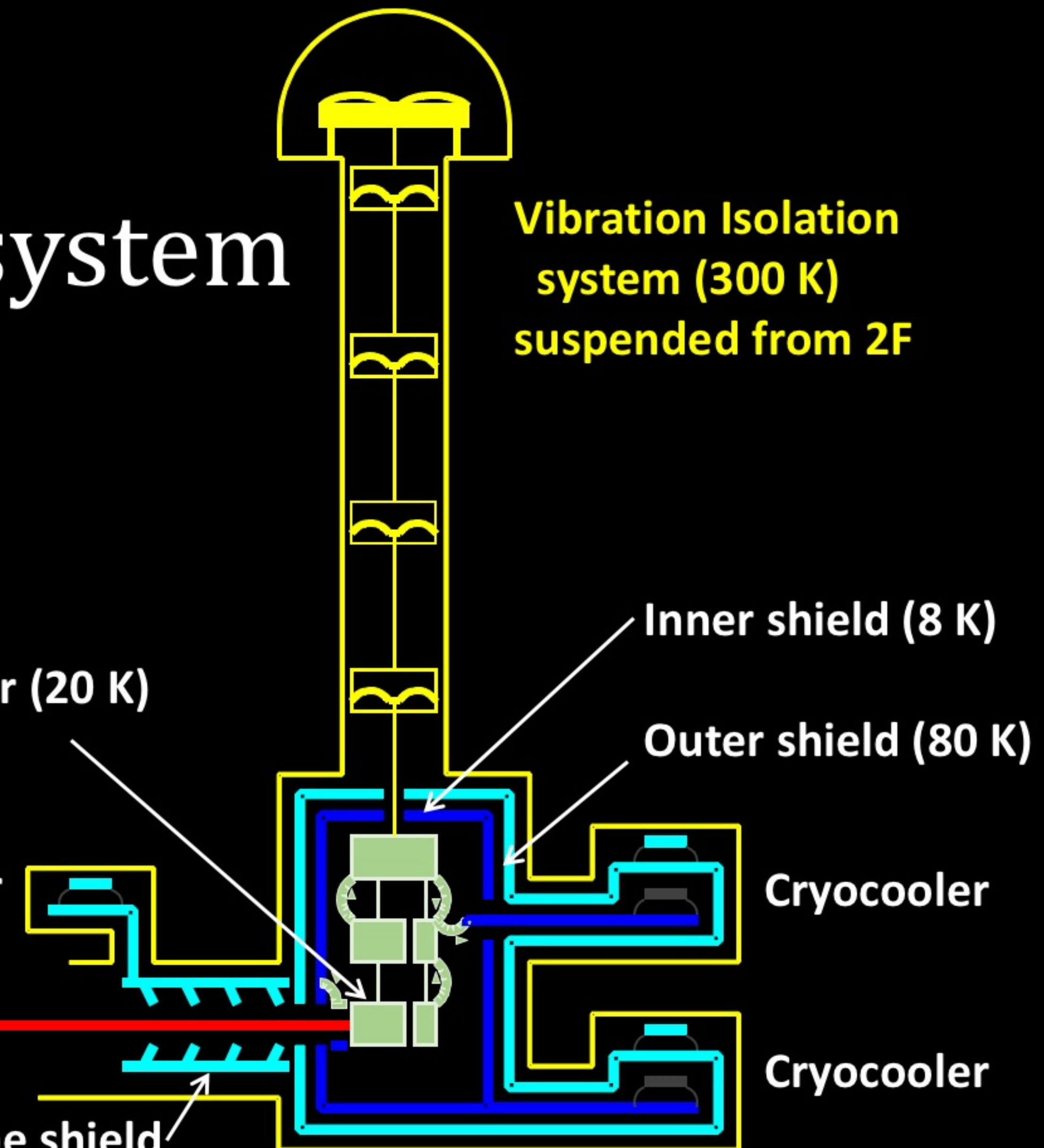



July, 2017



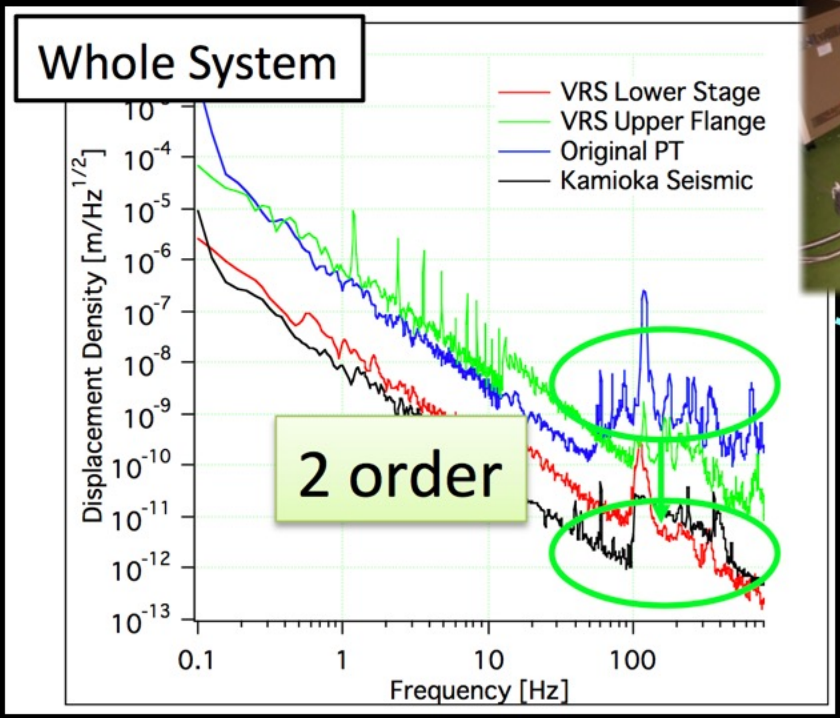

July, 2017

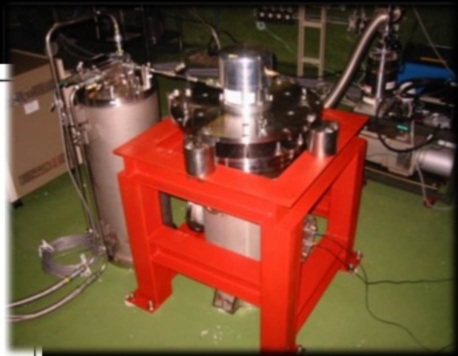
KAGRA Cryogenic system

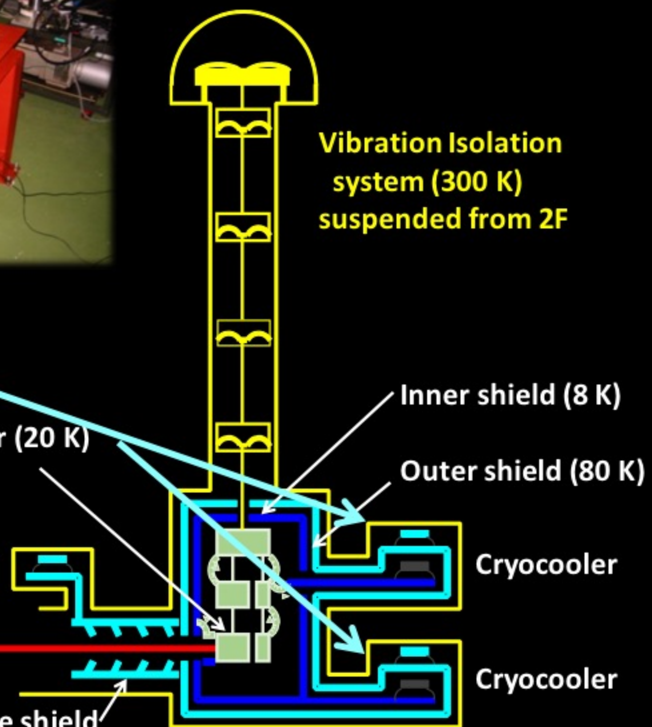


Key cryogenic developments

Achievement of low vibration pulse-tube cryo-cooler

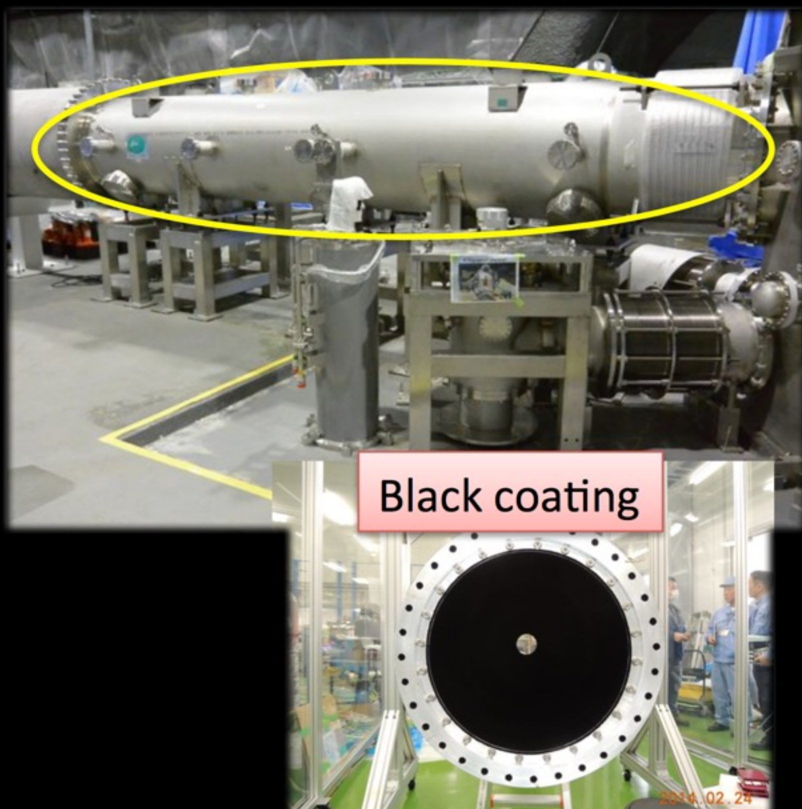




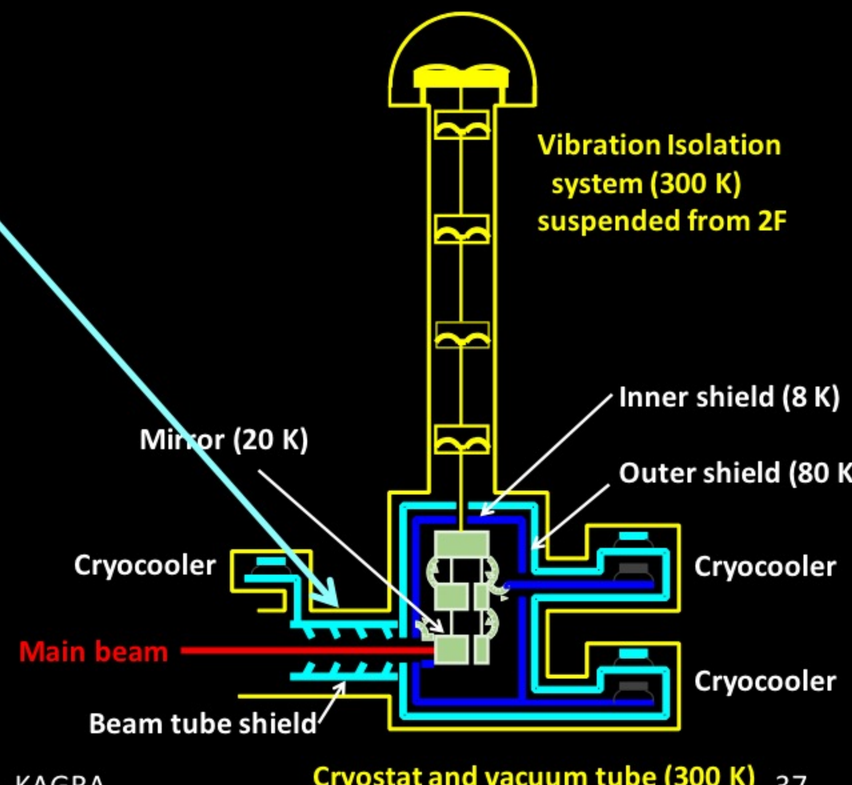


T. Tomaru et. al., Cryocoolers 13, (2005) 695

Key cryogenic developments



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



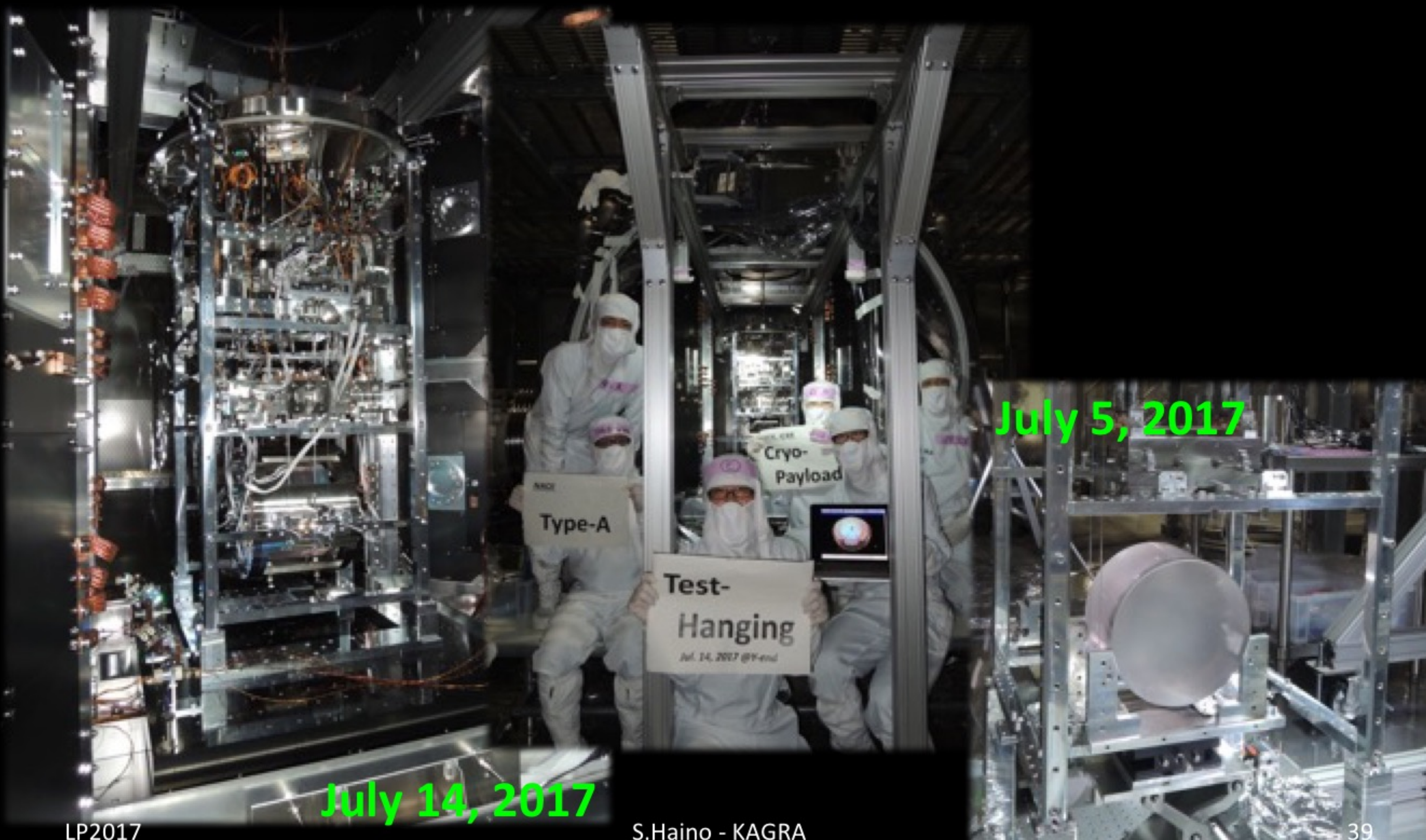
T. Tomaru et. al., J.J. A. P. 47 (2008) 1771

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



Vacuum System

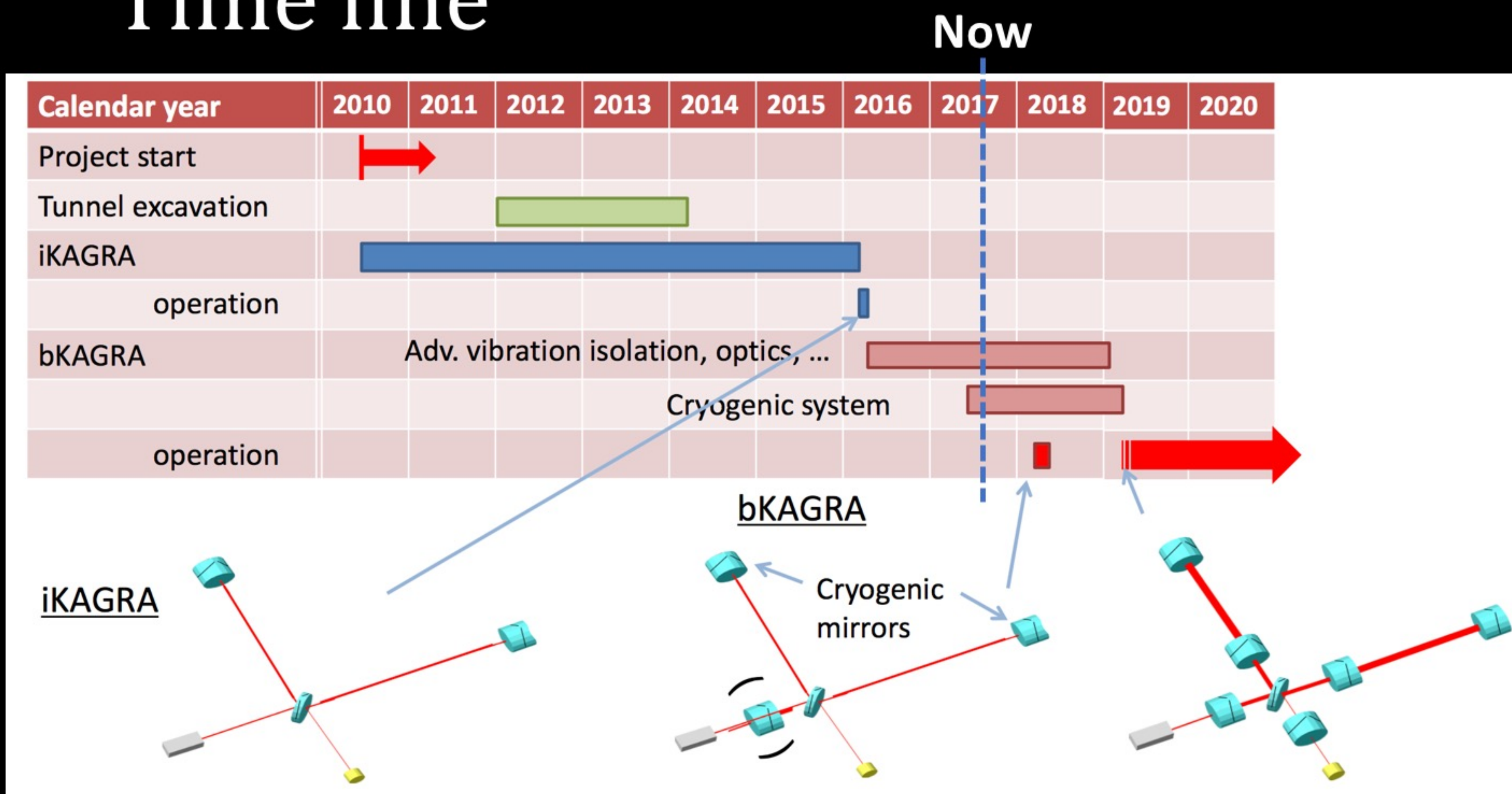
- In order to minimize the laser scattering noise ultra-high vacuum (10^{-7} Pa) is required

- 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

Time line



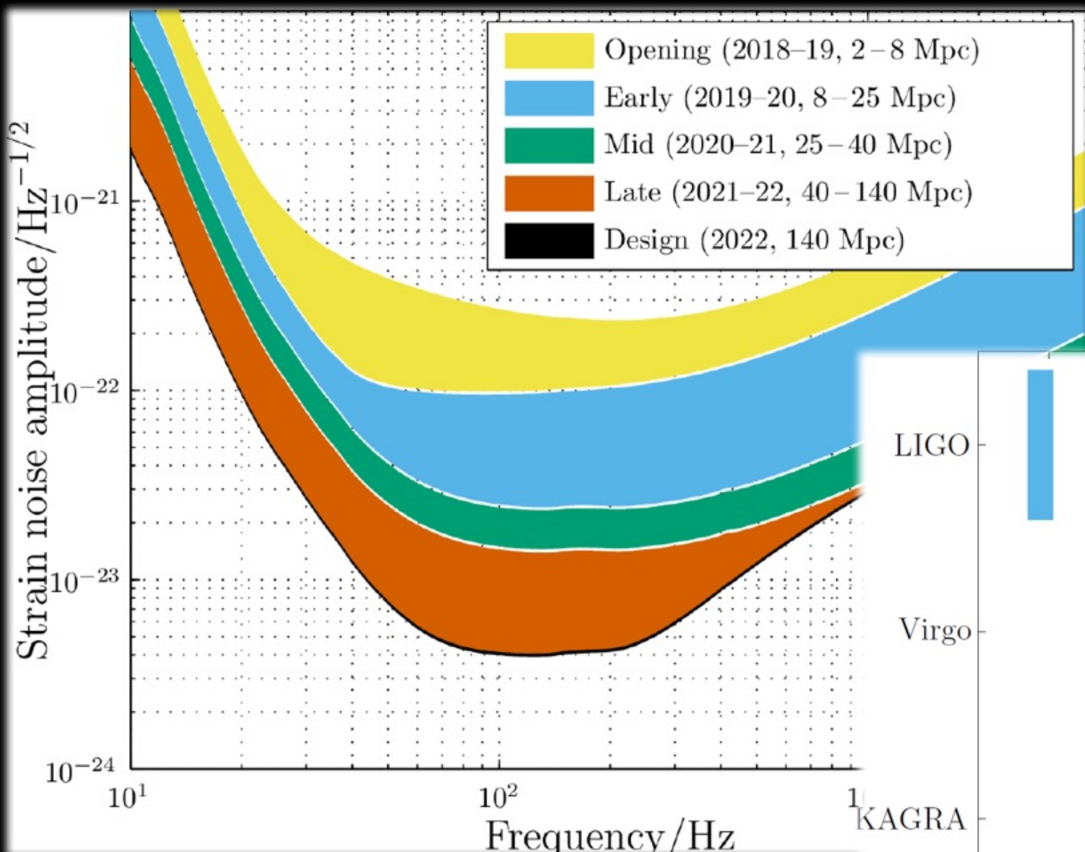
Room temperature

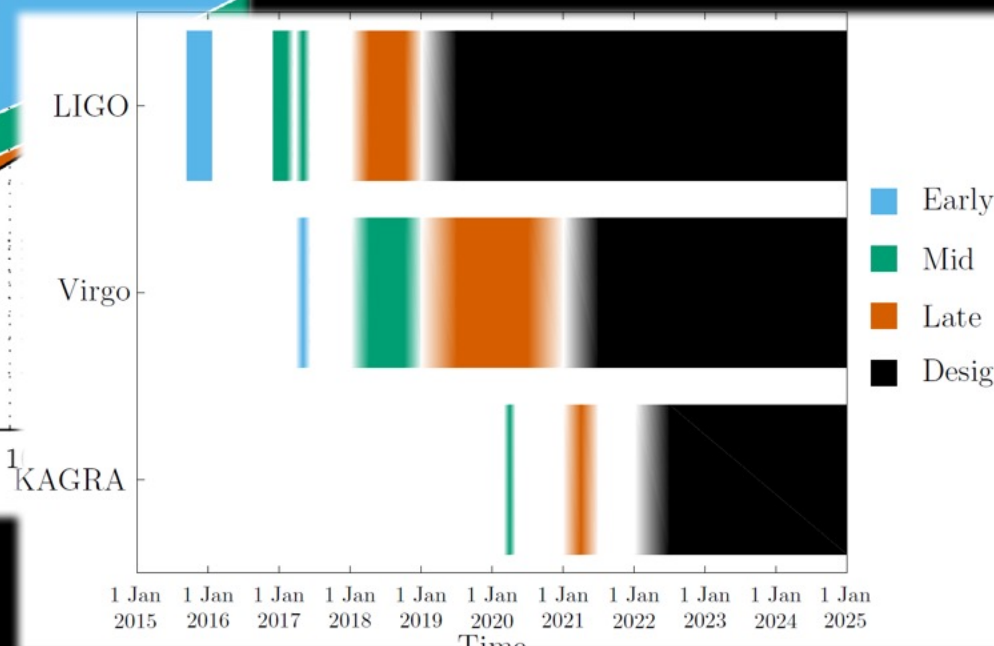
Cryogenic

Final configuration

Observation Scenario

- With 25-40 Mpc in 2020, 40-140 Mpc in 2021





Living Reviews in Relativity 19, 1 (2016)
to be updated

Summary

- GW will allow us to explore new physics and early Universe
- The next milestone is to build world wide network
- KAGRA is the first km-scale GW detector at underground and with cryogenic mirrors based on many particle accelerator technologies
- We expect to have physics results around ~2020