Current status of KAGRA Cryogenic Gravitational Wave Telescope in Japan

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on behalf of the KAGRA collaboration
ICRR, the University of Tokyo

Toyama International Symposium on “Physics at the Cosmic Frontier”
2019/03/07-09, Toyama University

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- Brief review of Gravitational Wave
  - Gravitational waves
  - Laser interferometer
  - Recent discoveries

- Introduction of KAGRA
- Current status of KAGRA
- Future
- Summary

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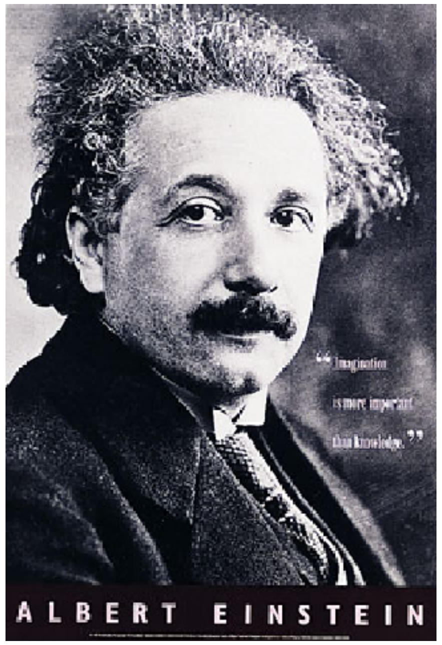
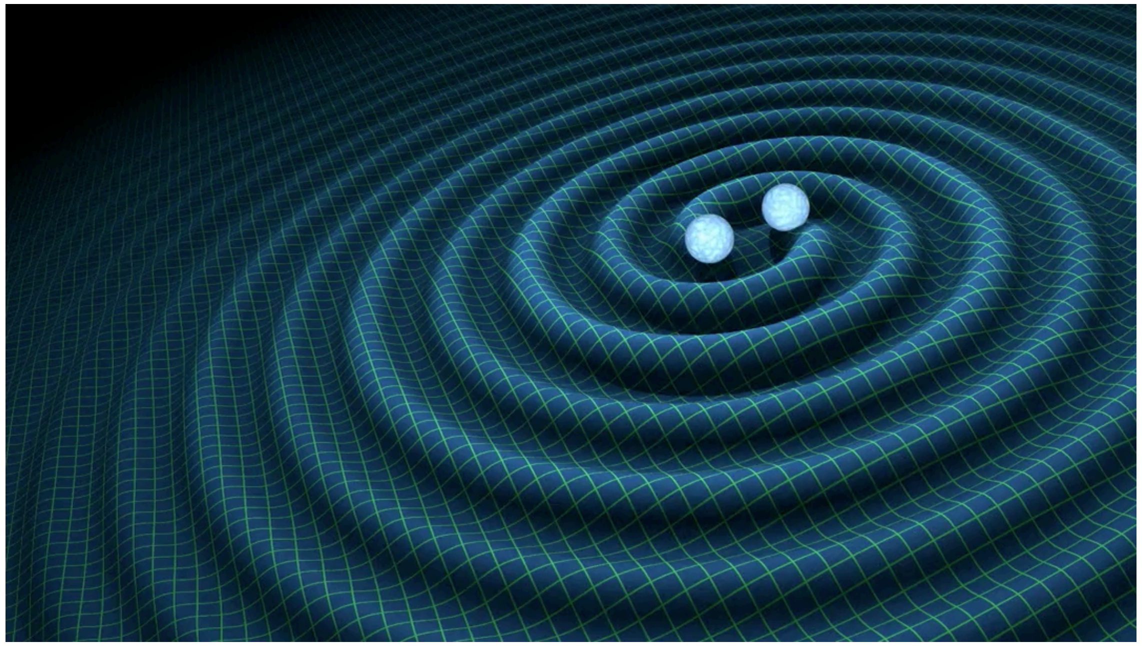
What is Gravitational Waves?





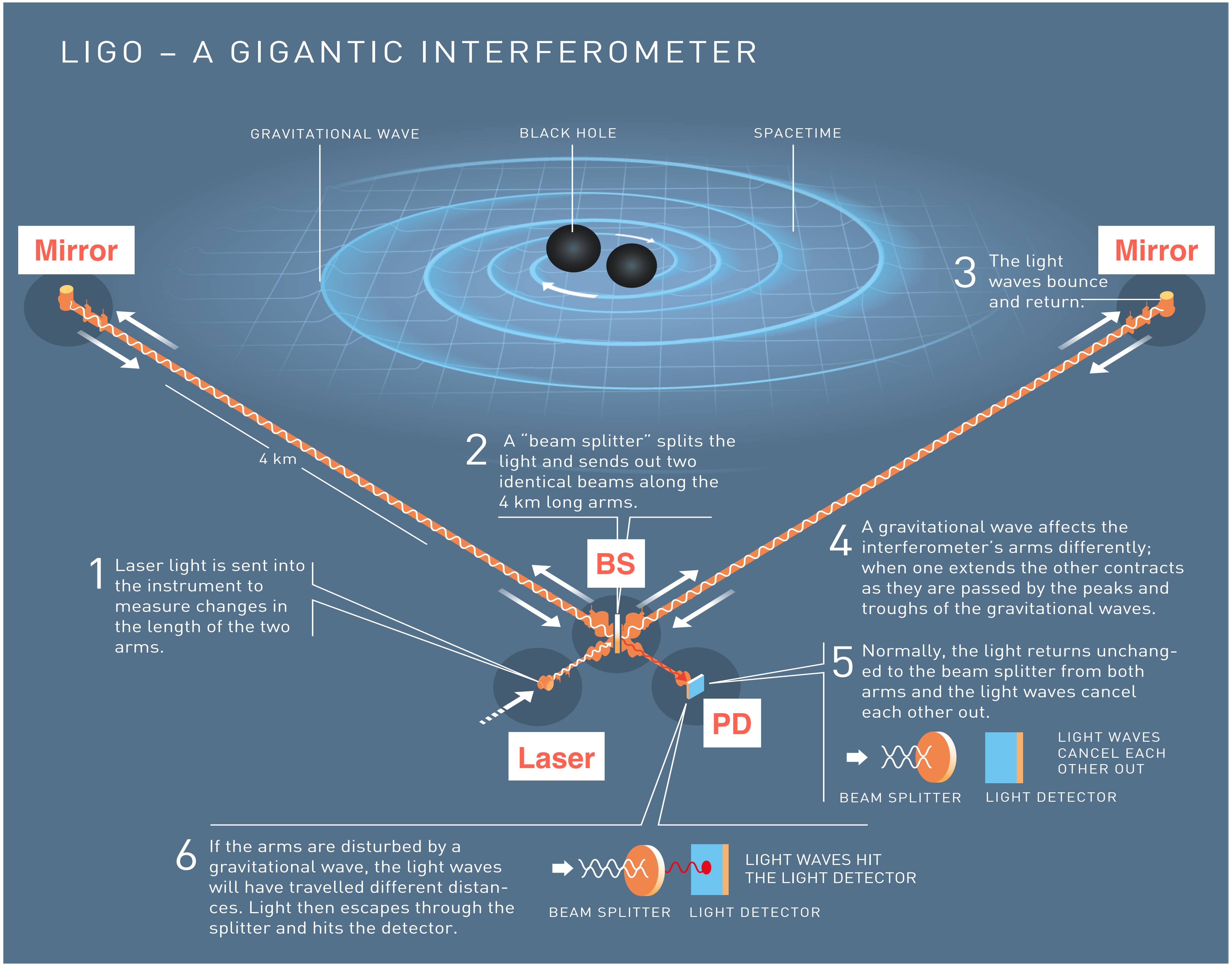
Compact star binary system is an ideal GW source.
Compact star: Black hole, Neutron star, and so on.

- GW was predicted in the General Theory of Relativity in 1916.
- GW is ripples of the space-time.
- GW is transverse wave traveling with light speed.
- GW has two polarization.
- GW can be generated by non-spherical motion of mass.
- We can not generate detectable GW signals in our Lab..
- GW sources are in the Universe.
    - The first detection of GW from BBH merger on 14 September 2015 by aLIGO. GW150914
    - The first detection of GW from BNS merger on 17 August 2017 by aLIGO and aVIRGO. GW170817
    - Total 11 GW signals have been detected so far.
    - Other source candidates: Supernovae, Pulsar, and so on.

- Importance of of GW detection.
    - Experimental tests of the General relativity.
    - New window to see the Universe. -> GW astronomy.

- Laser interferometers with suspended mirrors are the current major GW detectors in the world.

Principle of GW detection by a laser interferometer

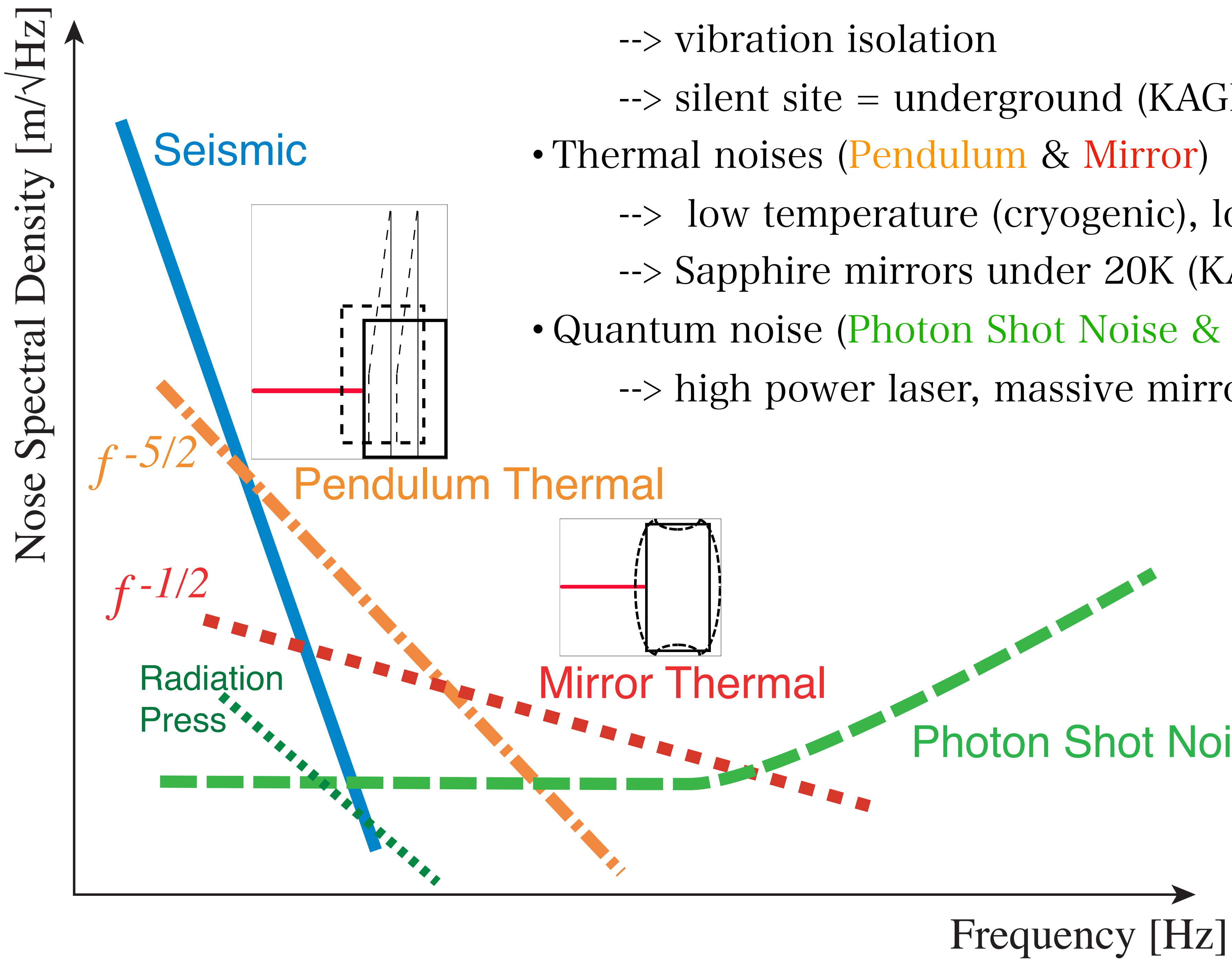


- Typical order of displacement: 10^{-20}m/rtHz
- Typical order of amplitude of GWs: 10^{-23} /rtHz

THE NOBEL PRIZE IN PHYSICS 2017
POPULAR SCIENCE BACKGROUND

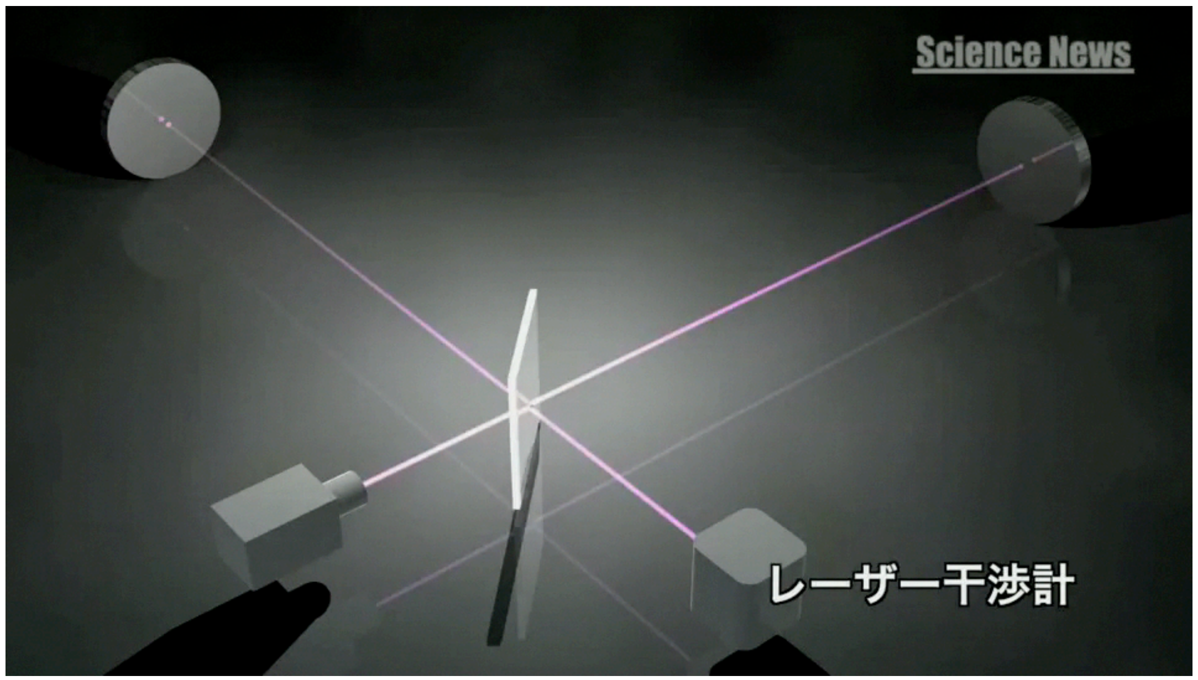
Fundamental noises

- **Seismic**
  - --> vibration isolation
  - --> silent site = underground (KAGRA)
- Thermal noises (Pendulum & Mirror)
  - --> low temperature (cryogenic), low dissipation
  - --> Sapphire mirrors under 20K (KAGRA)
- Quantum noise (Photon Shot Noise & Radiation Pressure Noise)
  - --> high power laser, massive mirror



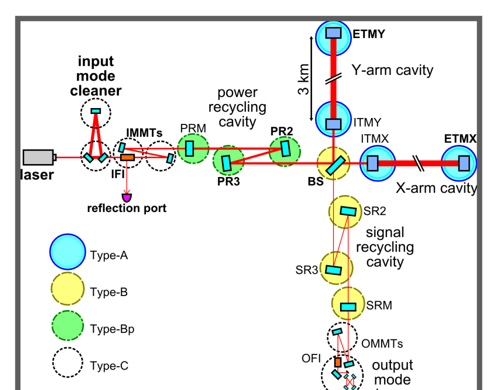
Real laser interferometer

Principle
Michelson interferometer



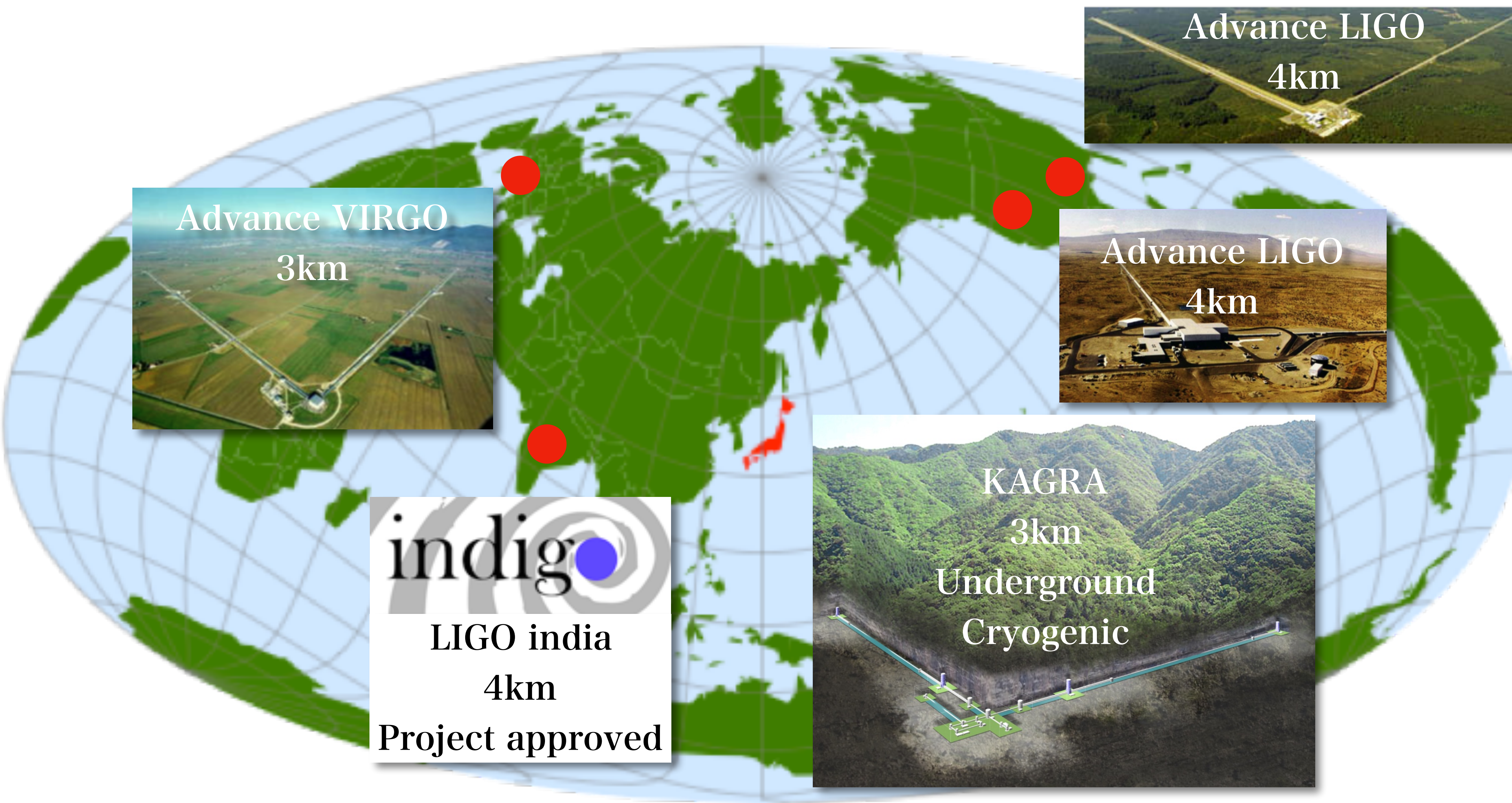
If you want to detect GW signals, your interferometer should have…

- Long base line,
- Much more complicated optical configuration,
- High power laser and high quality optics,
- Vibration isolation systems for optics,
- Large vacuum system, and so on.



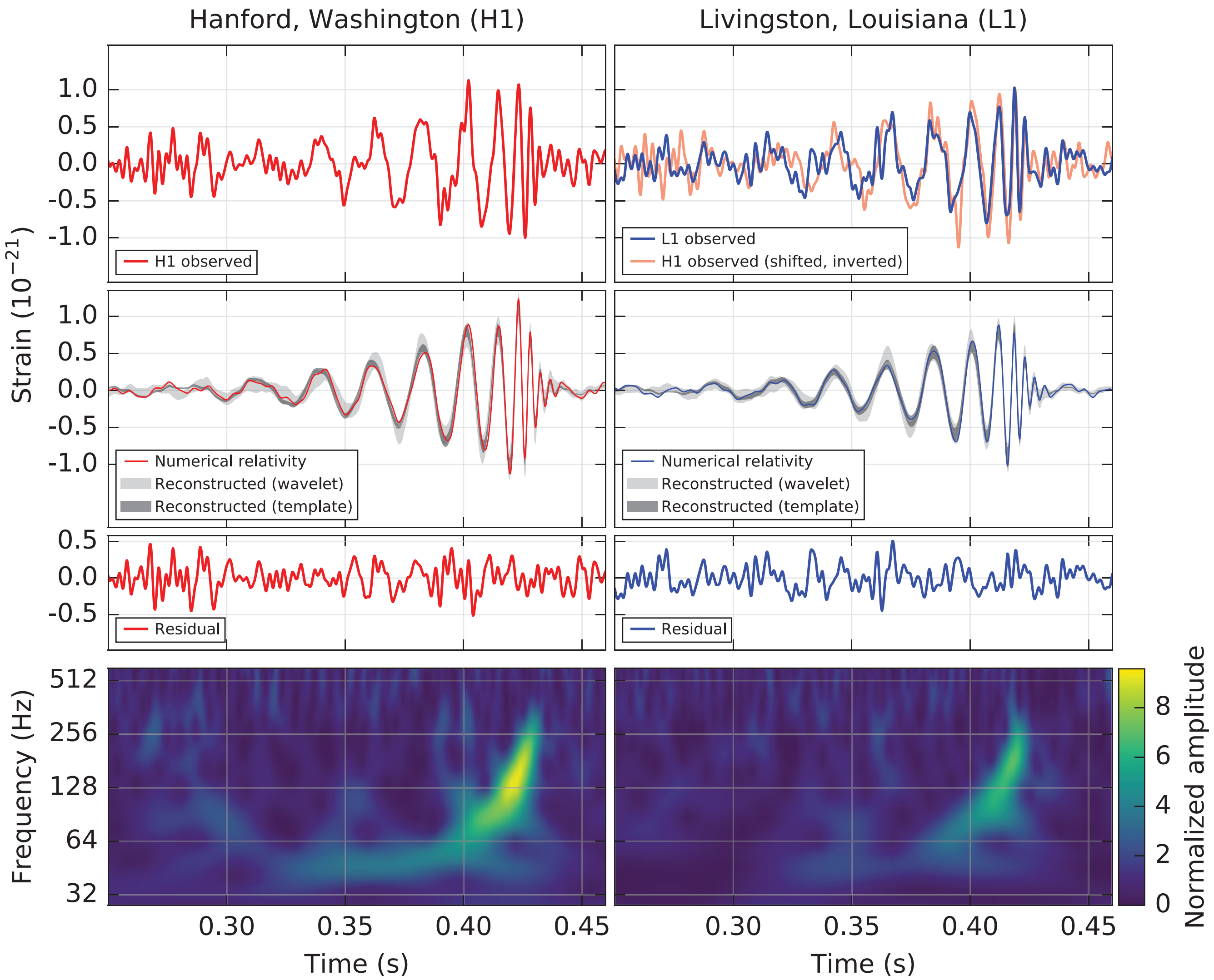
Complicated! Expensive!! Massive!!!

Global network of GW detectors in future

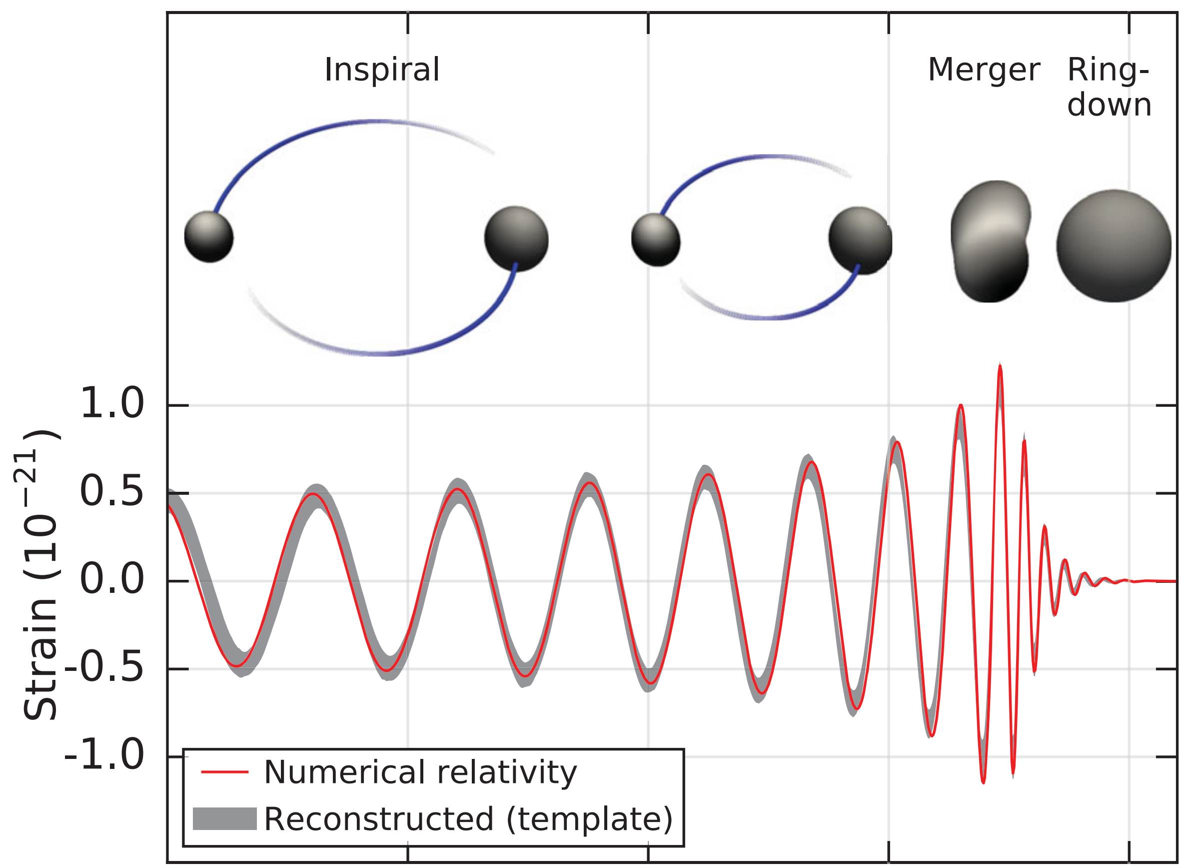


KAGRA will join the network as the 4th detector.

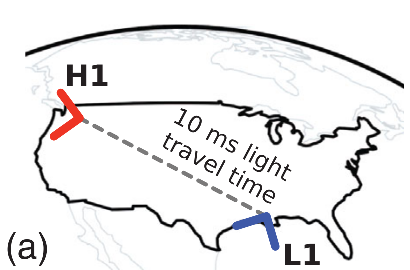
GW Signal



Observed signal of GW150914



Estimated gravitational wave signal GW150914



Primary black hole mass	$36^{+5}_{-4}M_\odot$
Secondary black hole mass	$29^{+4}_{-4}M_\odot$
Final black hole mass	$62^{+4}_{-4}M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Observation of Gravitational Waves from a Binary Black Hole Merger

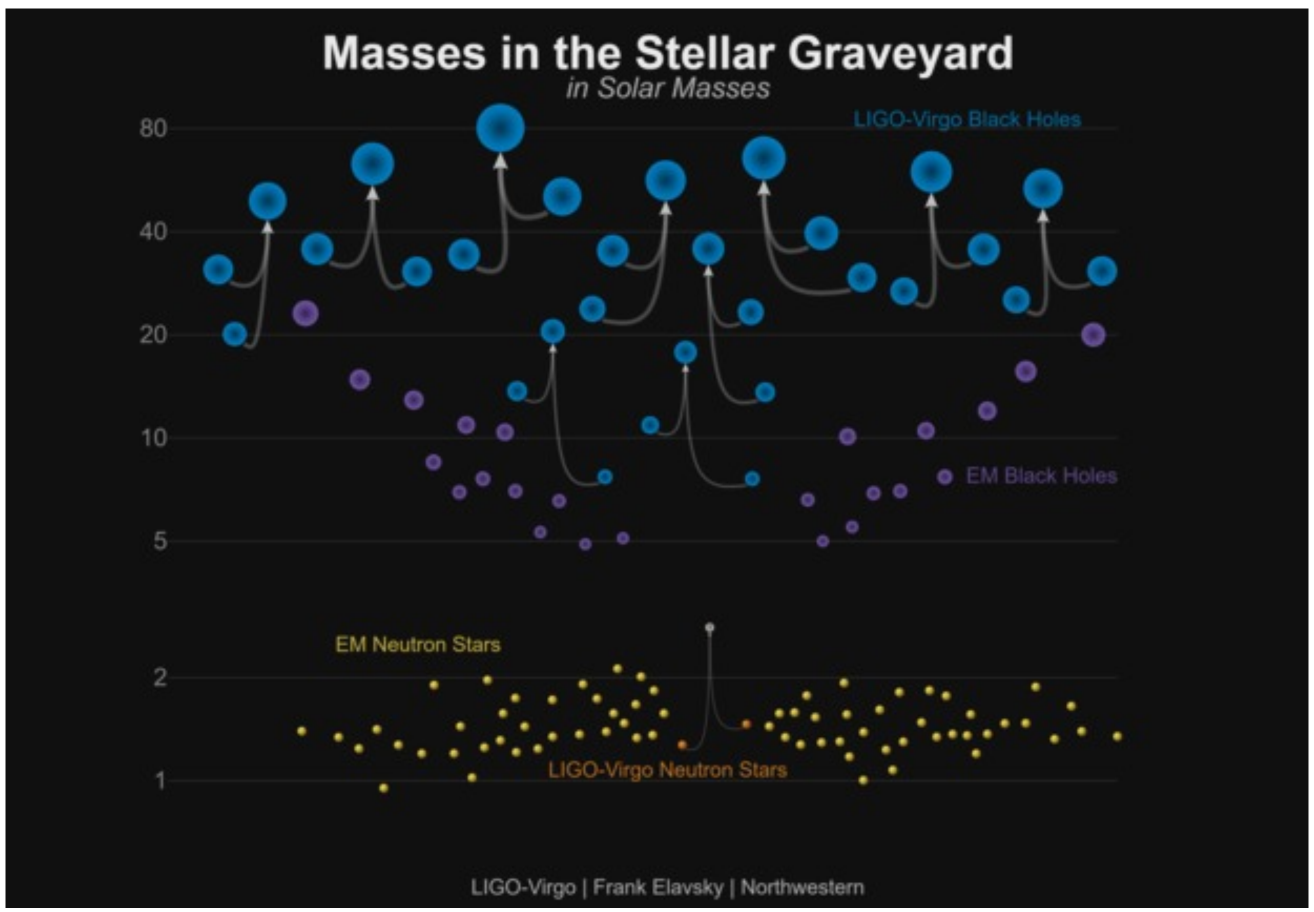
PRL 116, 061102 (2016)

GW detection in Observation 1&2

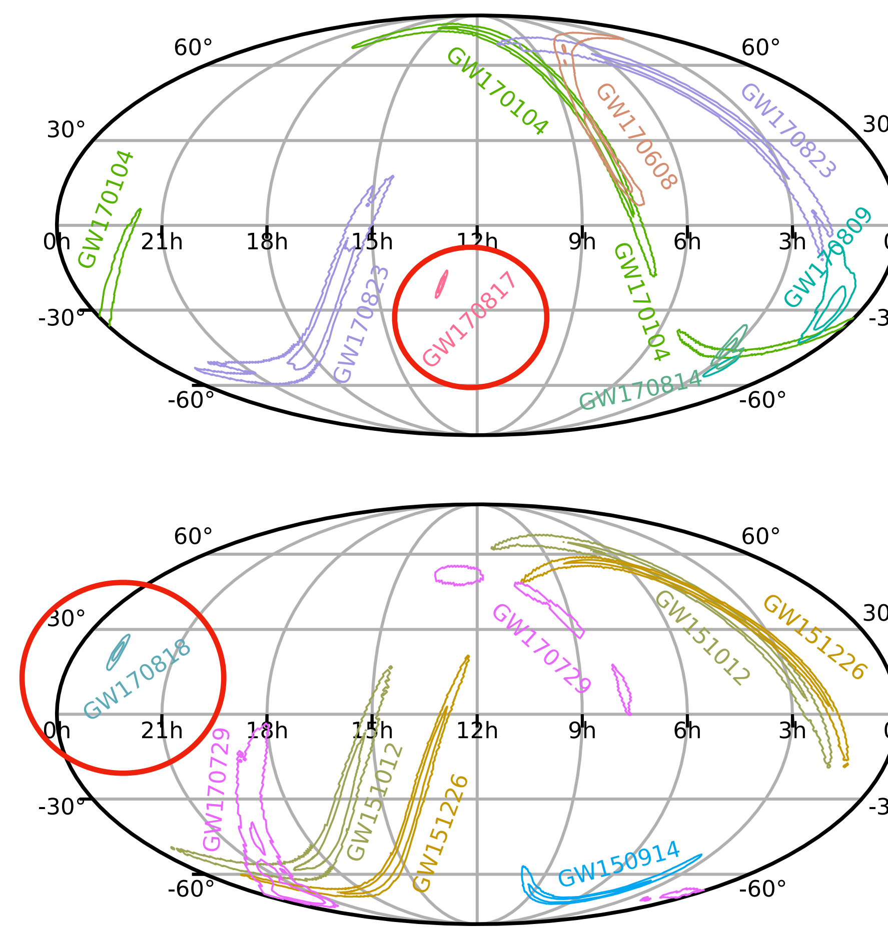
O1: 2015/Sep./12 - 2016/Jan./19

O2: 2016/Nov./30 - 2017/Aug./25 (Virgo joined from Aug. 1)

O3 will start from 2019/Apr./1 (1 year observation is planned)



10 BH-BH binary and 1 NS-NS binary



Sky localization map

GW170814&GW170817 have been observed by L&V

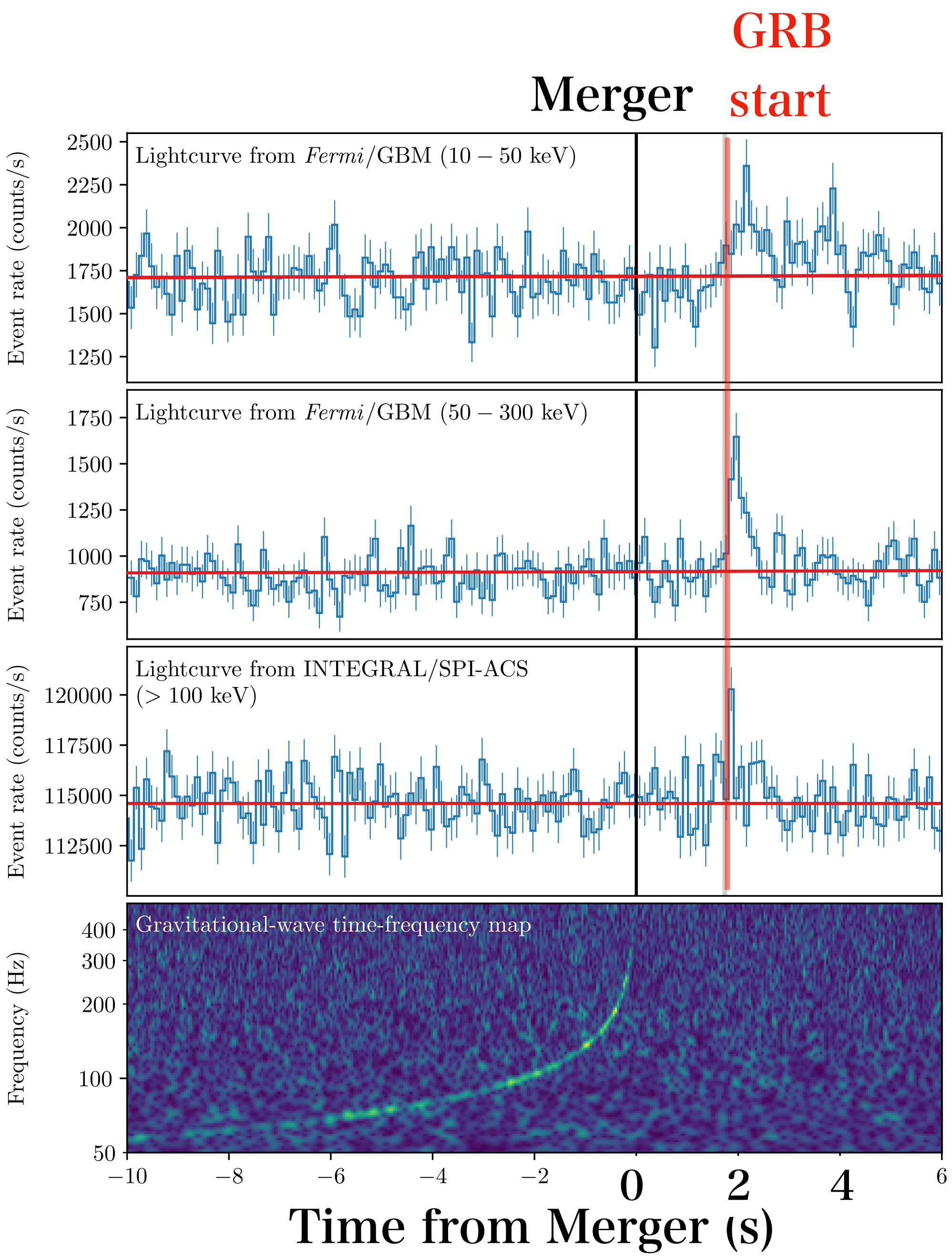
Localization accuracy improved

https://www.ligo.caltech.edu/image/ligo20181203a

GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs

Multi-messenger astronomy

GW detection triggered EM follow up observations

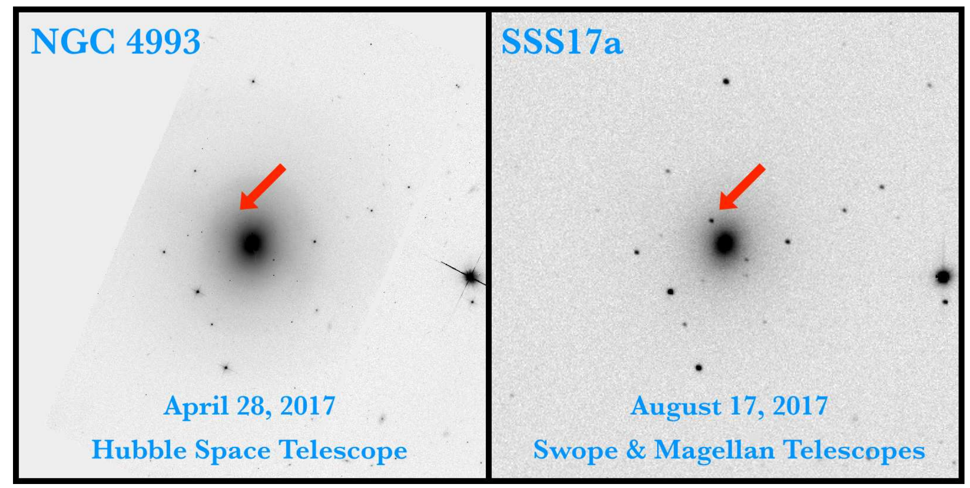


Short Gamma Ray Burst 1.7sec after GW170817

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L13 (27pp), 2017 October 20

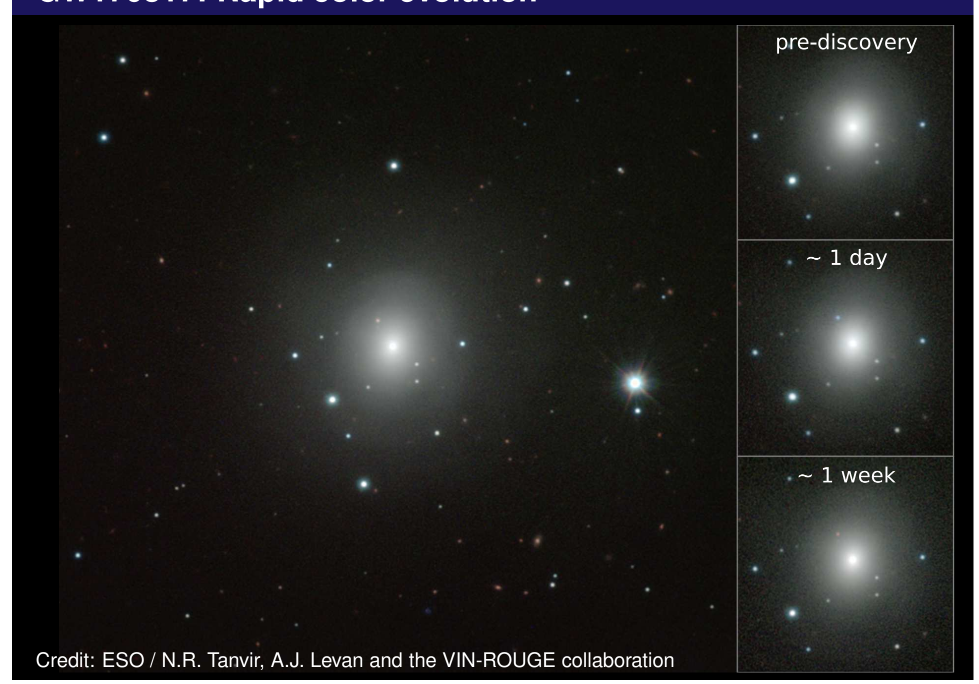
GW170817: Counterpart discovered in NGC 4993

- Discovered 10.9 hours after merger
- Host galaxy: NGC 4993, elliptical galaxy, constellation Hydra, 40 Mpc ~ 130 Mly

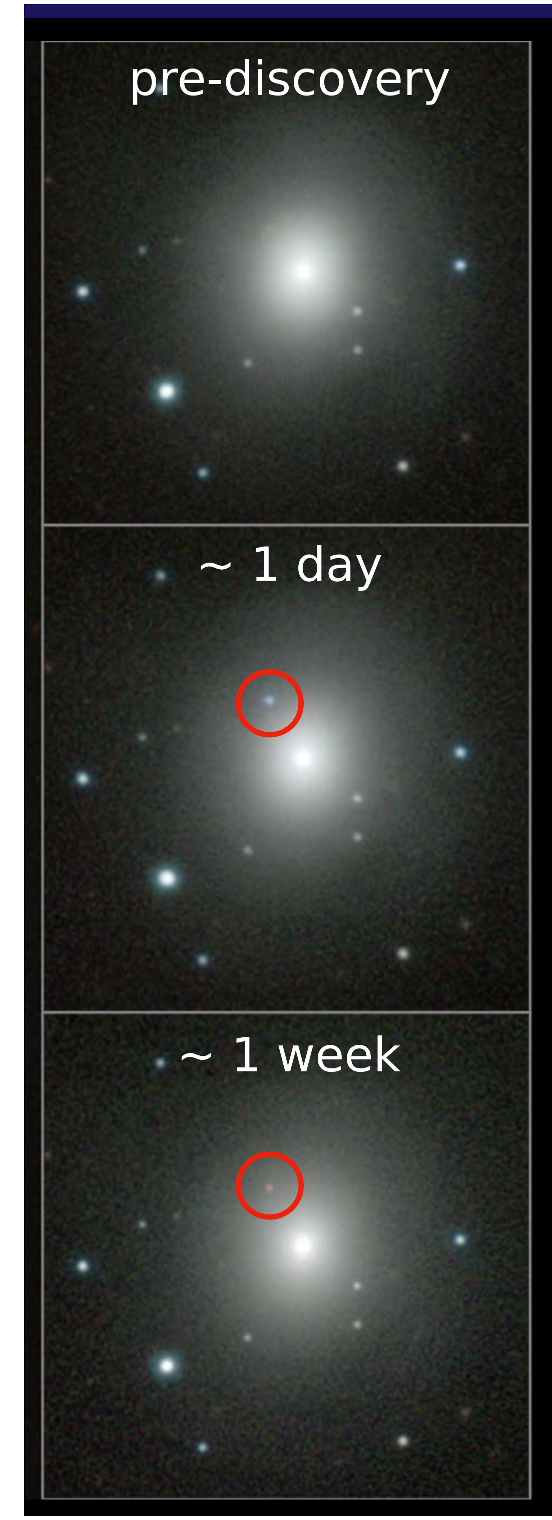


Credit: 1M2H Team / UC Santa Cruz & Carnegie Observatories / Ryan Foley

GW170817: Rapid color evolution

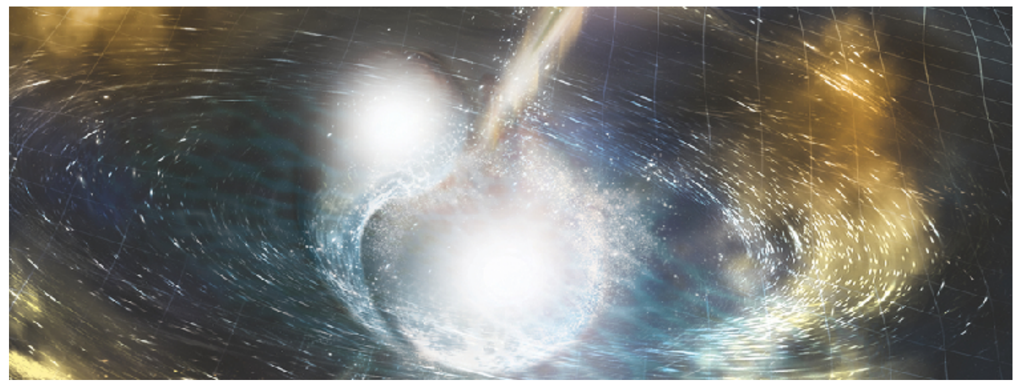


r-process has been observed



Congratulations!

Detection of GW170817 & Multi-Messenger astronomy



by the way… What did KAGRA in that day?

KAGRA作業連絡書		2017/8/17	
発信日	2017/08/16	発信者	内山隆

レーザーハザード	1) GIF(Xarm500m, 2000m KAGRA真空ダクトの壁側）立ち入る際は新谷君に許可を得た上で、グリーン用保護メガネを着用。真空ダクトの通路側は保護メガネ無しで通行可能。
	2）中央実験室：IMMラインより奥、クラックリング実験エリア(Yfront+X側)

エリア	作業予定	
中央	IOO作業 7名　kokeyama, kawamura, nogawa, nakamura, hirata, chen, telada	
	VIS作業 5名　shoda, hashimoto, kasuya, arai, yoshida	
	CRY作業 2名　hasegawa, miyoki	V-7
	VIS作業4名 mark, ohishi, enzo, kozu	
	クラックリング実験1名　kirii	
	DGS作業1名　yamamoto	
	IOO作業4名　kokeyama, furuhata, sakamoto, aritomi	
中央室、Y-end	CRY作業2名　kimura, miyamaoto	KEK-1, -2
Yend2F	AEL作業3名　kamiizumi, tomura, shimode	
X-end 2F	VIS作業 2名　takahashi, okutomi	NAOJ-2, V-6, -10
Xend	CRY作業3名　ushiba, hasegawa, fukunaga	V-
全域	坑内管理 hayakawa, nakada	

KAGRA working list of the day.

- KAGRA was in bKAGRA phase 1.
- 32 people entered the KAGRA site.
- Many kinds of installation works have been done.
  - IOO, VIS, CRY, DGS, AEL, and so on.
- NO OBSERVATION AT ALL.

We couldn't any contribution to the event.

↓

We have **strong wish** to contribute to science like them.

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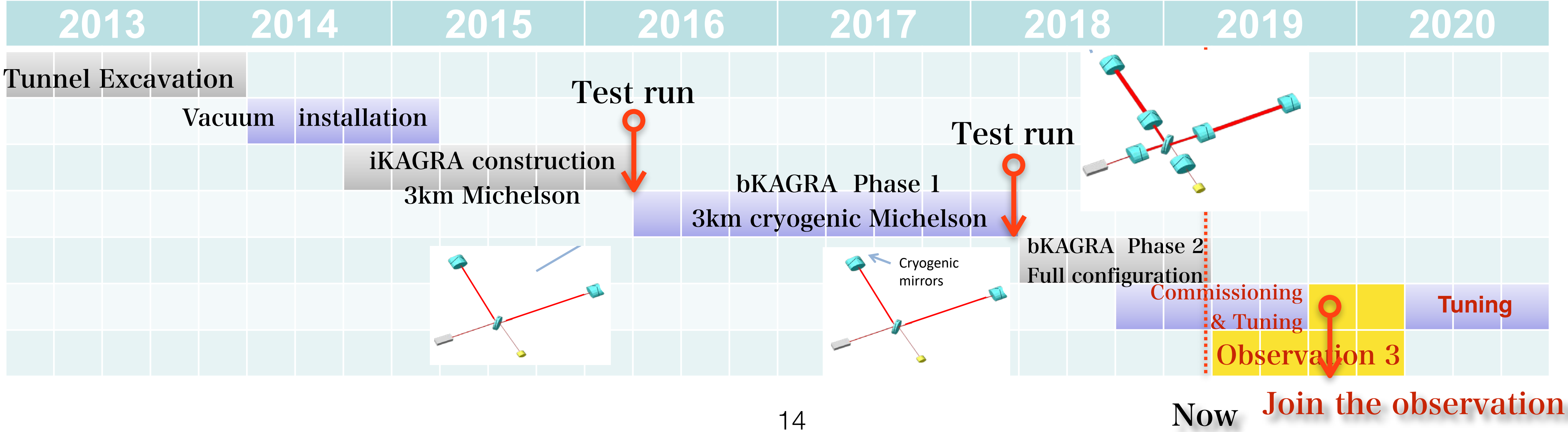
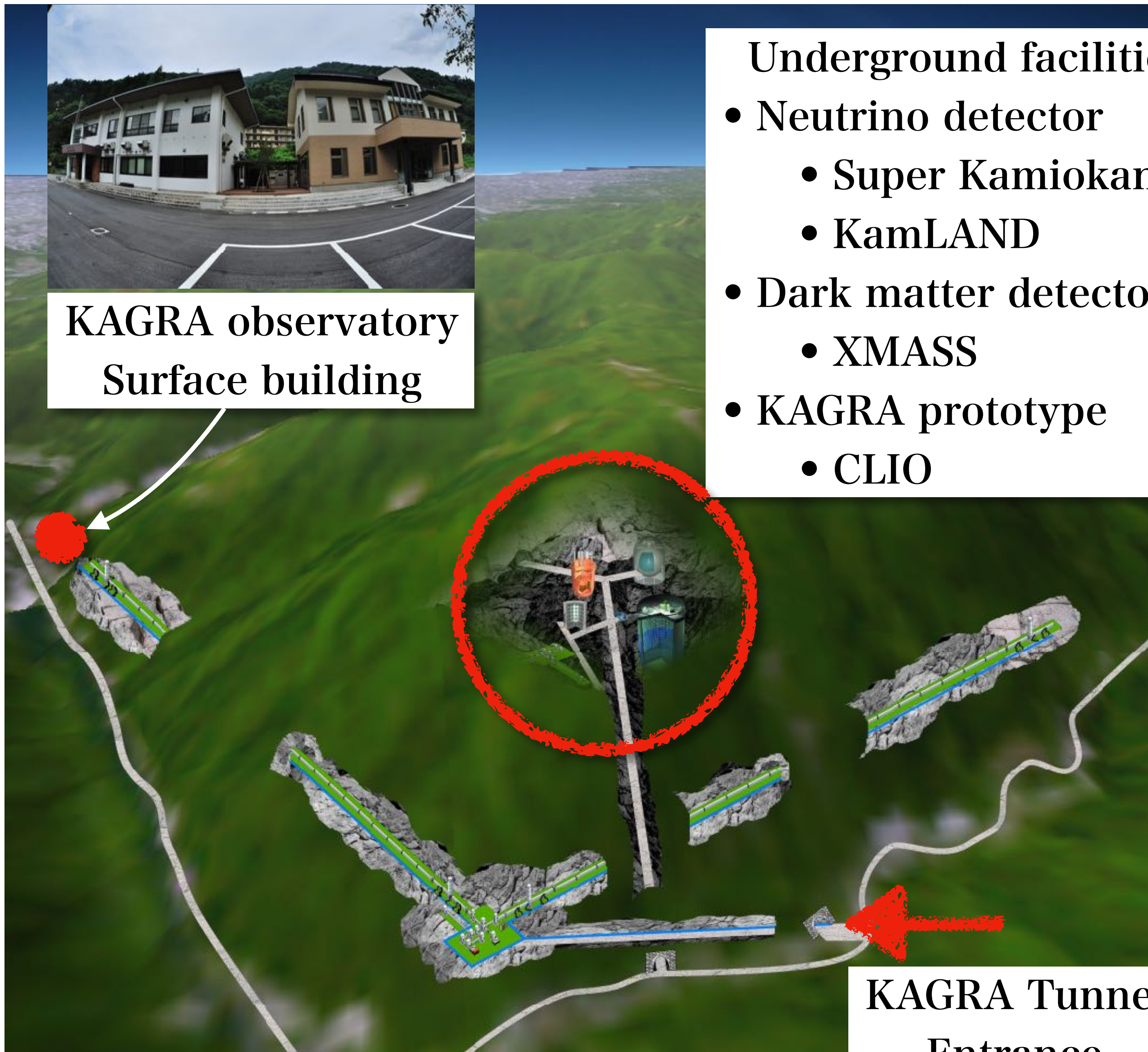
KAGRA

- Laser interferometric gravitational wave detector with 3km arm length.
- Key features of KAGRA
    - KAMIOKA underground site.
    - Use of cryogenic mirrors.
- PI: Prof Kajita
- 460 collaborators
- 97 institutes
- 15 countries
- Project started from 2010.6.



Kamioka mine
KAGRA site



KAGRA observatory
Surface building

Underground facilities

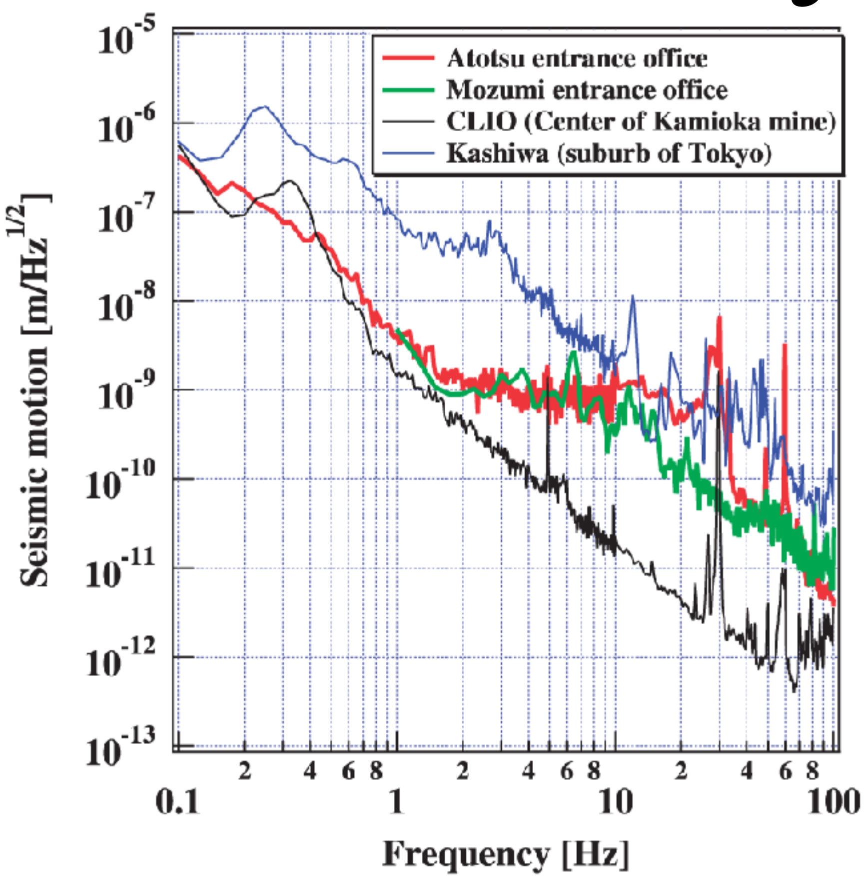
- Neutrino detector
    - Super Kamiokande
    - KamLAND
- Dark matter detector
    - XMASS
- KAGRA prototype
    - CLIO

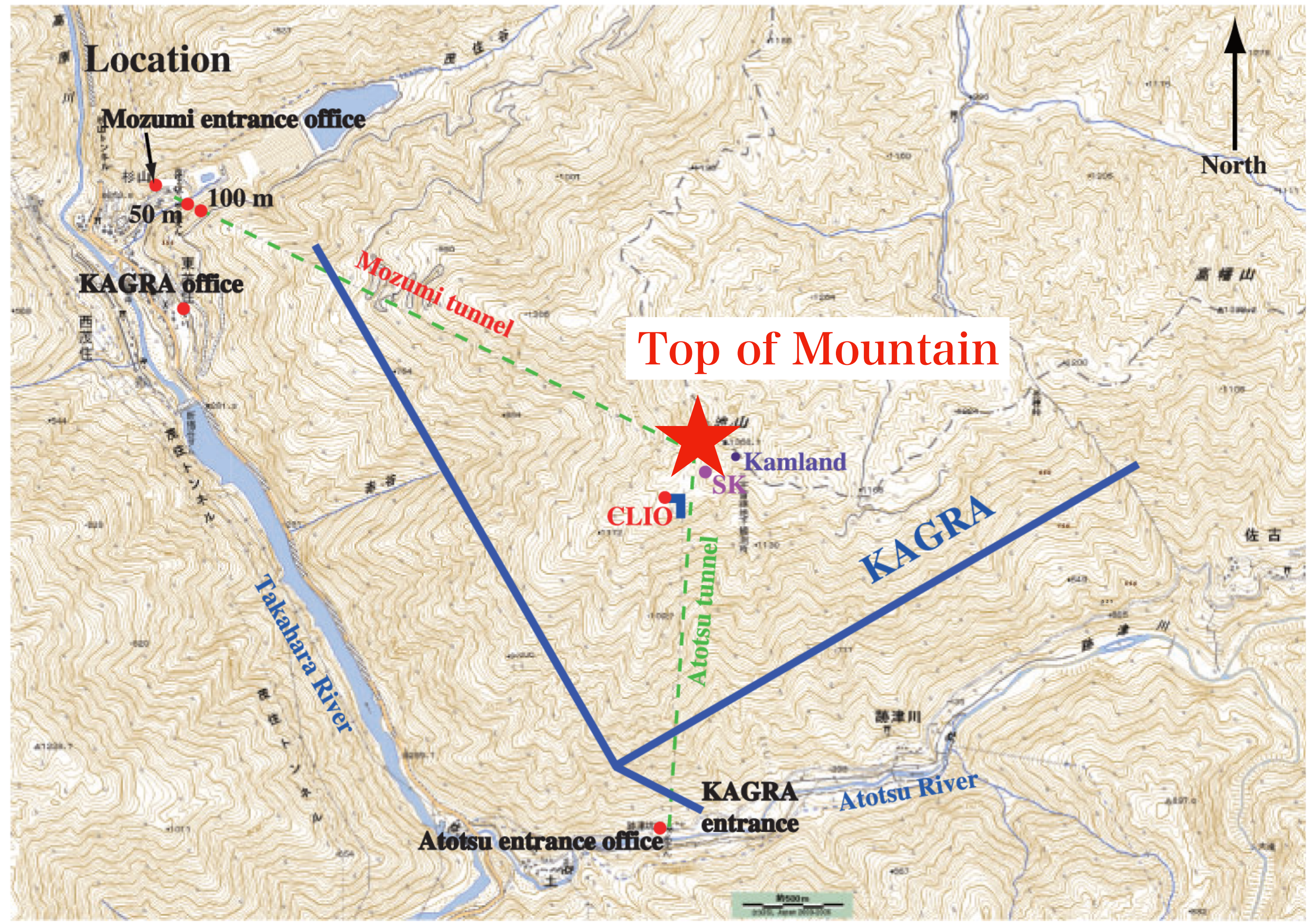
KAGRA Tunnel
Entrance

Kamioka
300 km from Tokyo

Tokyo

Why underground



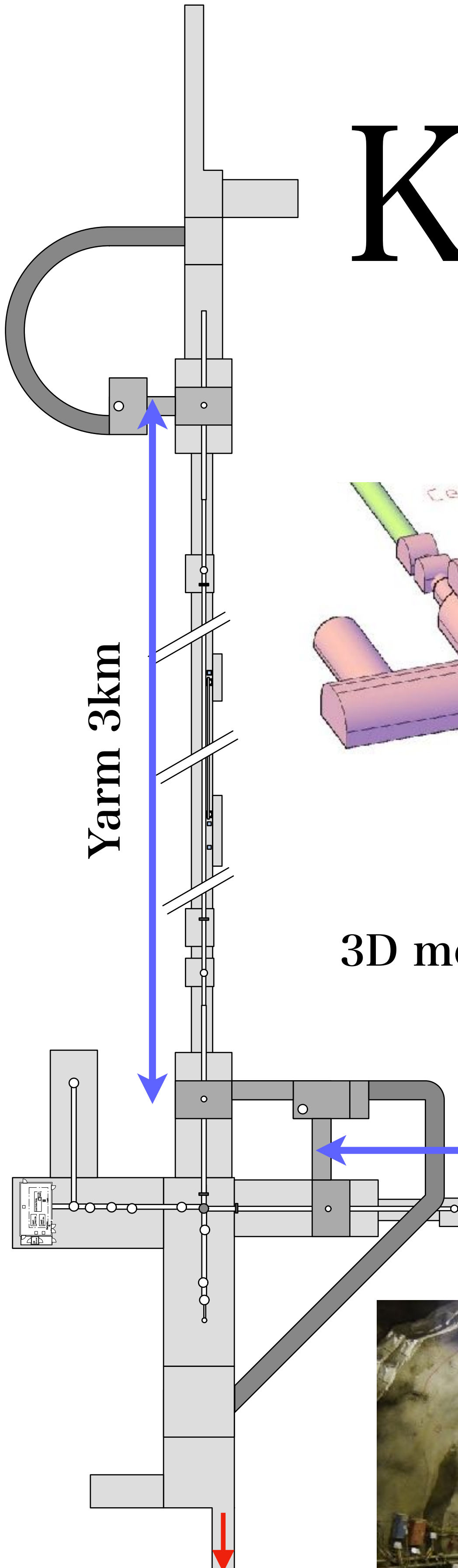


- Seismic motion in **underground** is 1/100 of that in city (Kashiwa).
- Seismic motion in non-city (Atotsu & Mozumi) is as large as that in city above 10Hz.
- Seismic motion at 50m inside from tunnel entrance is as small as in **underground**.
- Exp. rooms of KAGRA are inside more than 200m from surface of the mountain.

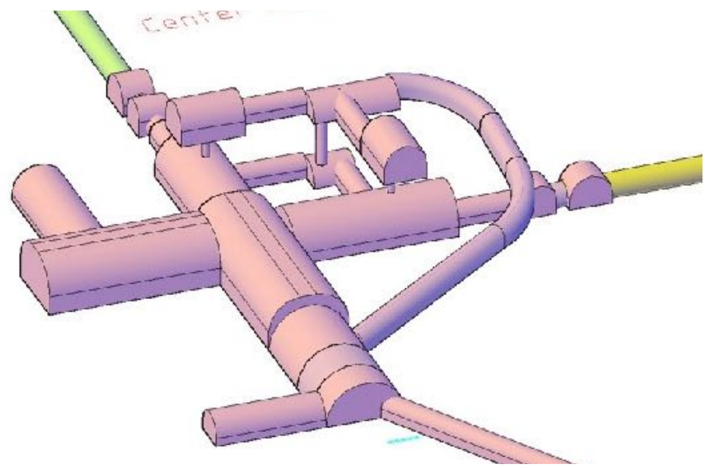
Construction of KAGRA: an underground gravitational-wave observatory

Progress of Theoretical and Experimental Physics, Volume 2018, Issue 1, 1 January 2018, 013F01, https://doi.org/10.1093/ptep/ptx180

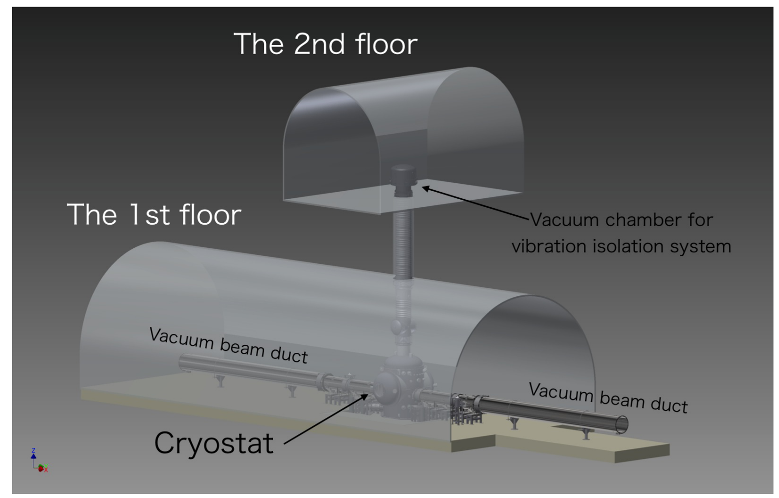
KAGRA tunnel



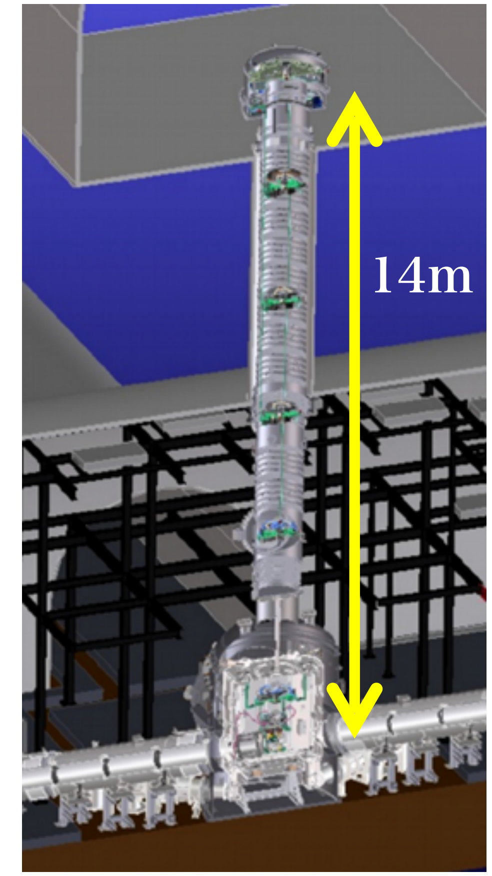
KAGRA Tunnel Entrance



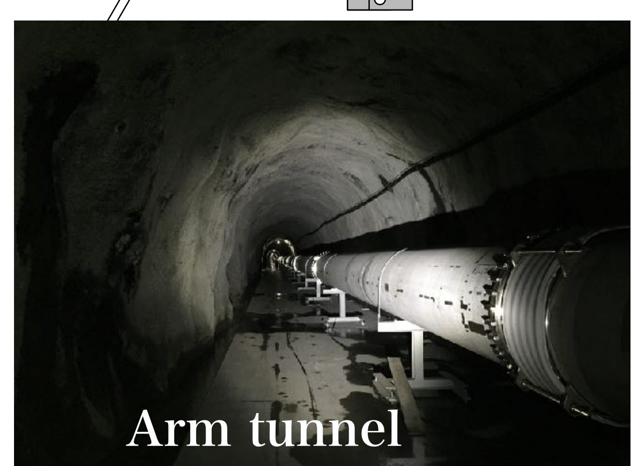
3D model of Center area



Two layers structure for a test mass suspension



- Total length：7,694m (Arm tunnels 6,000m, Experiment rooms 817m, Access tunnels 880m).
- Total volume：146,000m^3.
- Method：NATM(New Austrian Tunneling Method).
- Total number of blasting: 2,952.
- Total amount of fire powder: 518,318kg
- Company：Kajima corporation.
- Period of the construction：2012/5-2014/3. ~22months.



Why use cryogenic

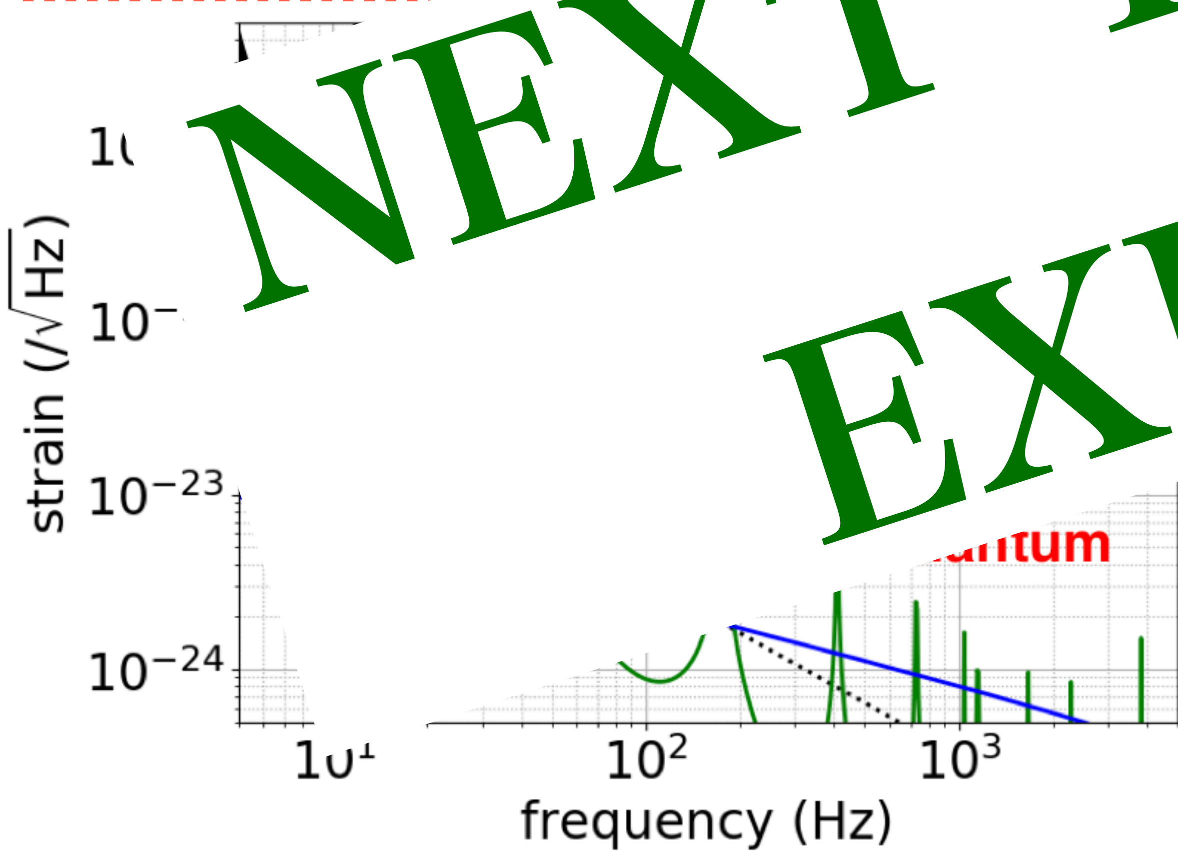
- Thermal noise is a fundamental noise in interferometric GW detectors.
- Power of the thermal noise is proportional to temperature.
- To reduce the thermal noise, we developed a method to cool a mirror and its suspension system.
    - Even the same dissipation, power of the thermal noise is 1/15 at 20K.
    - In this case, amplitude is about 1/4.
- Additional merits;
    - Smaller thermal lensing effect
    - Lower risk of param

- Always heating up mirrors by laser absorption.
    - Heat transfer method is necess
    - Thermal conduction i … or cooling.
        - Mirrors … w

ead

d so on.

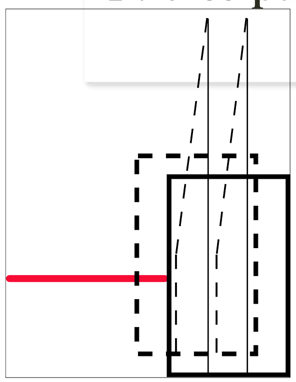
NEXT TALK will EXPLAIN



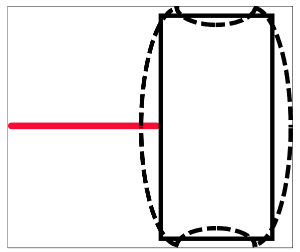
KAGRA estimated sensitivity

ψ

mplitude of thermal noise
T: temperature
Φ: dissipation (inverse of mechanical Q)



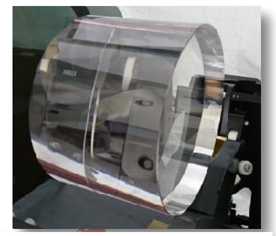
Suspension thermal noise



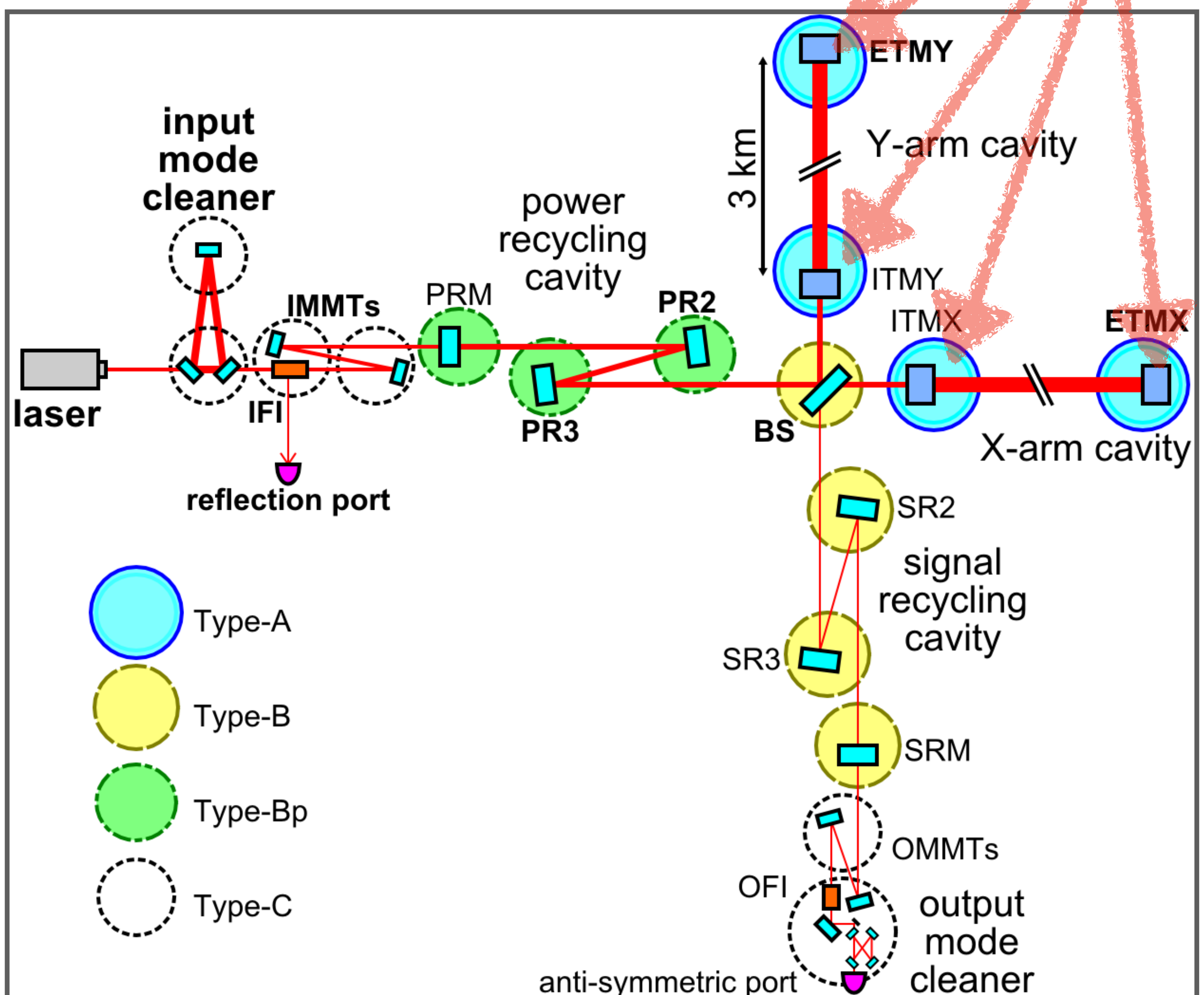
Mirror thermal noise

Idea is simple. Realization is difficult. We tried it.

Interferometer Configuration
Dual Recycled Fabry-Perot Michelson



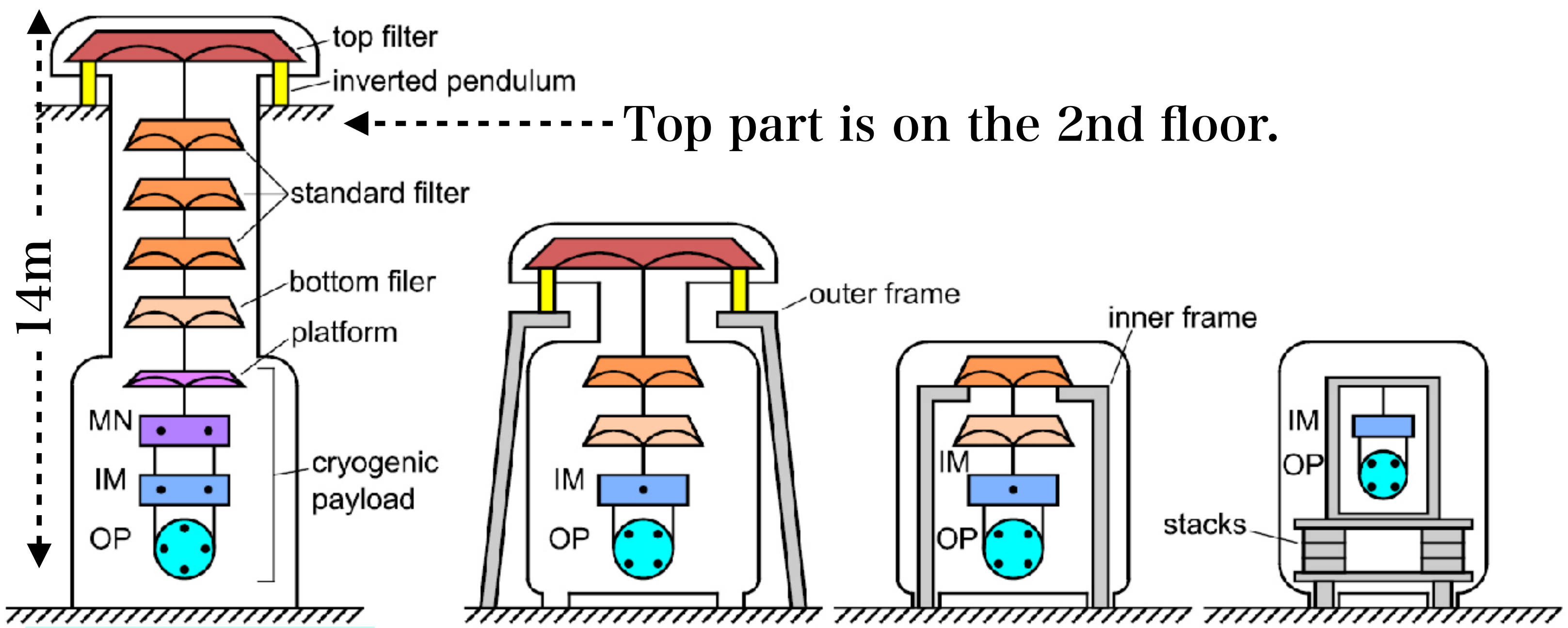
20K sapphire



Interferometer configuration of KAGRA

- Dual Recycled Fabry-Perot Michelson
  - Similar to Advanced LIGO and Advanced VIRGO.
  - Power recycling and signal recycling.
  - 3km Fabry-Perot cavities with Finesse of 1530.
- Laser
  - 1064nm, continuous wave.
  - Power: 2W -> 40W(2018) -> 140W
- **Differences from LIGO & VIRGO**
  - Underground site: Seismic noise reduction.
  - Cryogenic: Thermal noise reduction.
    - Cool test masses and suspension systems about 20K.
    - Test mass: Sapphire mirror (Dia. 220×150, 23kg)

Mirror Suspension System

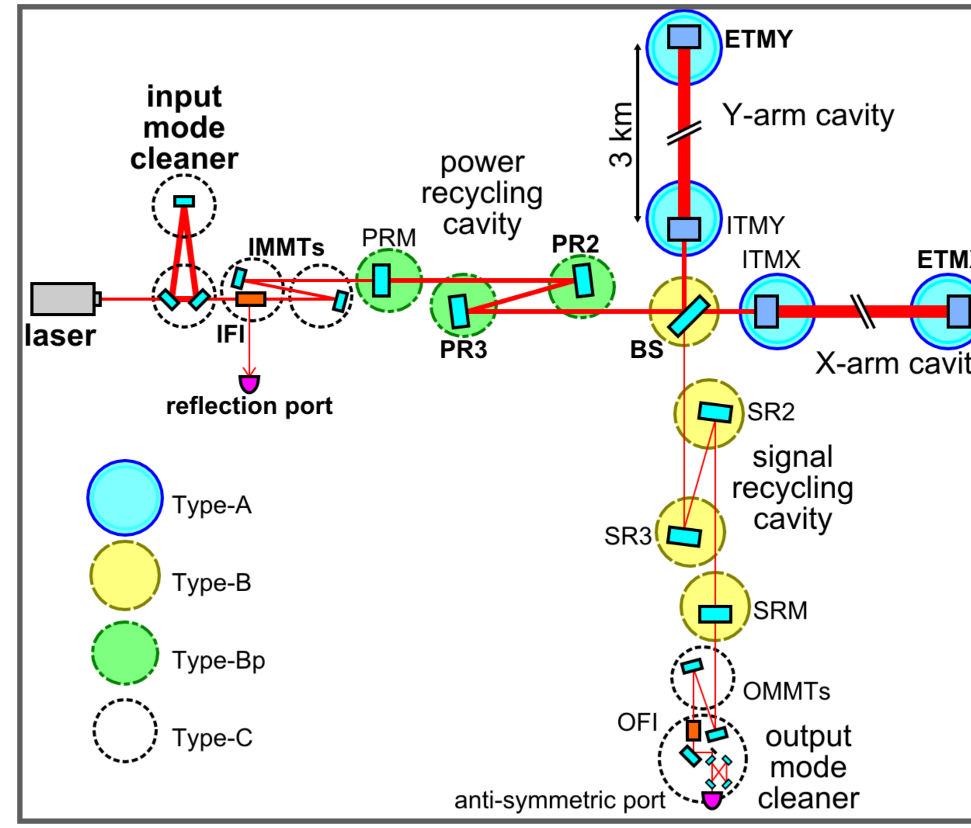


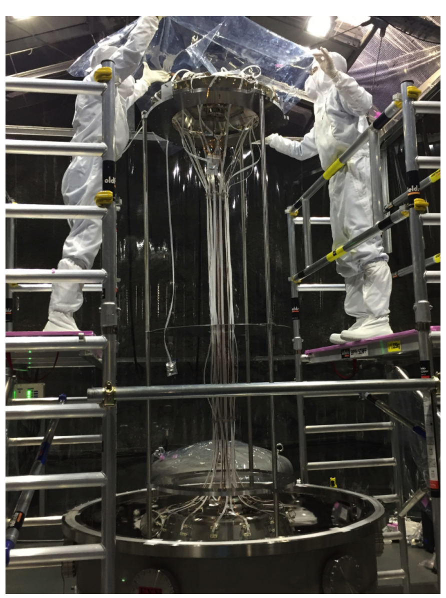
Type-A
for Test mass
14 m height
Cryogenic

Type-B
for BS and SRs

Type-Bp
for PRs

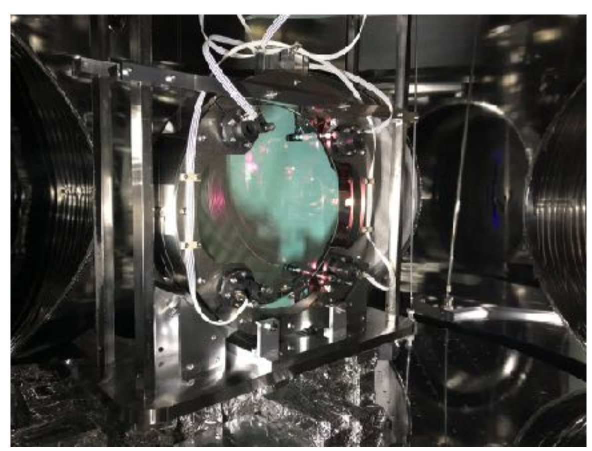
Type-C
for small optics





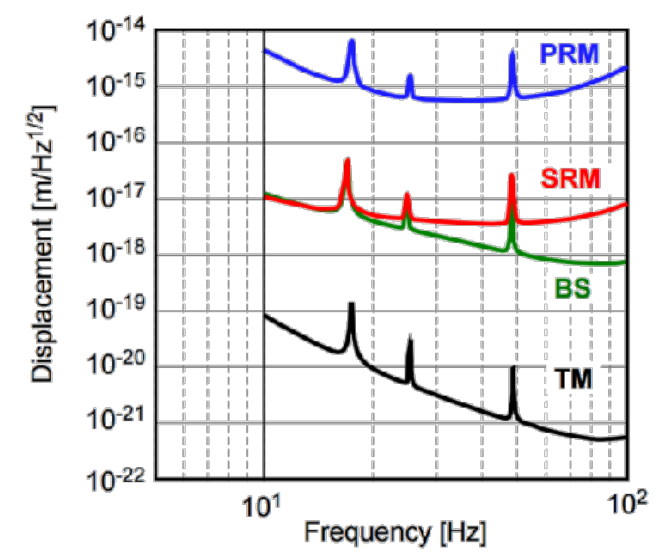
Type-A

Cryogenic payload



Beam splitter
Fused silica

Type-B



Req. of displacement of mirrors

Vacuum system

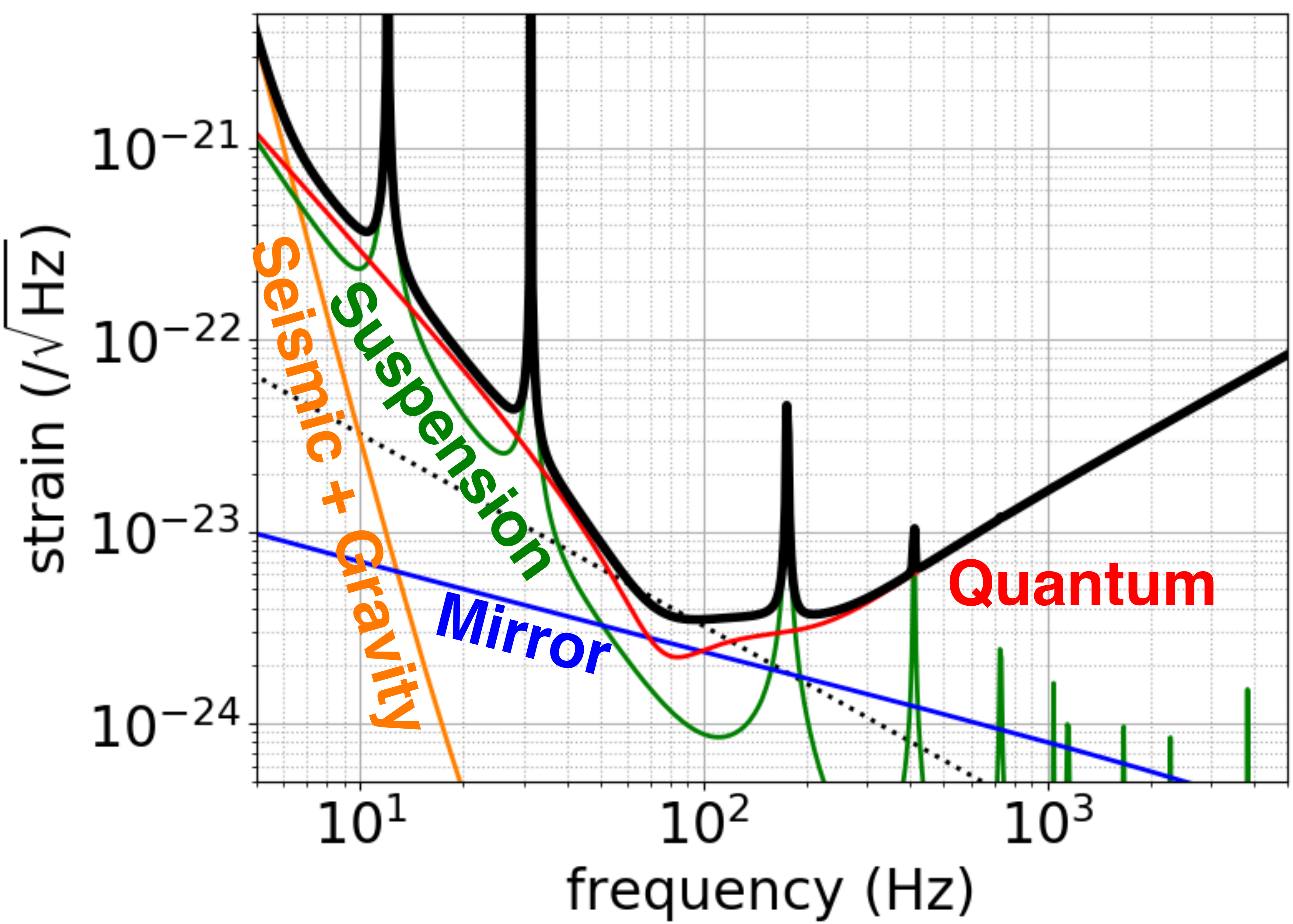
Vacuum chamber for BS
Achieved pressure
10^{-5} Pa

Cryostat for a sapphire mirror
(not connected to the 2nd floor)
Achieved pressure
10^{-5} Pa in cryogenic to 10^{-4} Pa in room T.

3km beam tube
(diameter of 800)
Achieved pressure
10^{-6} Pa (req. 10^{-7} Pa)

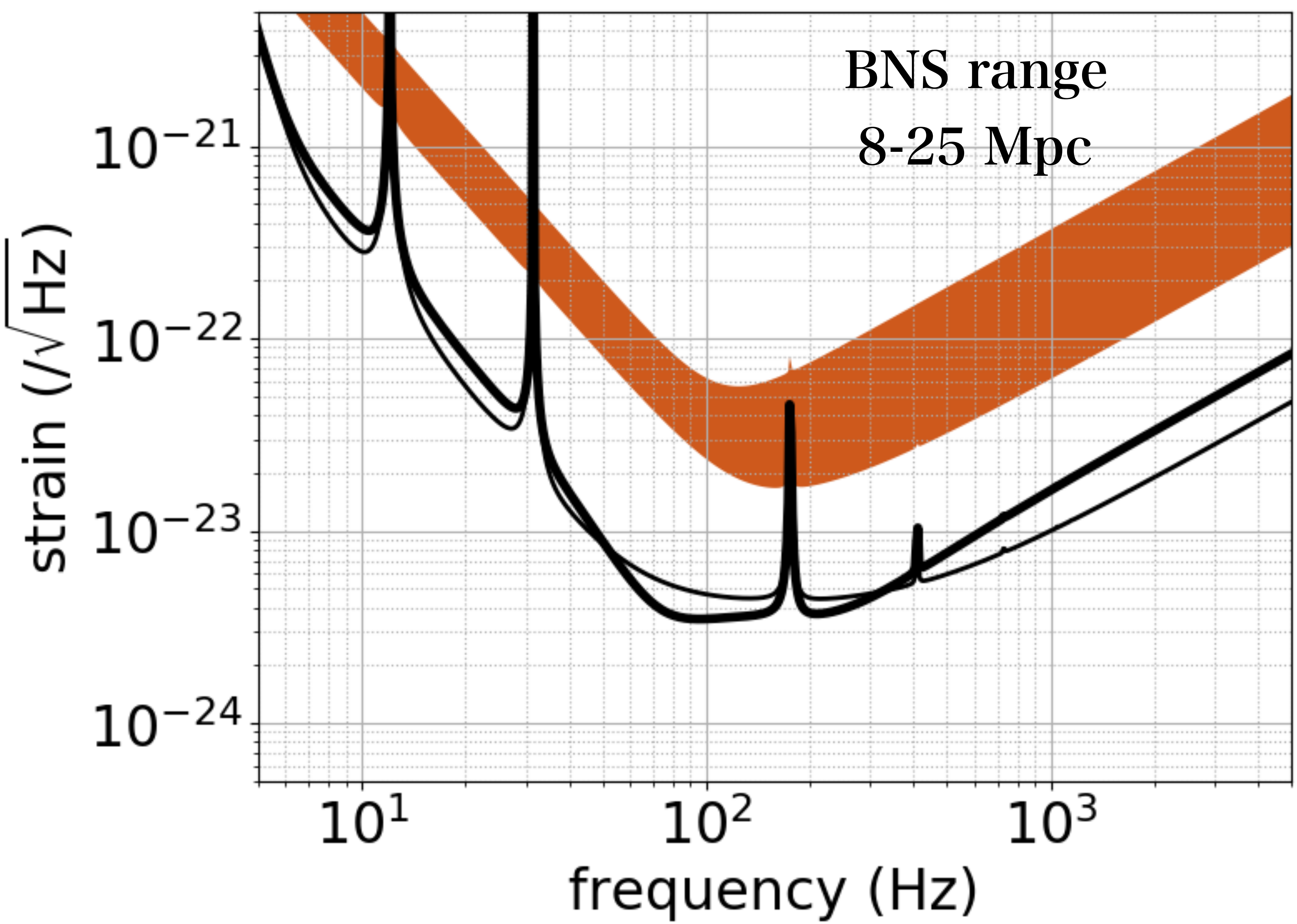
Design Sensitivity

Binary neutron star (BNS) range 153 Mpc



Target Sensitivity for O3

Aims for 10-30 W input, BRSE with R_SRM = 70%



Contribution to the O3

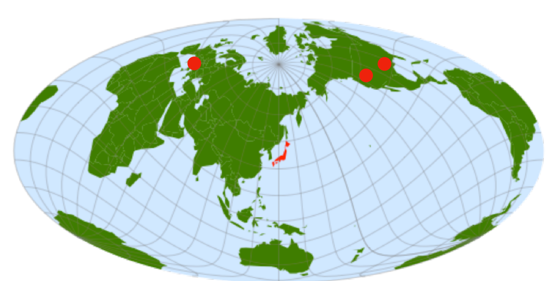
How much improvement for sky localization

Sky localization is a key measurement to proceed astronomy and science.

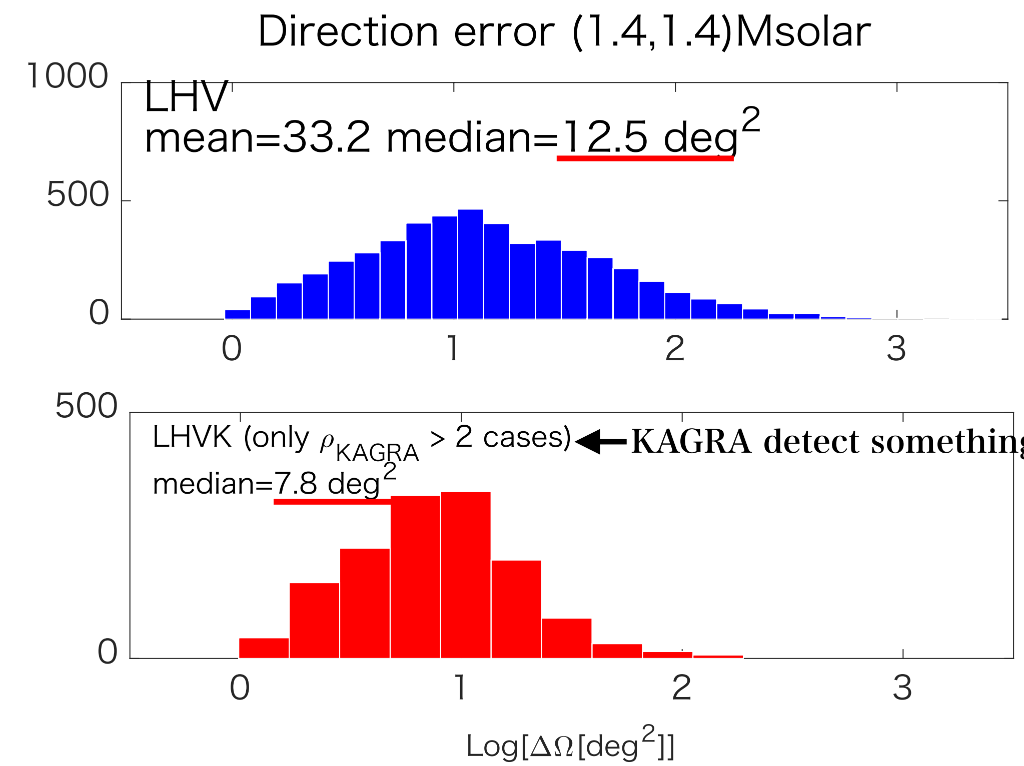
Case study

Source
Binary Neutron stars at 40Mpc (like GW170817)
Uniform distribution for sky location, inclination, polarization
5000 realizations

Sensitivity
BNS range (average observable distance with SNR=8):
KAGRA: 10Mpc
LIGO: 120Mpc (MidHighLateLow)
Virgo: 60Mpc (EarlyHighMidLow)



Method: Fisher matrix



$$\frac{\langle \Delta\Omega_{LHVK}(\rho_{KAGRA} > 2)\rangle}{\langle \Delta\Omega_{\rm LHV}\rangle} = 0.62$$

- For BNS sources at 40Mpc, if BNS range of KAGRA is 10Mpc, about 28% of events can be detected by KAGRA with SNR > 2.
- If that happens, median value of localization error by LHVK is about 40 % smaller compared with all sky LHV cases.
- This result is derived by both Nested sampling and Fisher matrix.
- For some limited number of events, the results are confirmed by LALInference.

- We thus conclude that if KAGRA's sensitivity is 10Mpc, there are cases in which KAGRA can derive good scientific results.

10Mpc observation range has chance to 40% improvement

H. Tagoshi
JGW-G1808260

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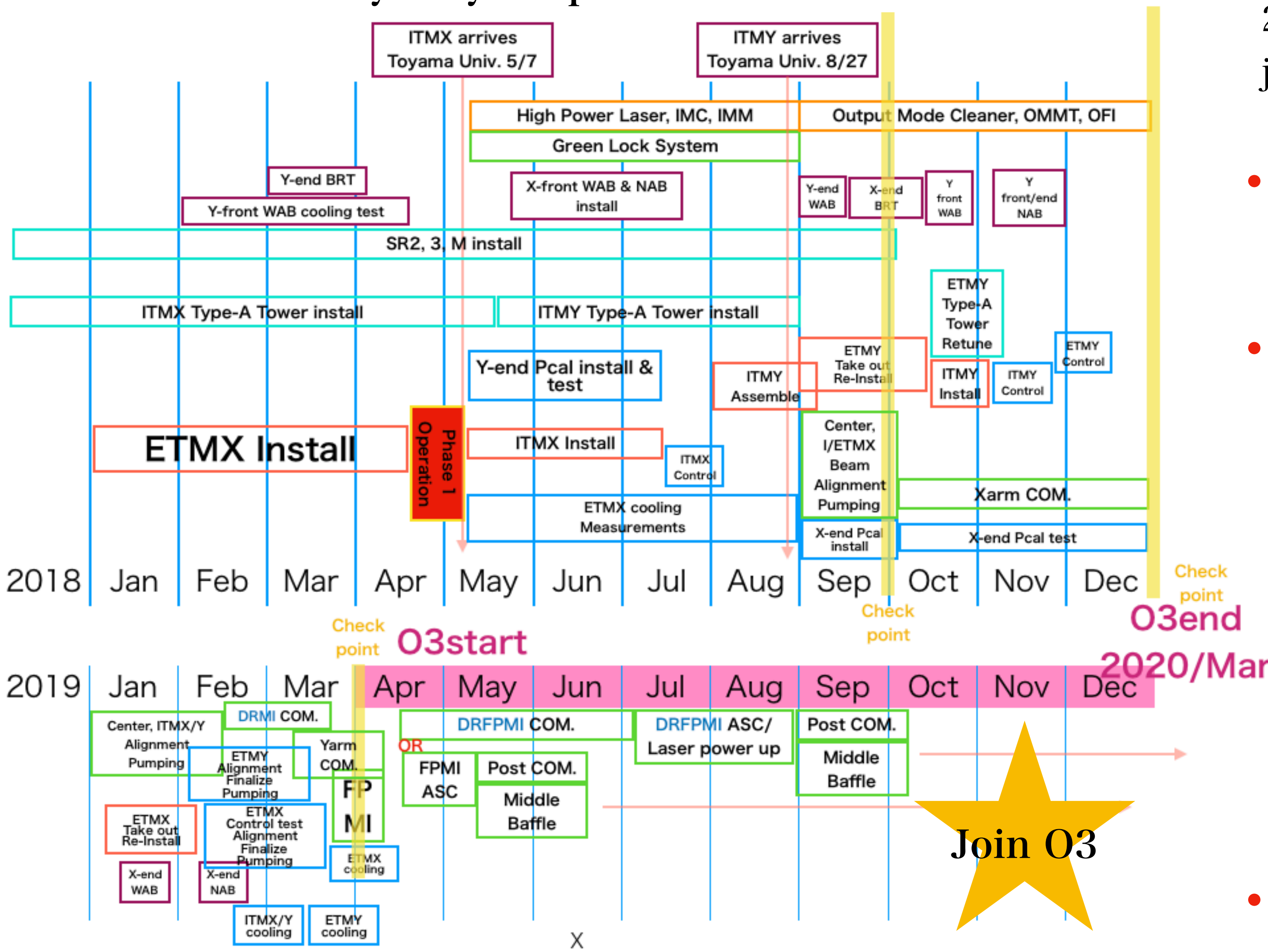
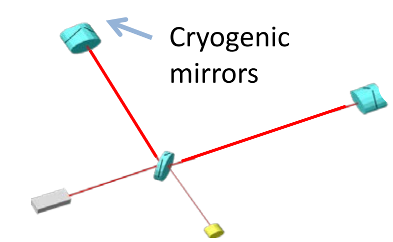
Progress in FY2018

Ver very very simplified KAGRA schedule



- We have completed bKAGRA Phase1 in May 2018. After then, we conducted many things to join O3 as early as possible.

- bKAGRA Phase1
  - 3km Cryogenic Michelson Interferometer



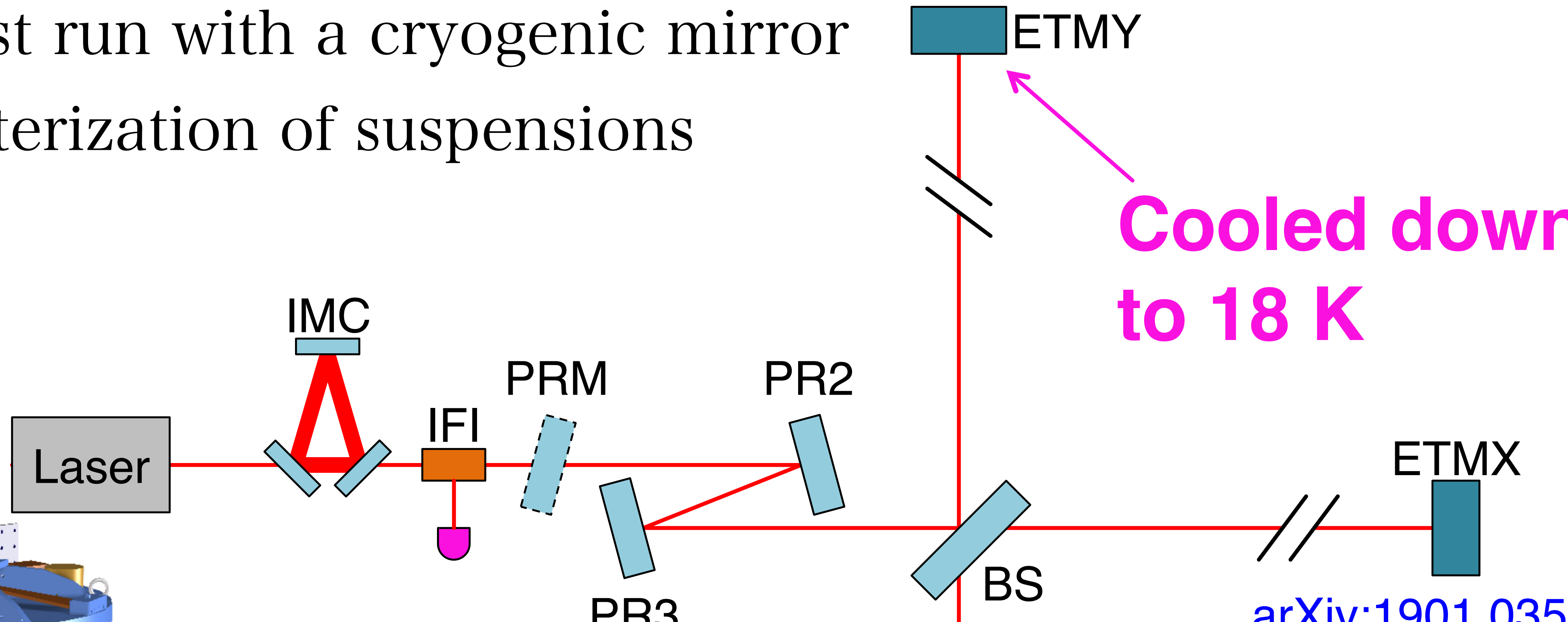
- Installation …Done!!
  - High power laser
  - Green lock system
  - Sapphire test masses
  - Calibration system
  - All other optics
  - Output optics
  - Optical baffles
  - Transmission beam monitor system

- Commissioning
  - X-arm 3km Fabry-Perot cavity (done)
  - DRMI (on going now)
  - Y-arm 3km Fabry-Perot cavity (start soon)
  - FPMI (start in March)
  - DRFPMI (After FPMI)

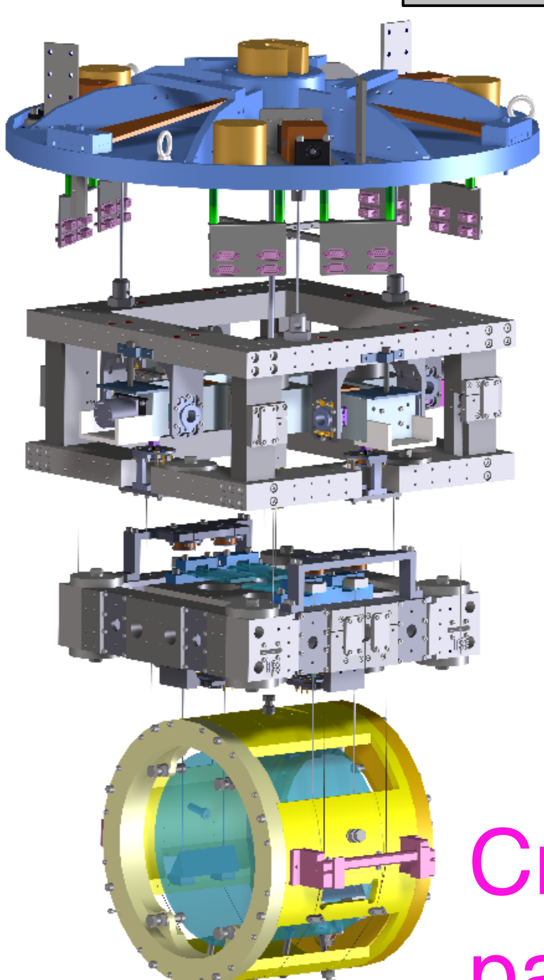
We have done on schedule!!

Phase 1 Operation

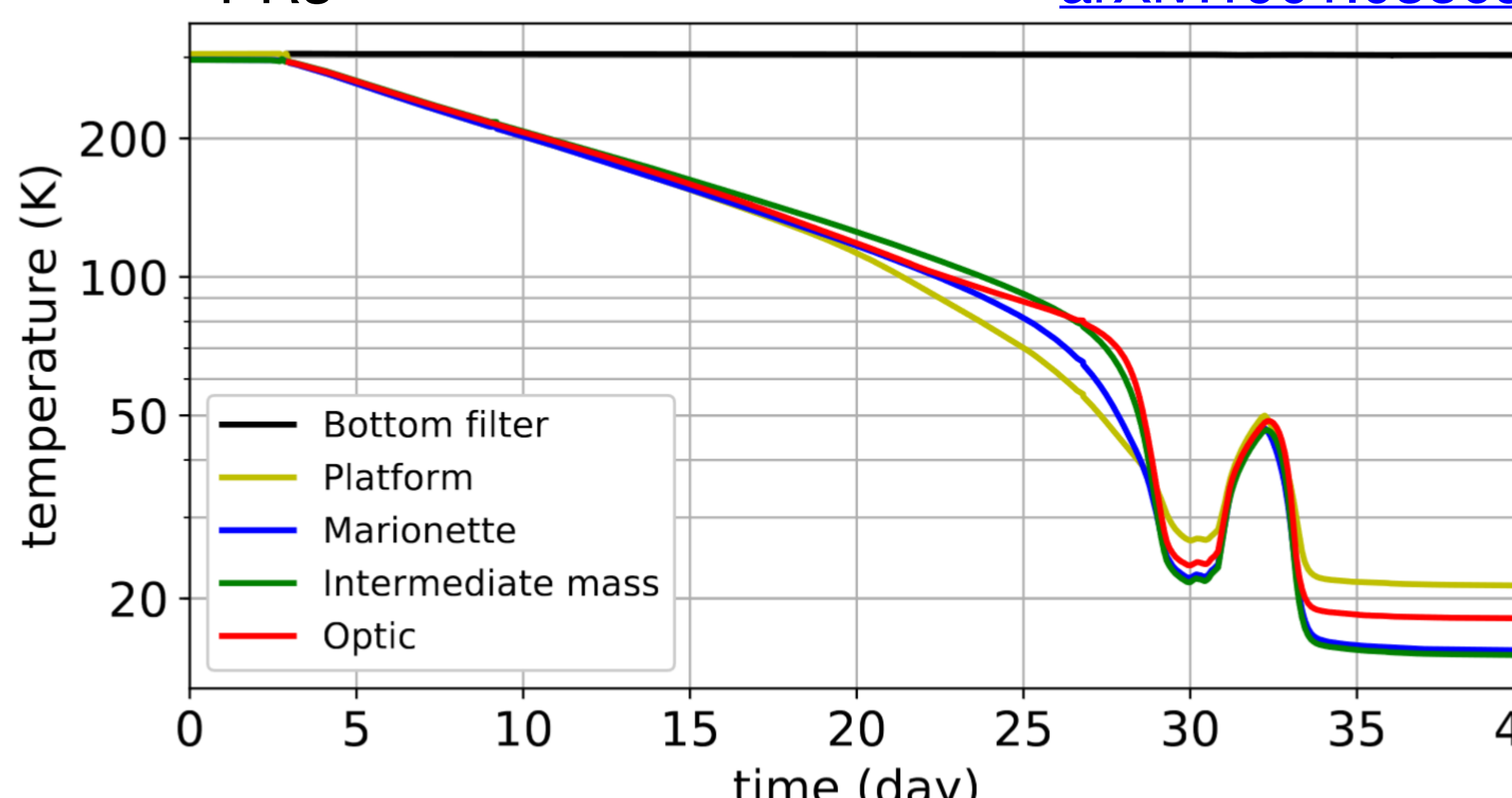
- First test run with a cryogenic mirror
- Characterization of suspensions



arXiv:1901.03569

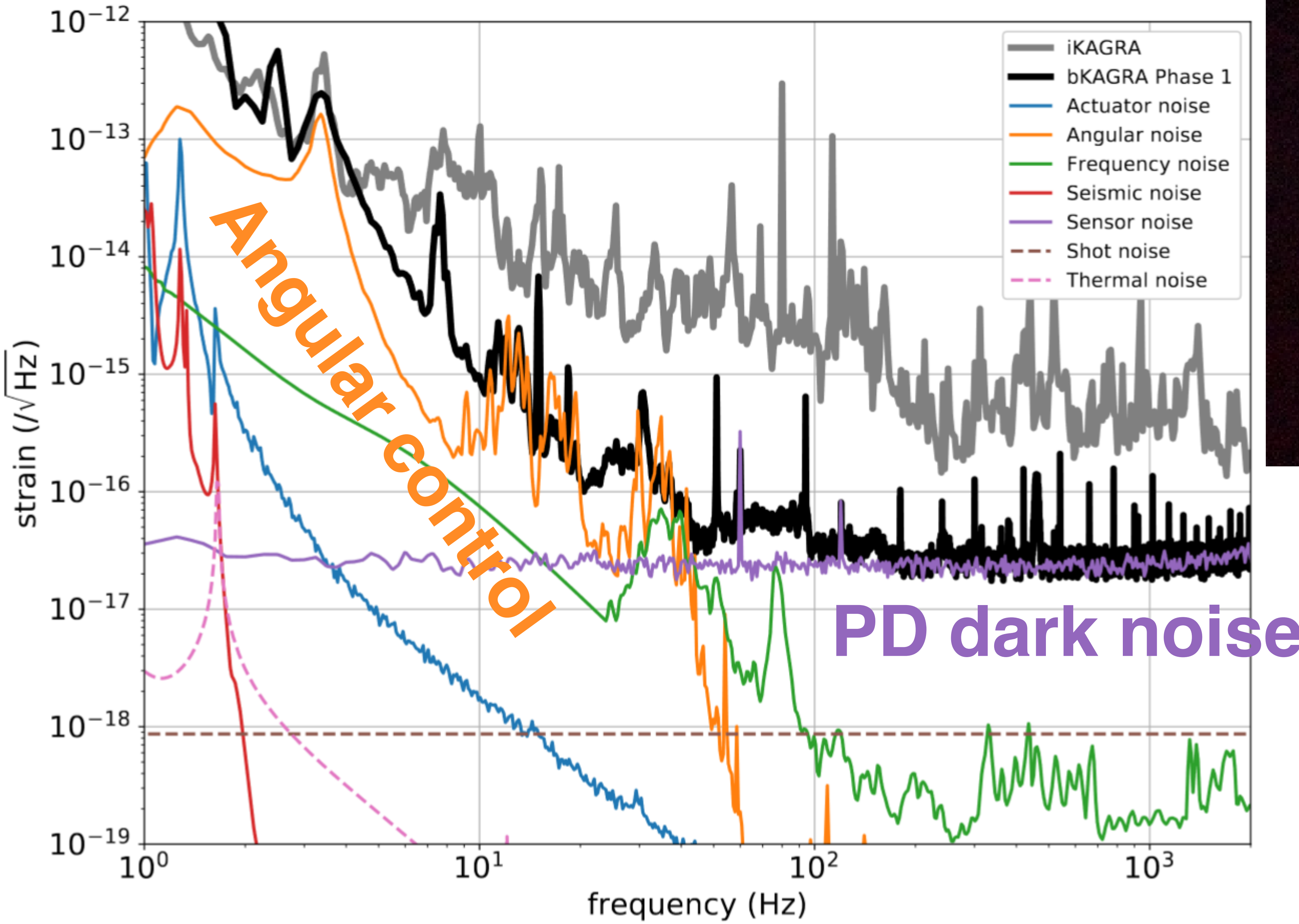


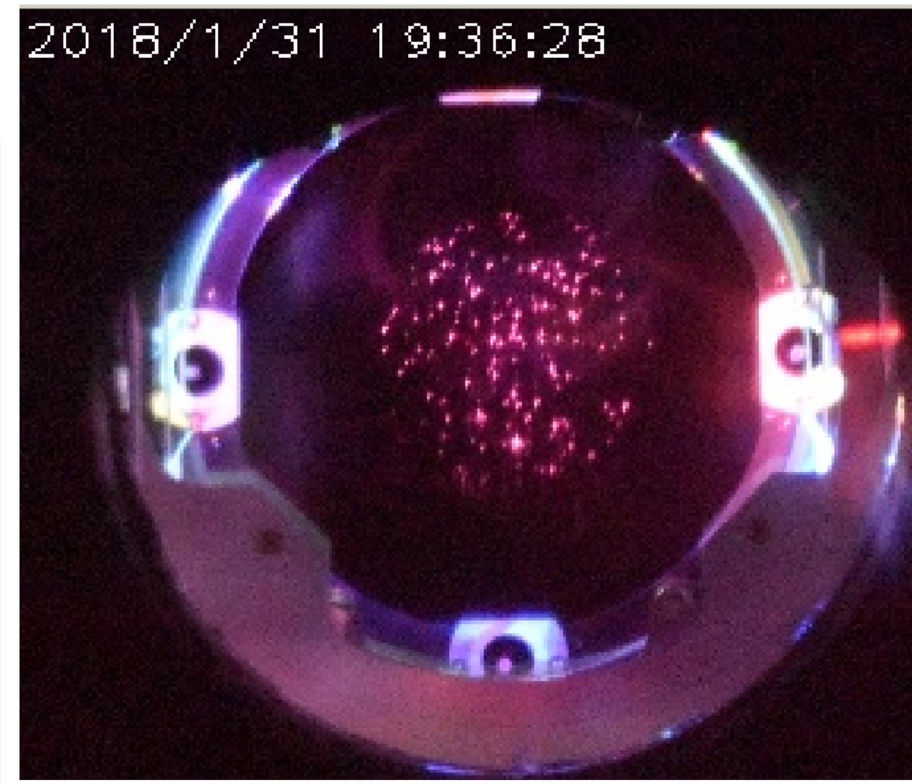
Cryogenic payload



Phase 1 Operation

- Sensitivity at 3e-17 /rtHz @ 100 Hz
- Gained experience in aligning and operating cryogenic interferometer

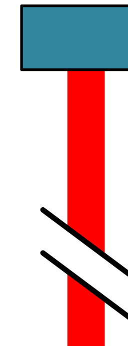




ETMY taken by telephoto camera

arXiv:1901.03569

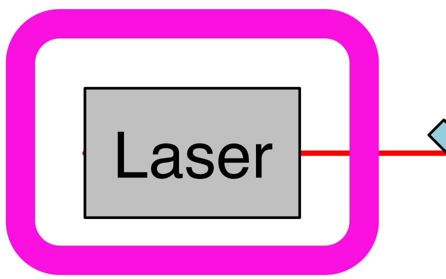
Installation Progress: High Power Laser

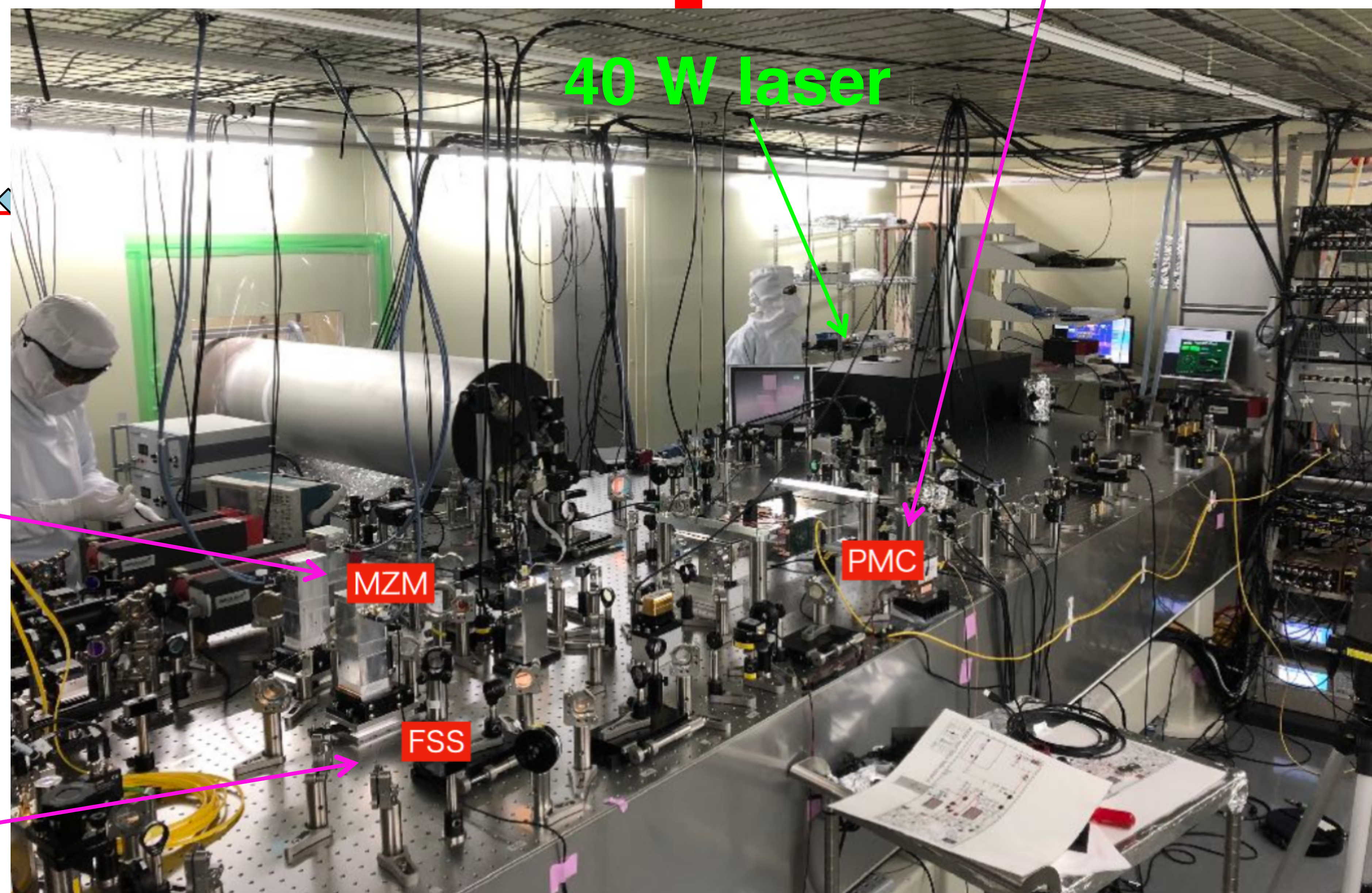


Pre-stabilized laser system fully operated at 40 W

Nov 9, 2018

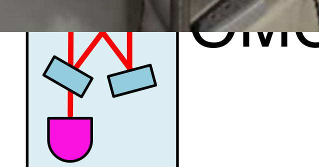
Pre-mode cleaner



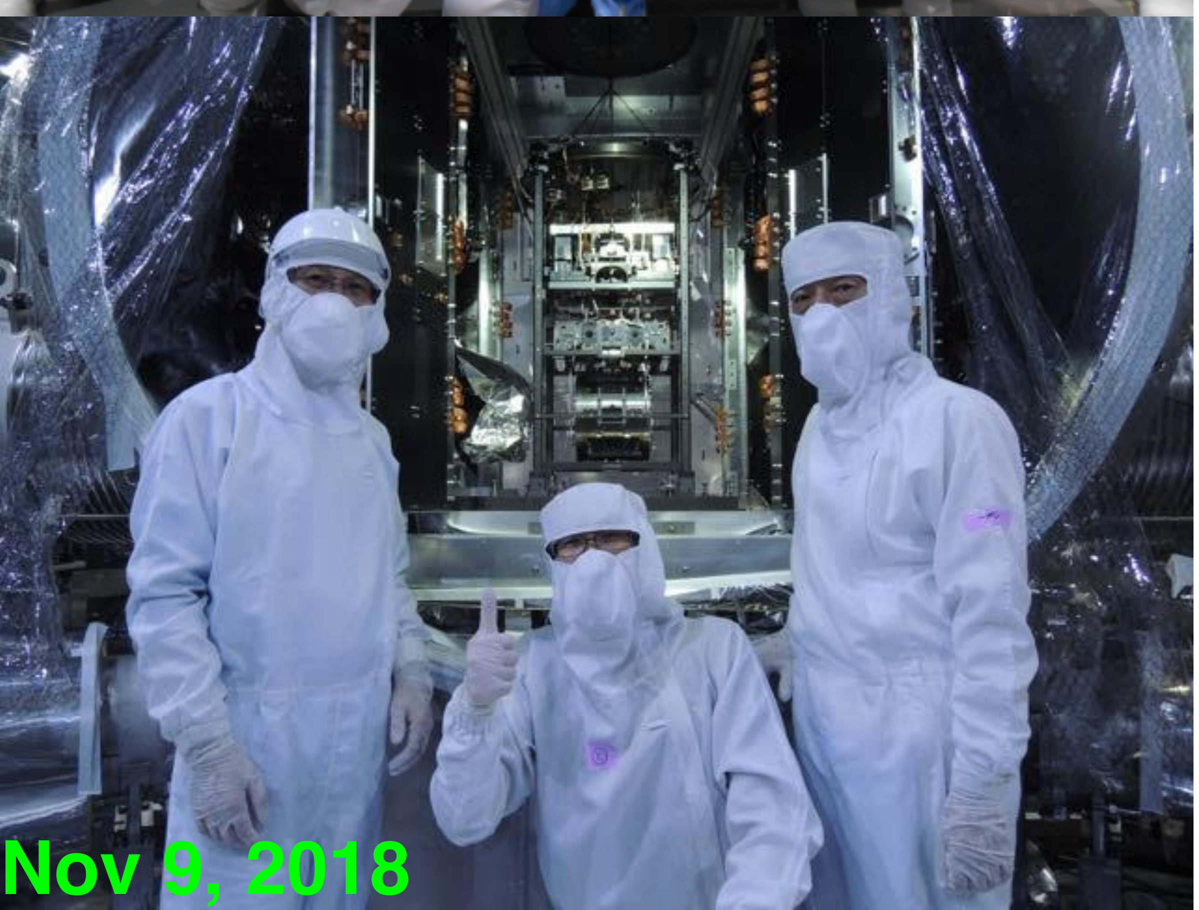


RF AM generation system for lock acquisition

Frequency reference cavity

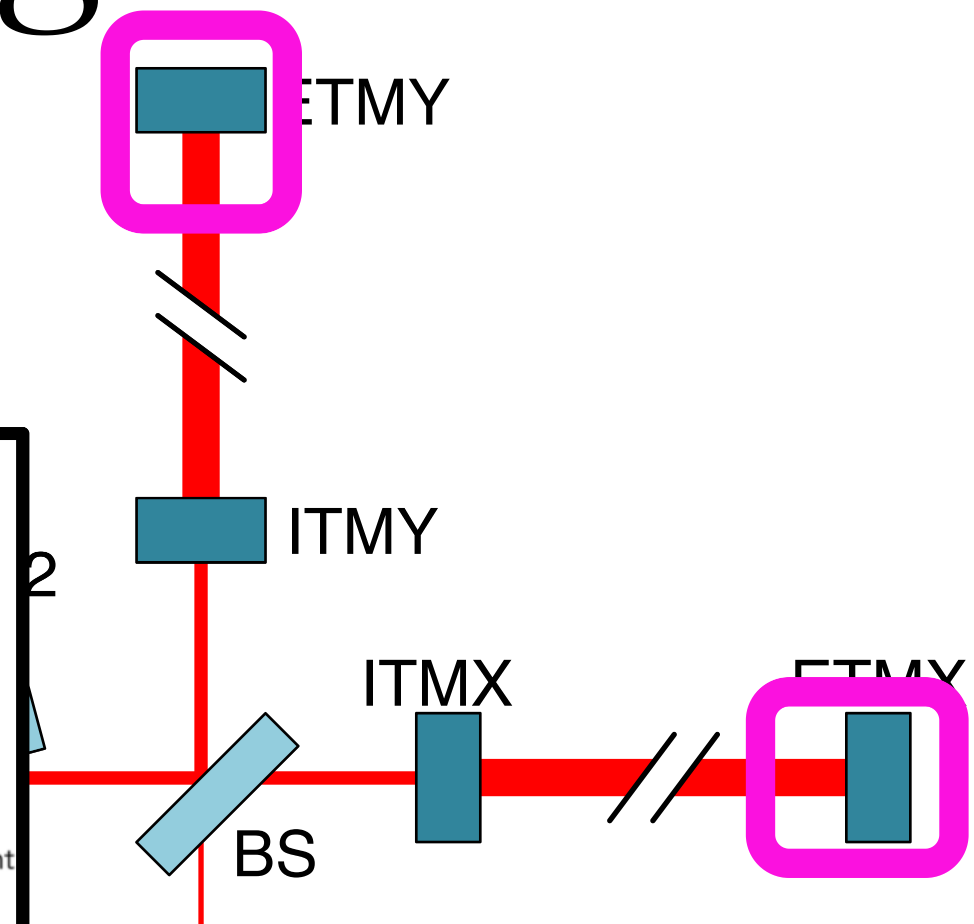


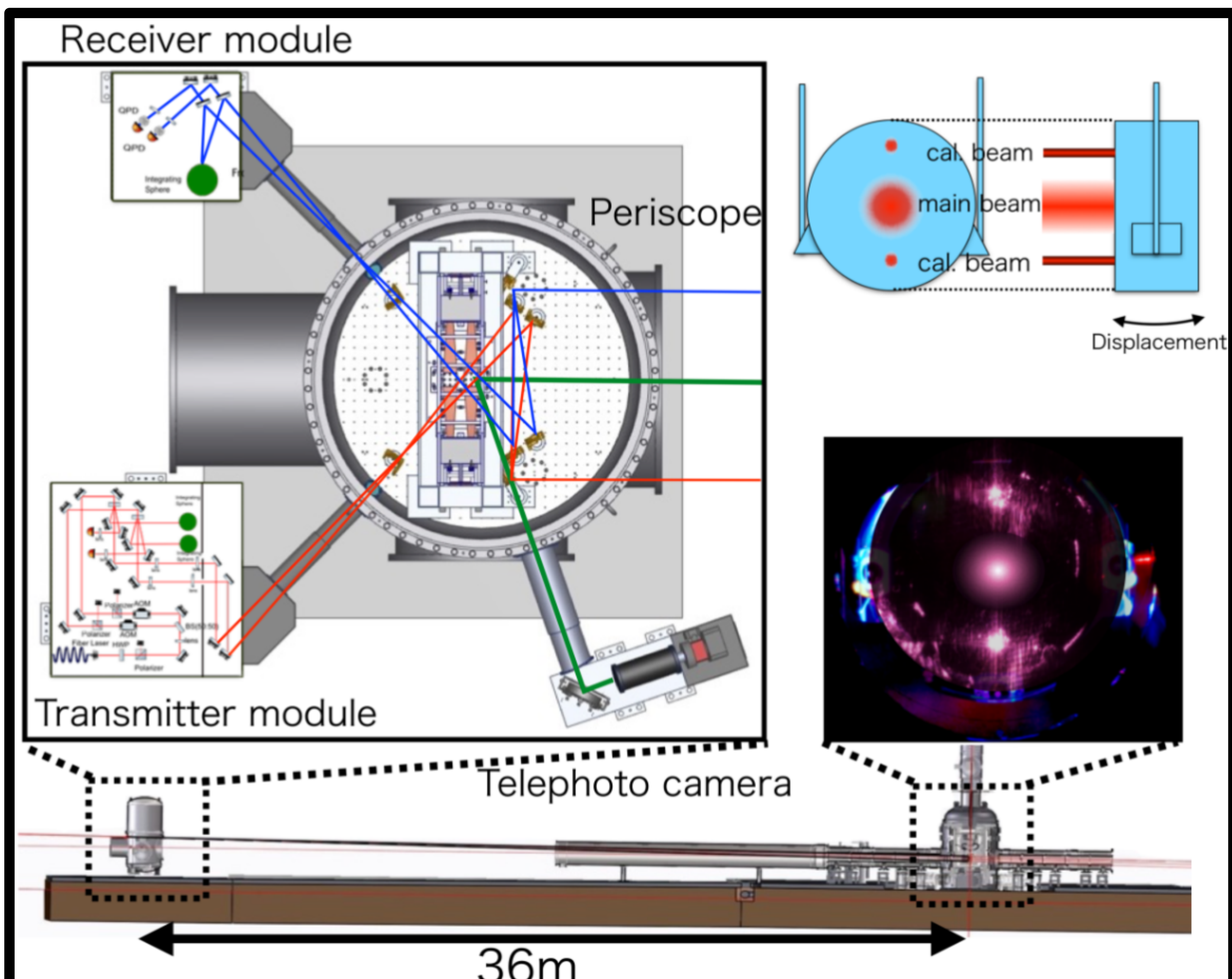
Installation Progress: Sapphire mirrors

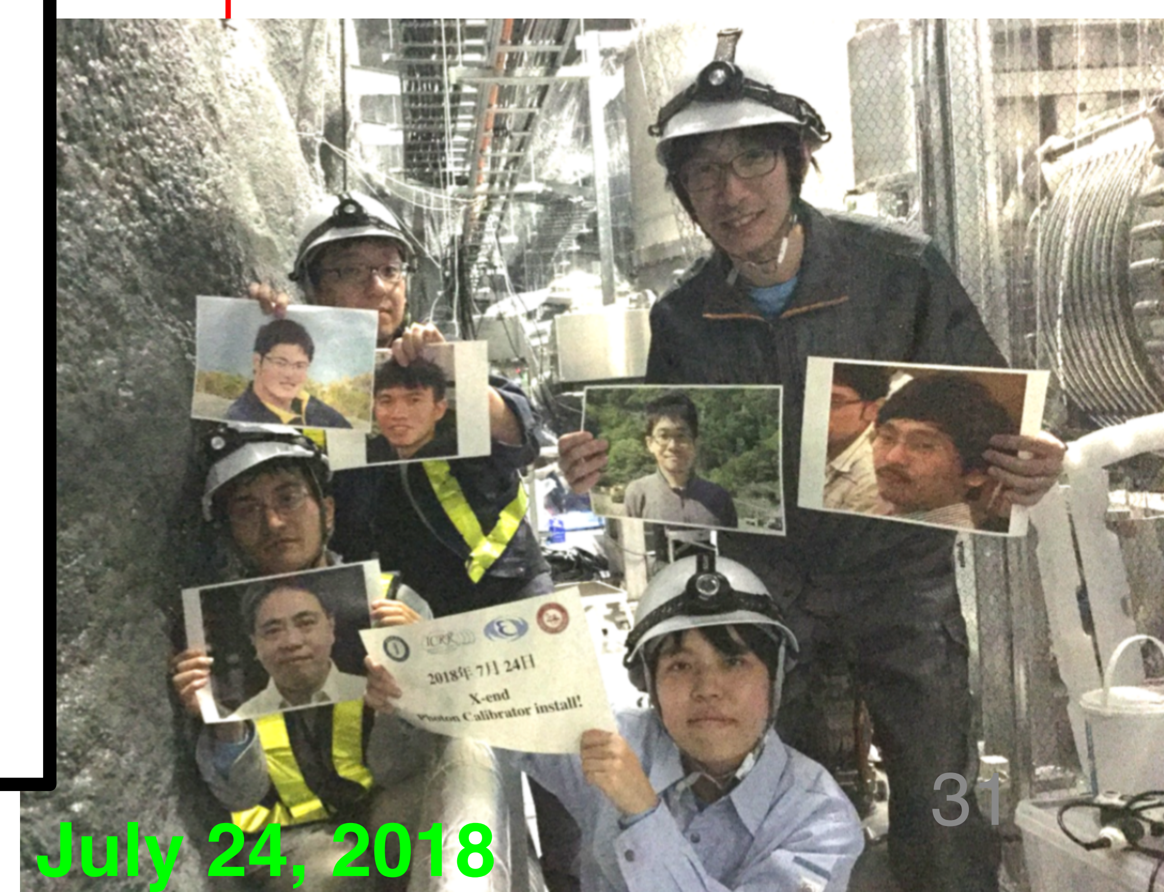


Installation Progress: PCal

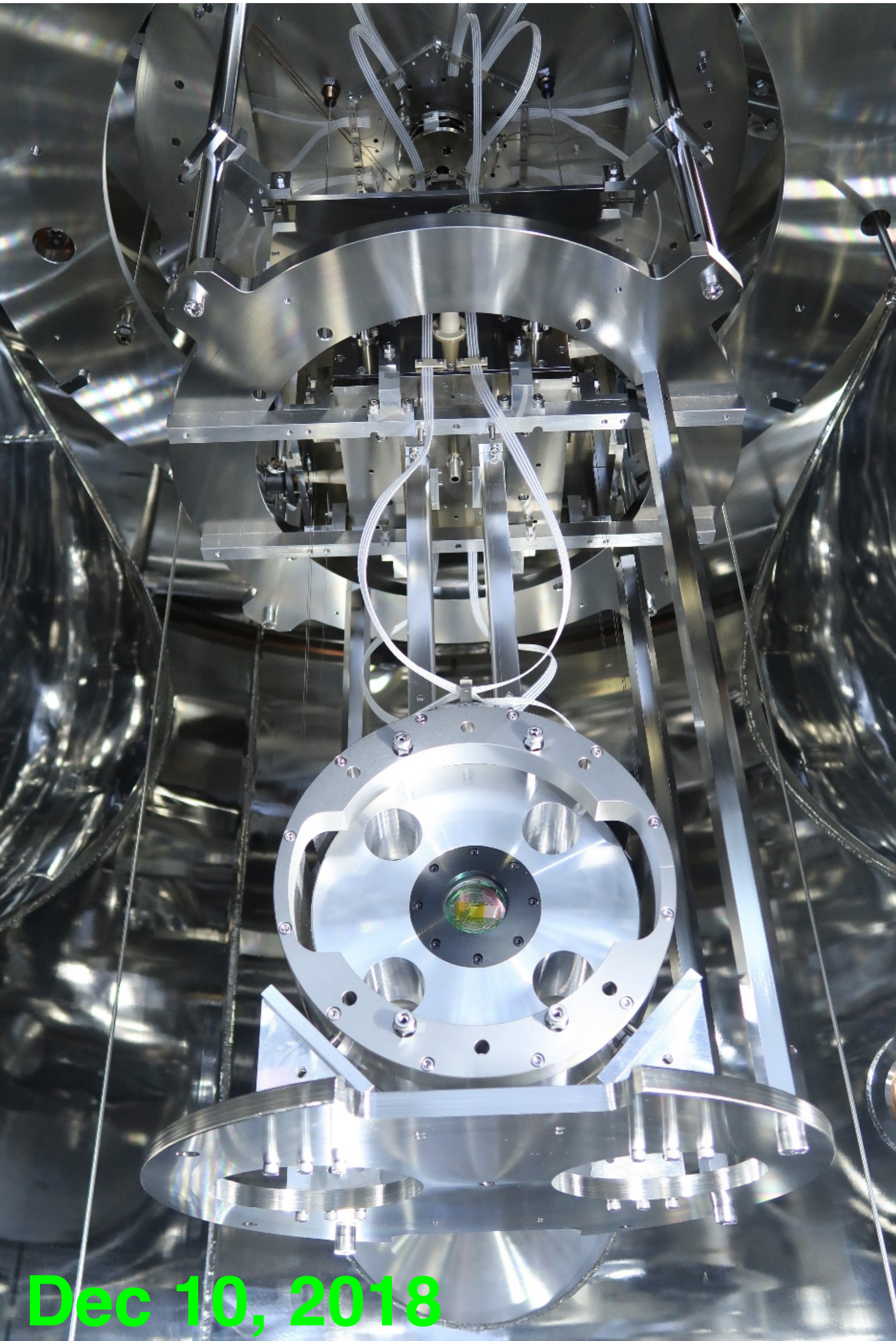
Photon calibrator installed to both ends

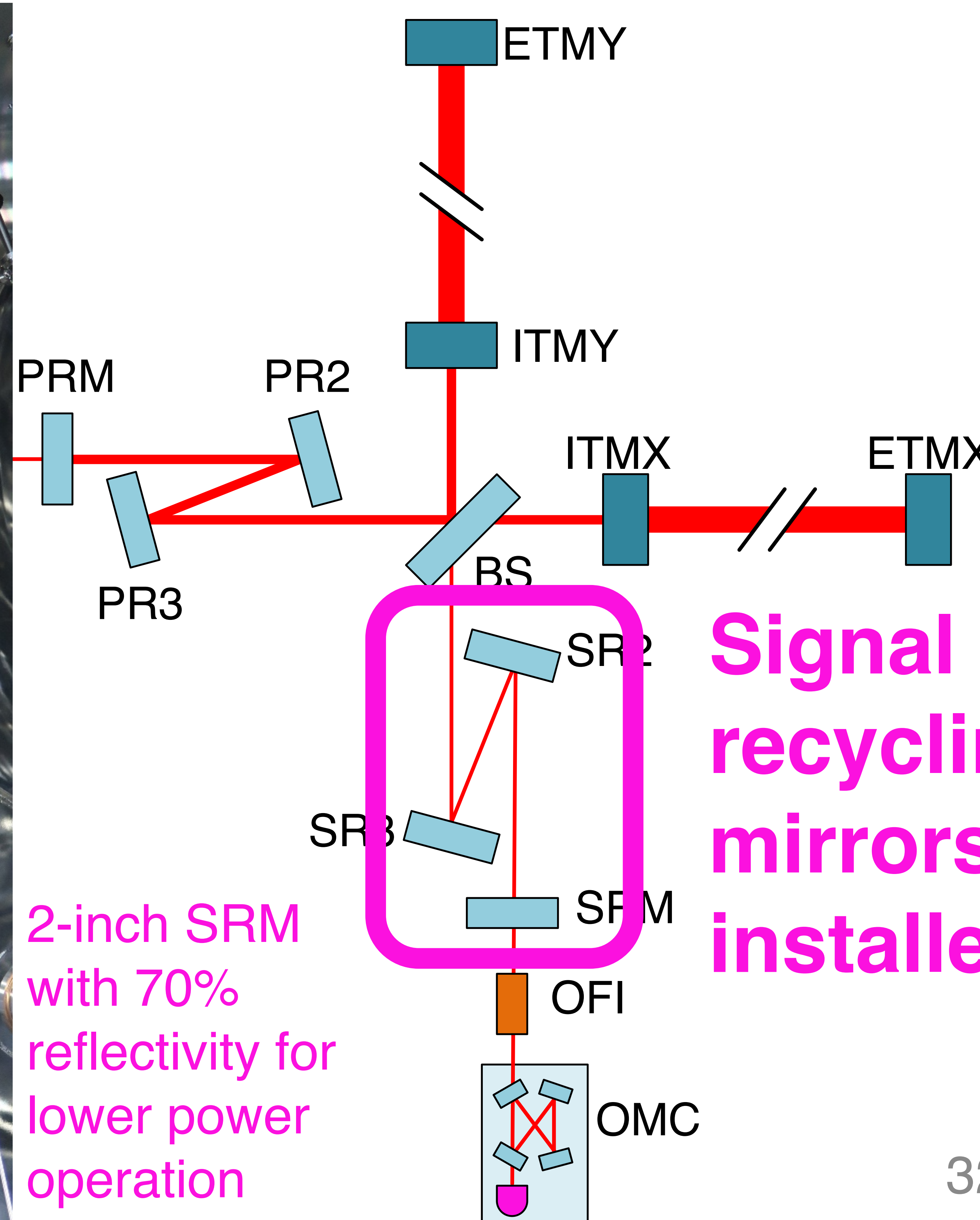






Installation Progress: SR Mirrors

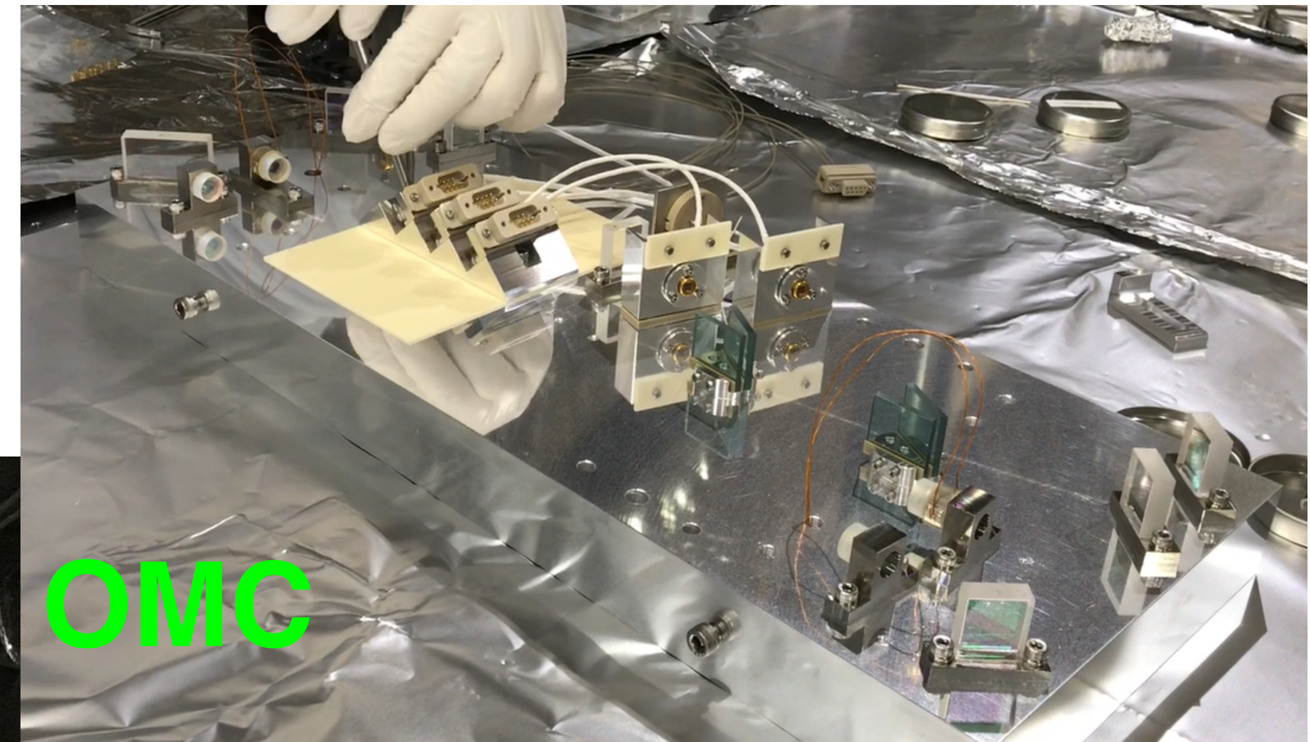


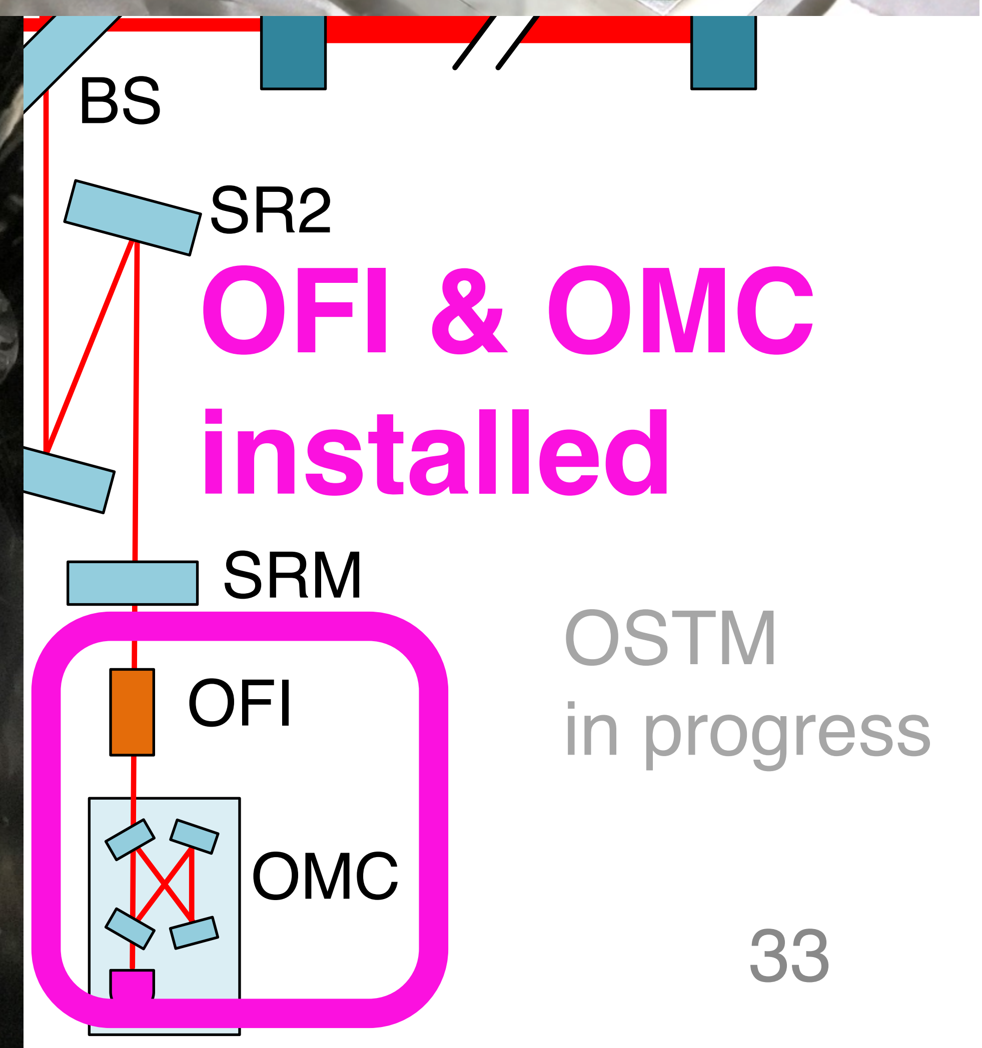


Signal recycling mirrors installed

2-inch SRM with 70% reflectivity for lower power operation

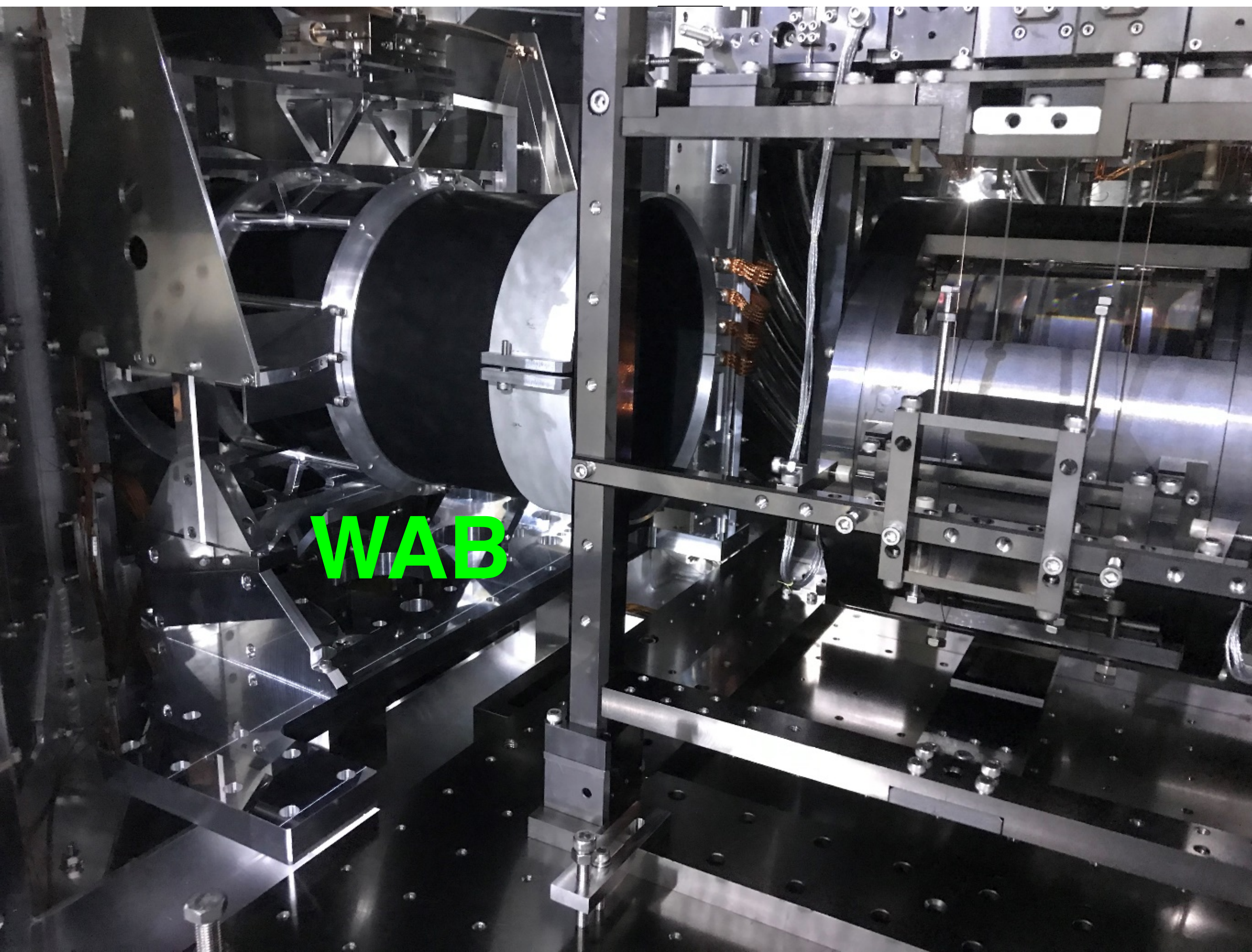
Installation Progress: Output Optics

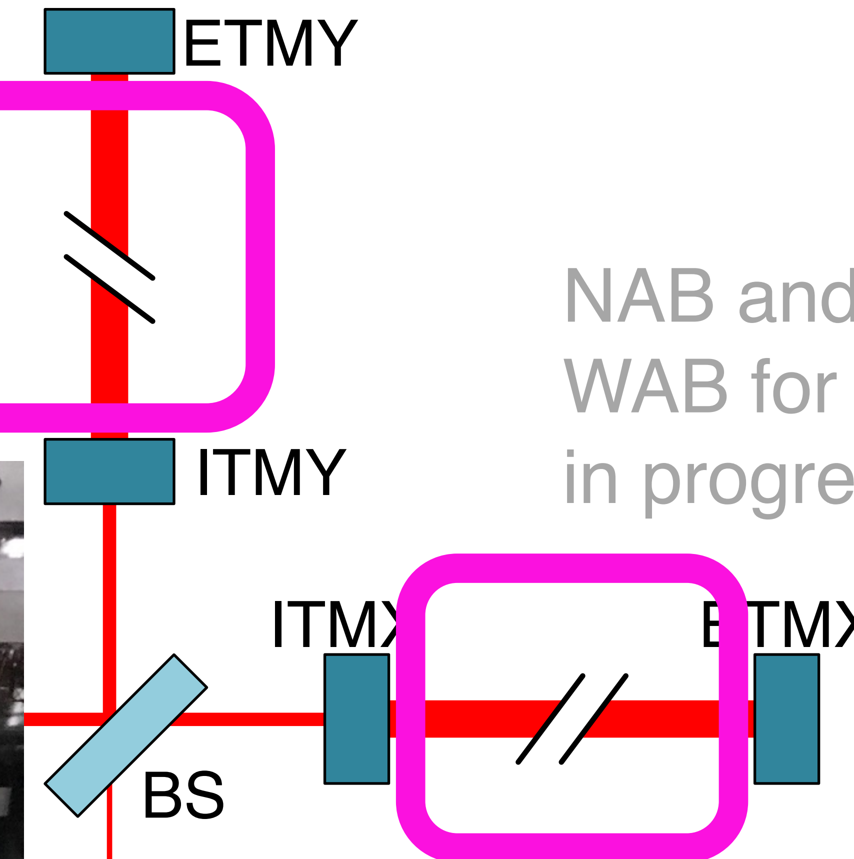




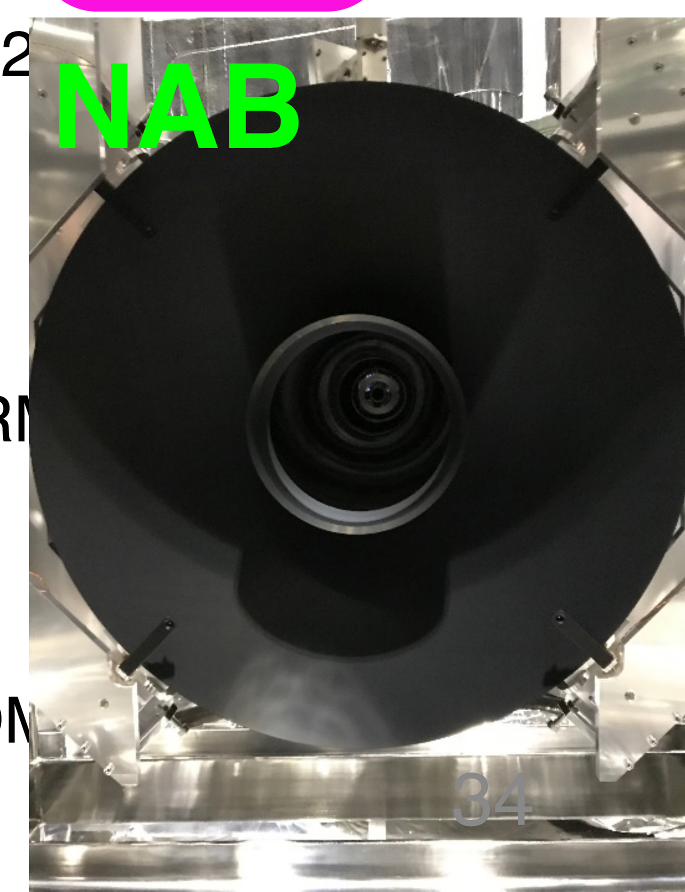
Installation Progress: Baffles

Narrow angle baffles,
Wide angle baffles
3 of 4 installed



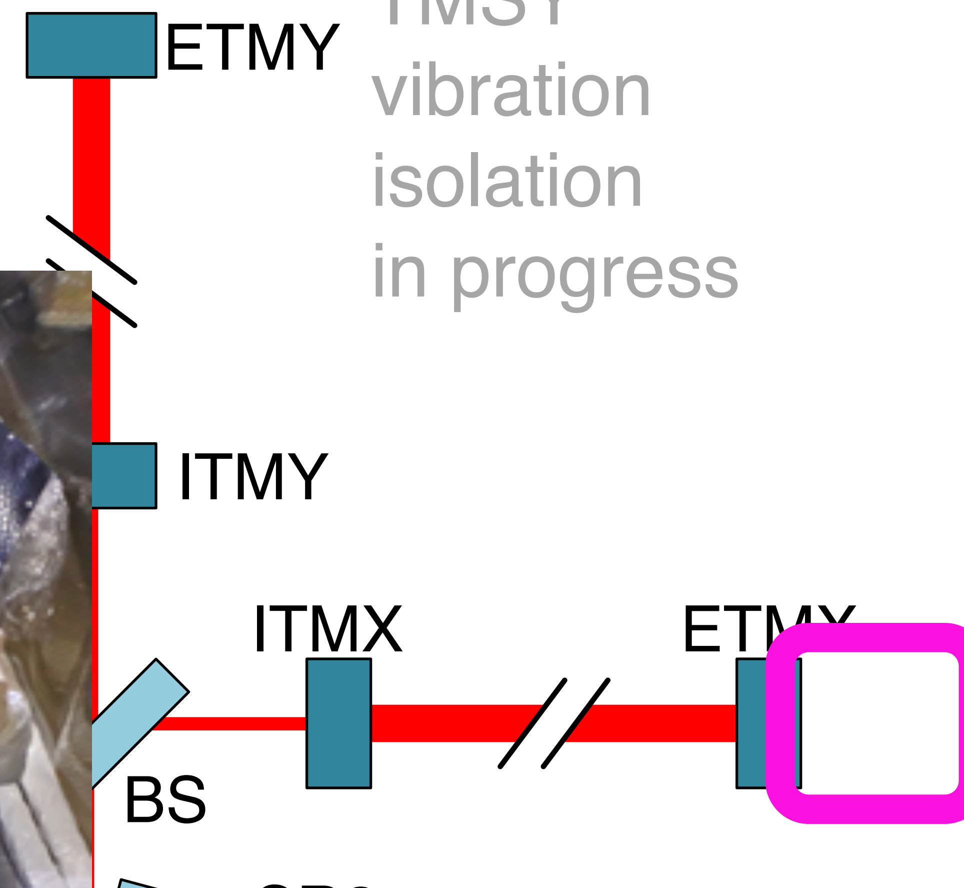


NAB and
WAB for EX
in progress

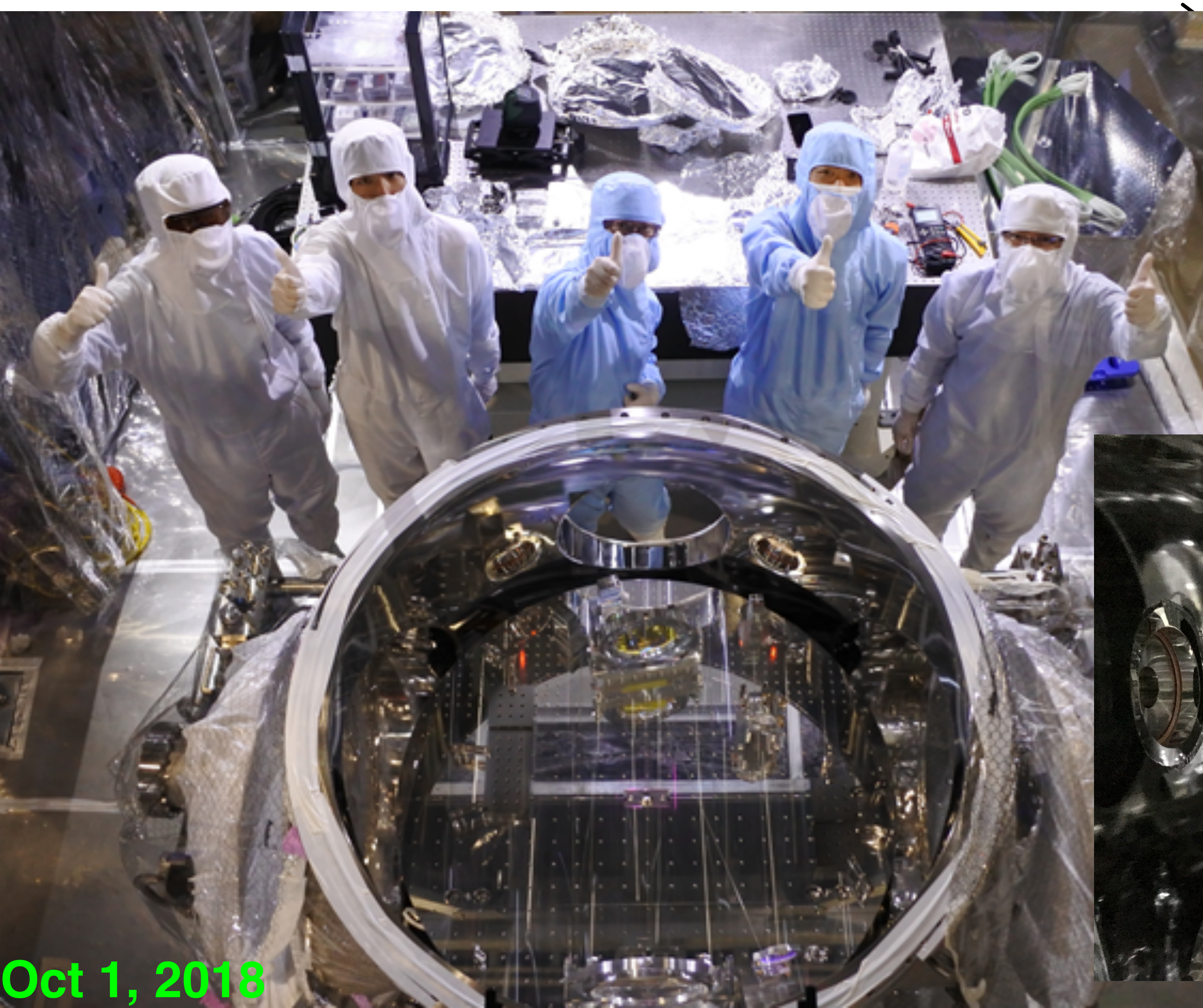


Installation Progress: Trans Mons

Both transmission monitor system installed

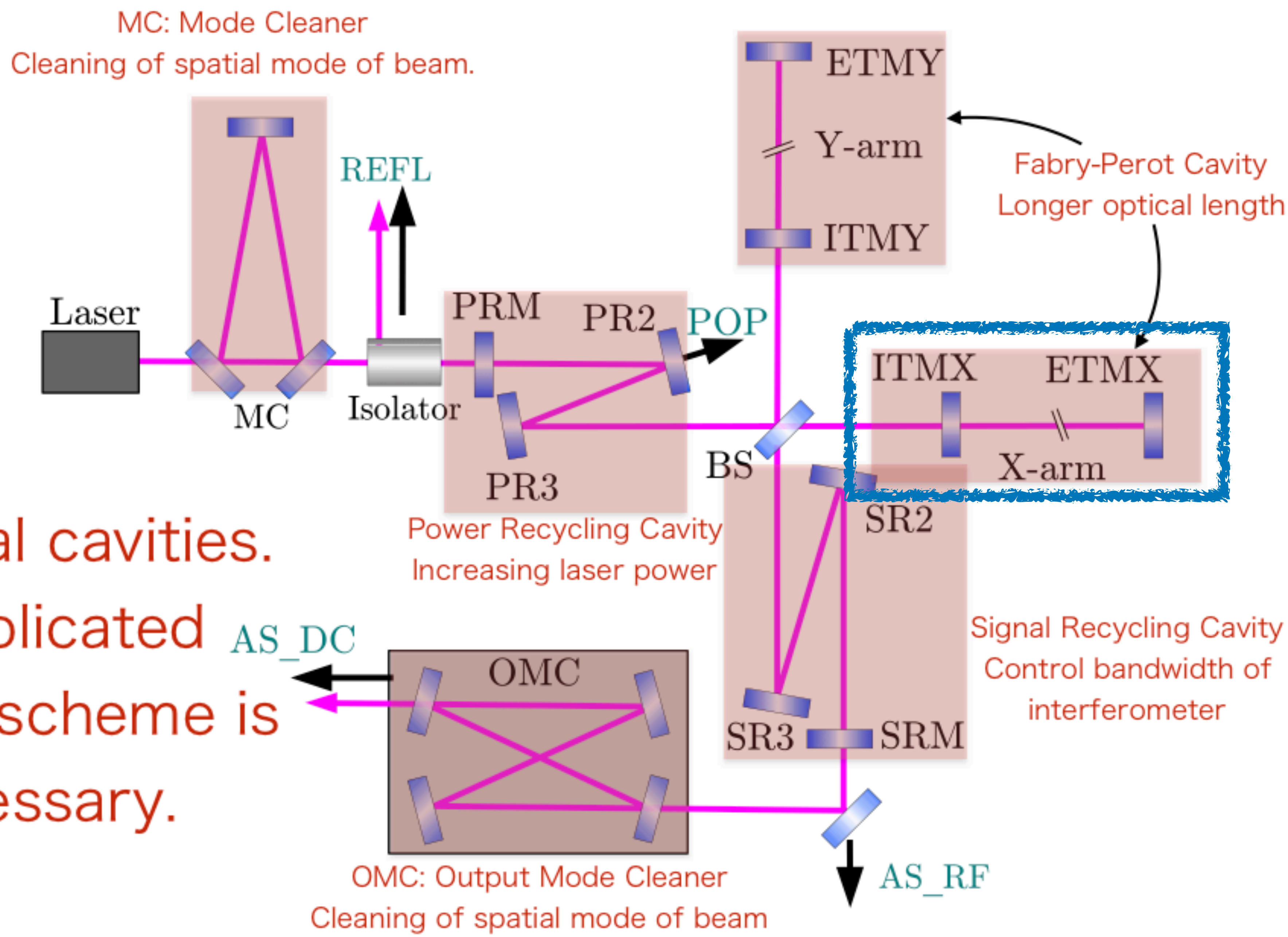


TMSY vibration isolation in progress



Commissioning

We have to keep 6 optical cavities in resonance by controlling laser frequency or optical length.



6 optical cavities.
Complicated control scheme is necessary.

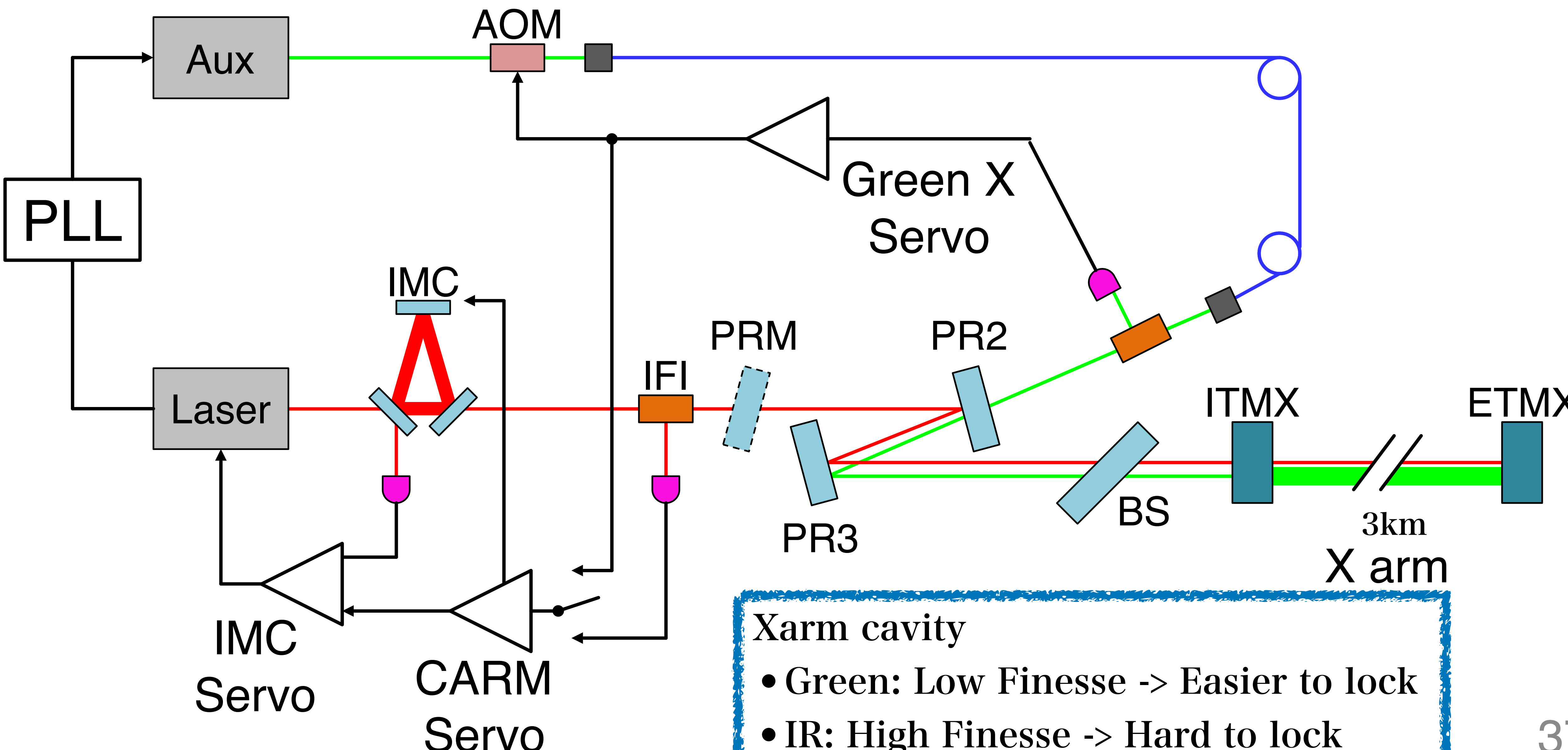
We are testing step by step along with installation works.

X-arm commissioning has been done in the last year.

Keep a cavity in resonance: Lock

X-arm Commissioning

- Purpose: Lock acquisition 3km arm cavity.
- We employ arm length stabilization system using green beam (Green Lock system).

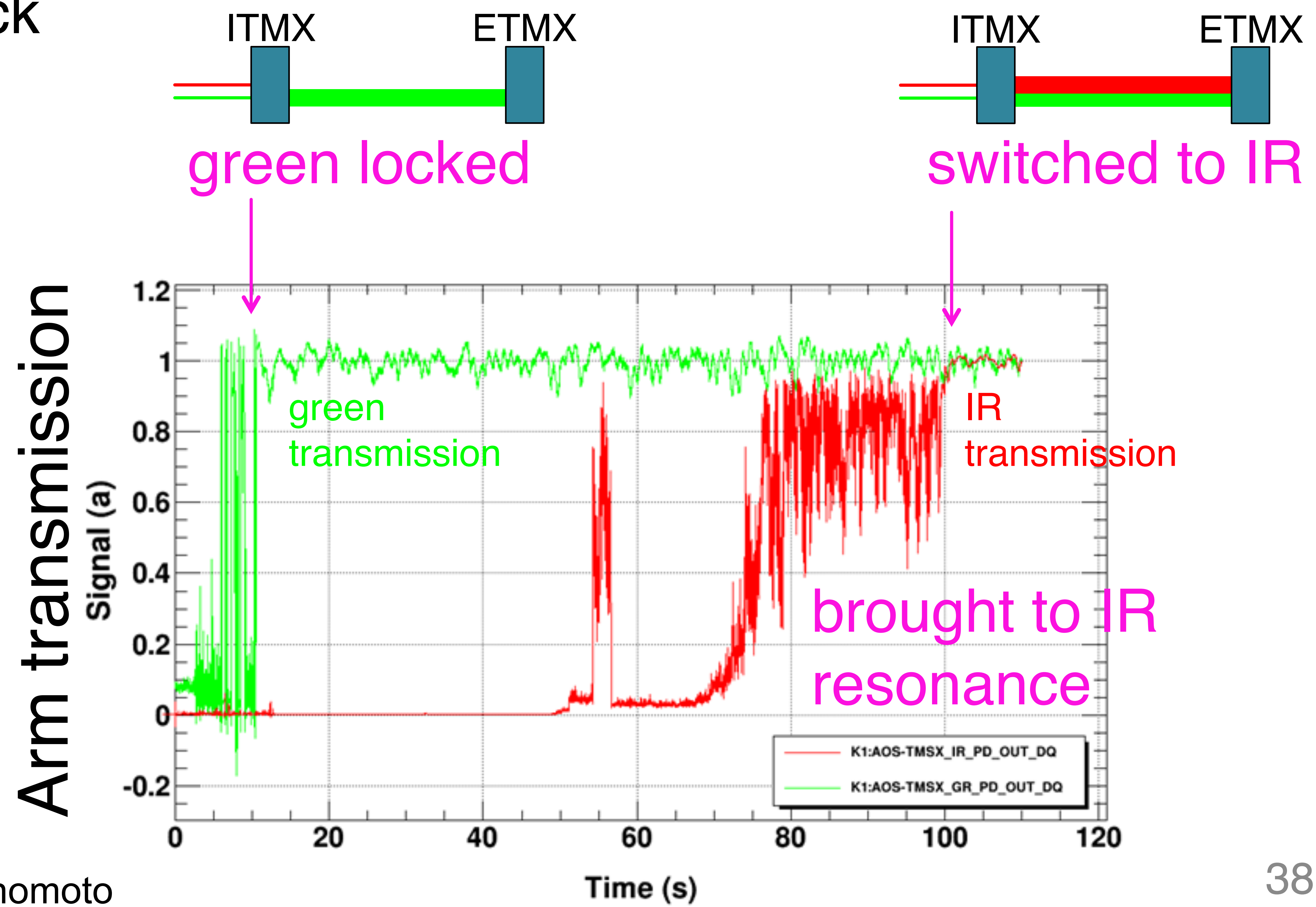


Xarm cavity

- Green: Low Finesse -> Easier to lock
- IR: High Finesse -> Hard to lock

X-arm Commissioning

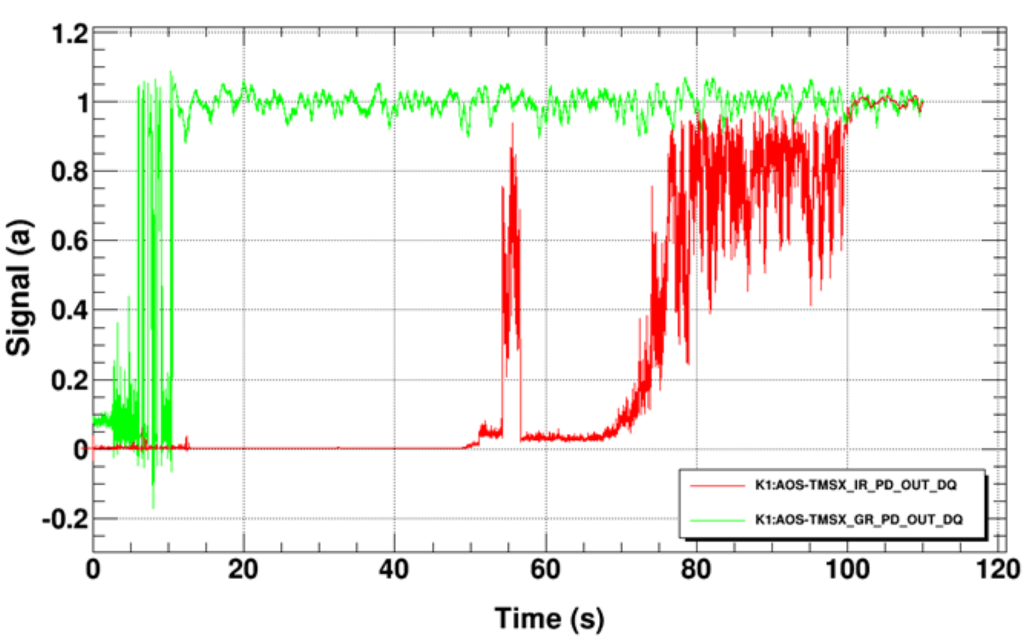
- Successfully switched directly from green lock to IR lock



Plot by Y. Enomoto

Video monitor of transmitted Green laser beam

Arm transmission



Finally we achieved 1day lock.

X-arm Characterization

- As expected, less than 100 ppm roundtrip loss

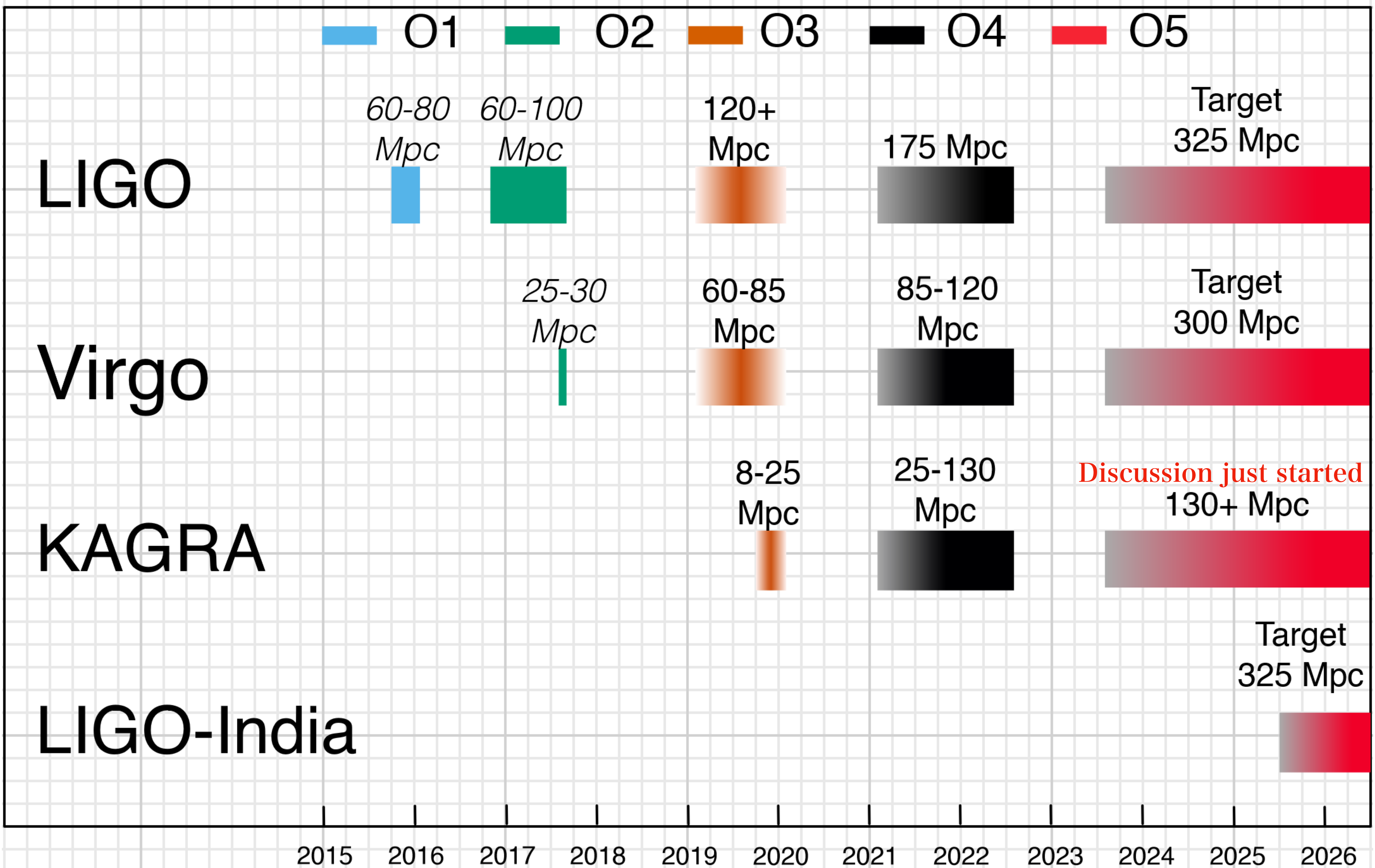
	Design	Measured
Finesse	1530	1411±2±30
ITMX transmission	0.4 %(+0.1 %)	0.44 %
Mode matching		91±1 %
Roundtrip loss	< 100 ppm	86±3 ppm
Arm length	3000 m	2999.990(2) m
Transverse mode spacing	34.80 kHz	34.79(5) kHz
Finesse (Green)	52	41.0±0.3
Mode matching (Green)		~70 %

Contents

- Brief review of Gravitational Wave
  - Gravitational waves
  - Laser interferometer
  - Recent discoveries

- Introduction of KAGRA
- Current status of KAGRA
- **Future**
- Summary

Observation Scenario



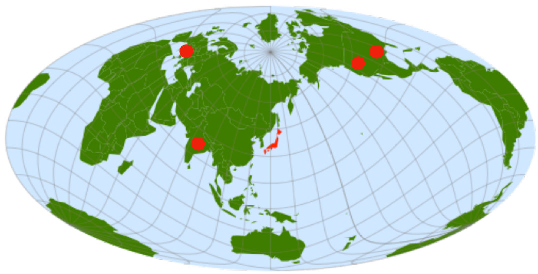
[Living Reviews in Relativity 21, 3 (2018)](); updated version available from
https://git.ligo.org/publications/detectors/obs-scenarios-2018/blob/master/Figures/ObsScen_fig2_v12.pdf

Sky localization accuracy in future (O4)
KAGRA reaches the target sensitivity

NS-NS @180Mpc (95%CI)

(1.4,1.4)Msun	LHV	LHVK
median of δΩ [Deg²]	30.25	9.5

L:LIGO-Livingston
H:LIGO-Hanford
V: Virgo
K: KAGRA
I: LIGO-India



J.Veitch et al., PRD85, 104045 (2012)
(Bayesian inference)
See also Rodriguez et al. 1309.3273

direction, inclination,
polarization angle
are given randomly

BH-NS @200Mpc

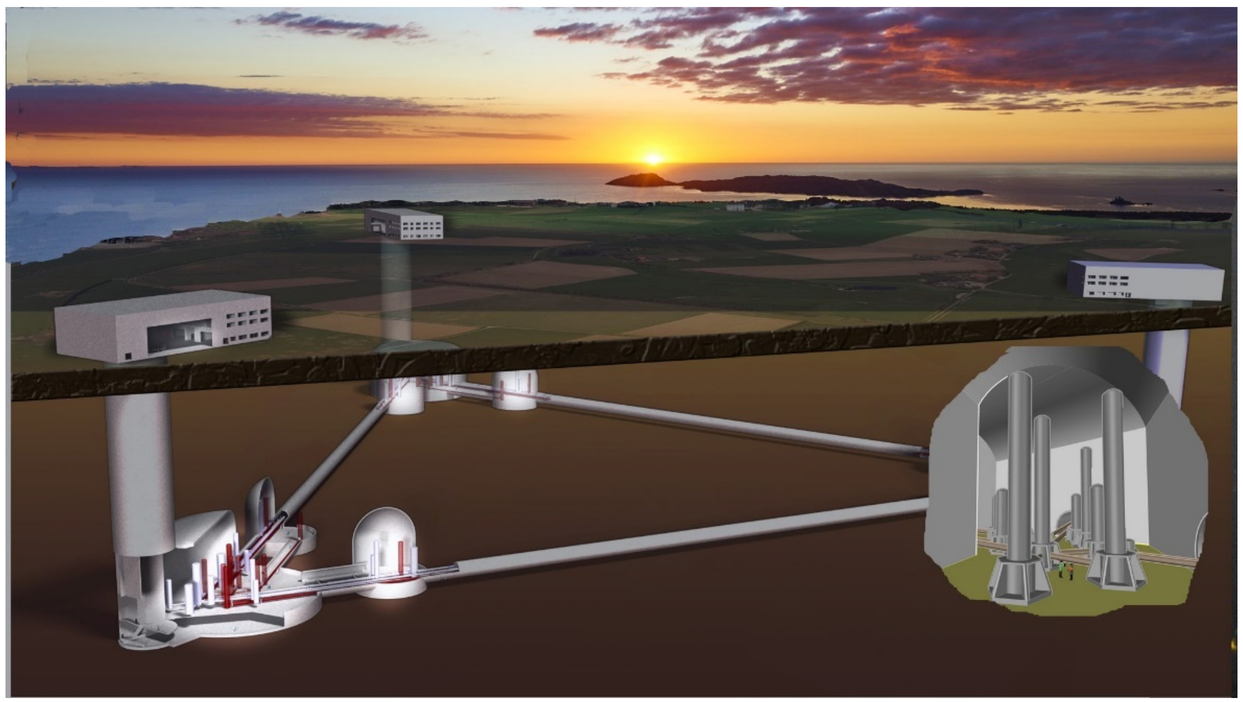
(10,1.4)Msun	LHV	LHVK	LHVKI
median of δΩ [Deg²]	21.5	8.44	4.86

(Tagoshi, Mishra, Arun, Pai, PRD90, 024053 (2014) , Fisher matrix)

Growth of the detector network promises better science in future.

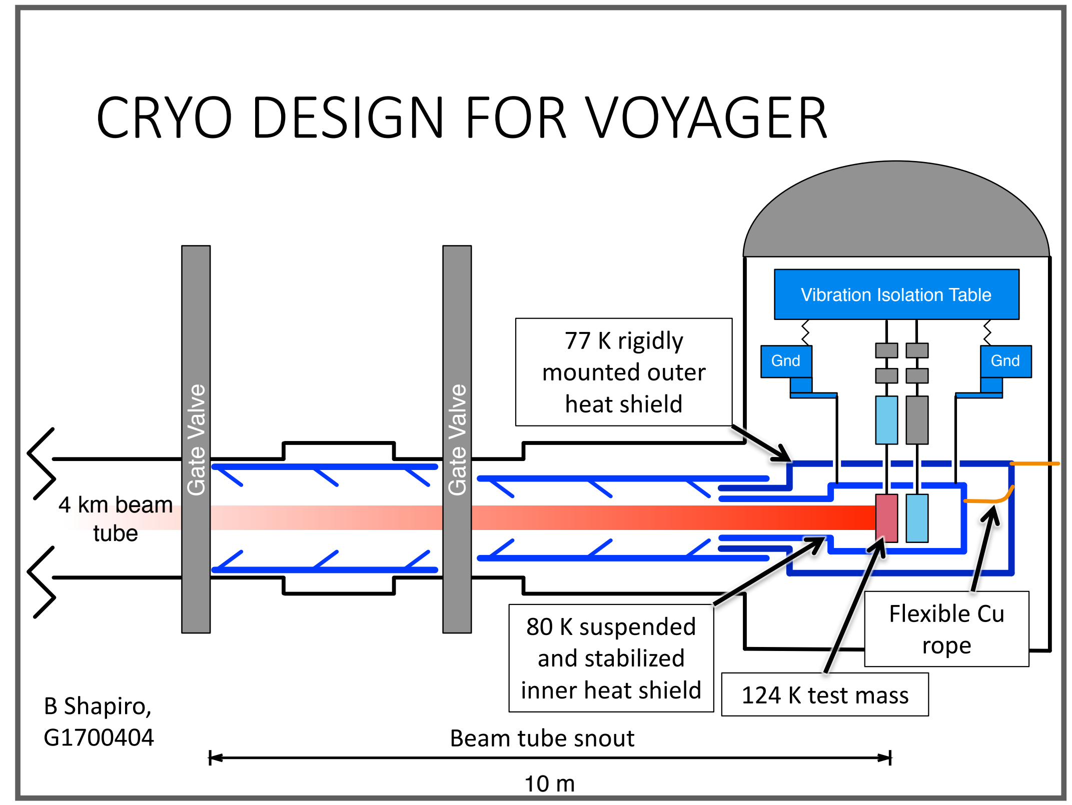
Future detectors

Ground based interferometer



Einstein Telescope

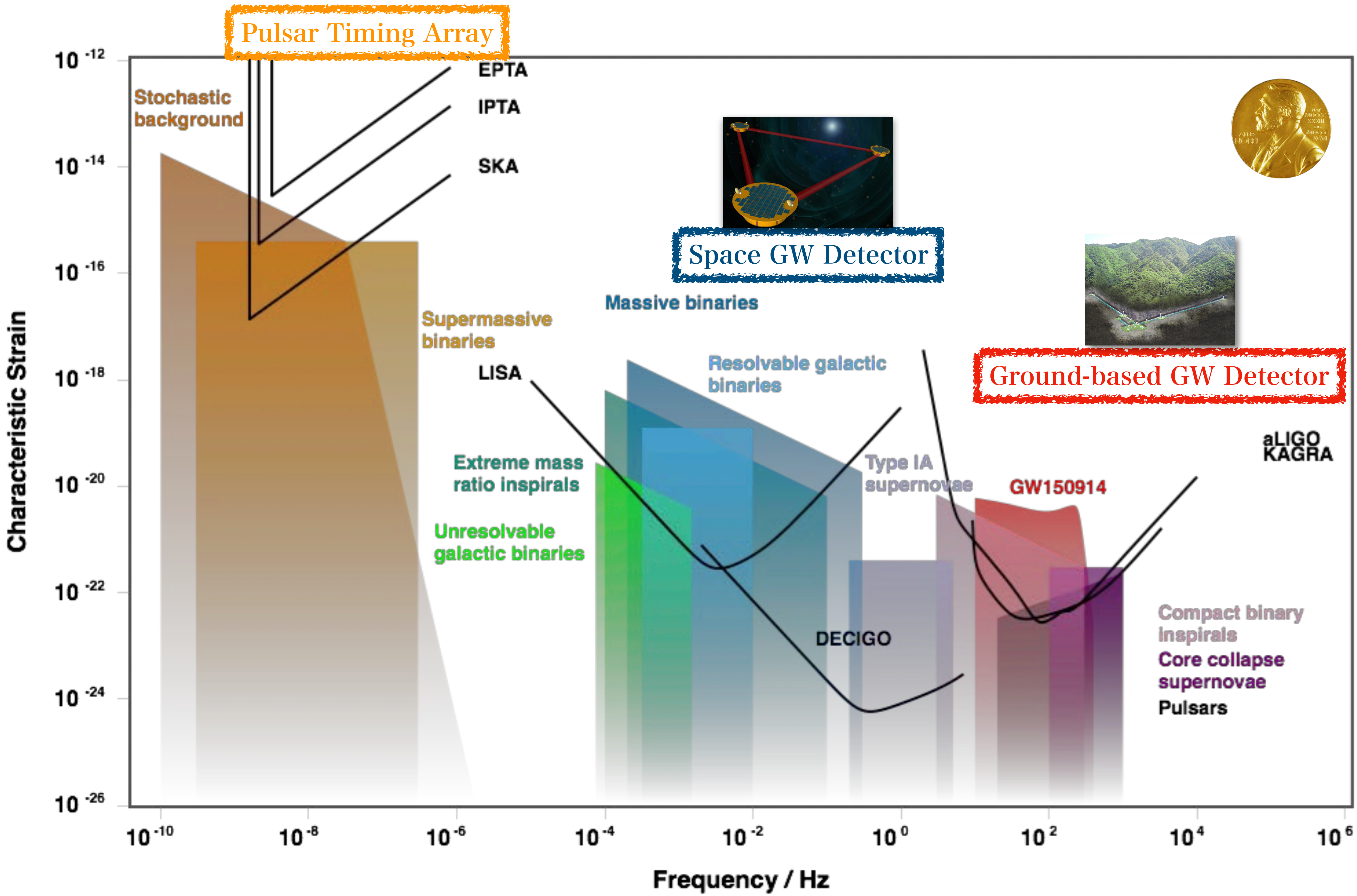
- Europe
- 10km Triangle
- Underground site & Cryogenic silicon mirror
- Observation ~2032?



VOYAGER

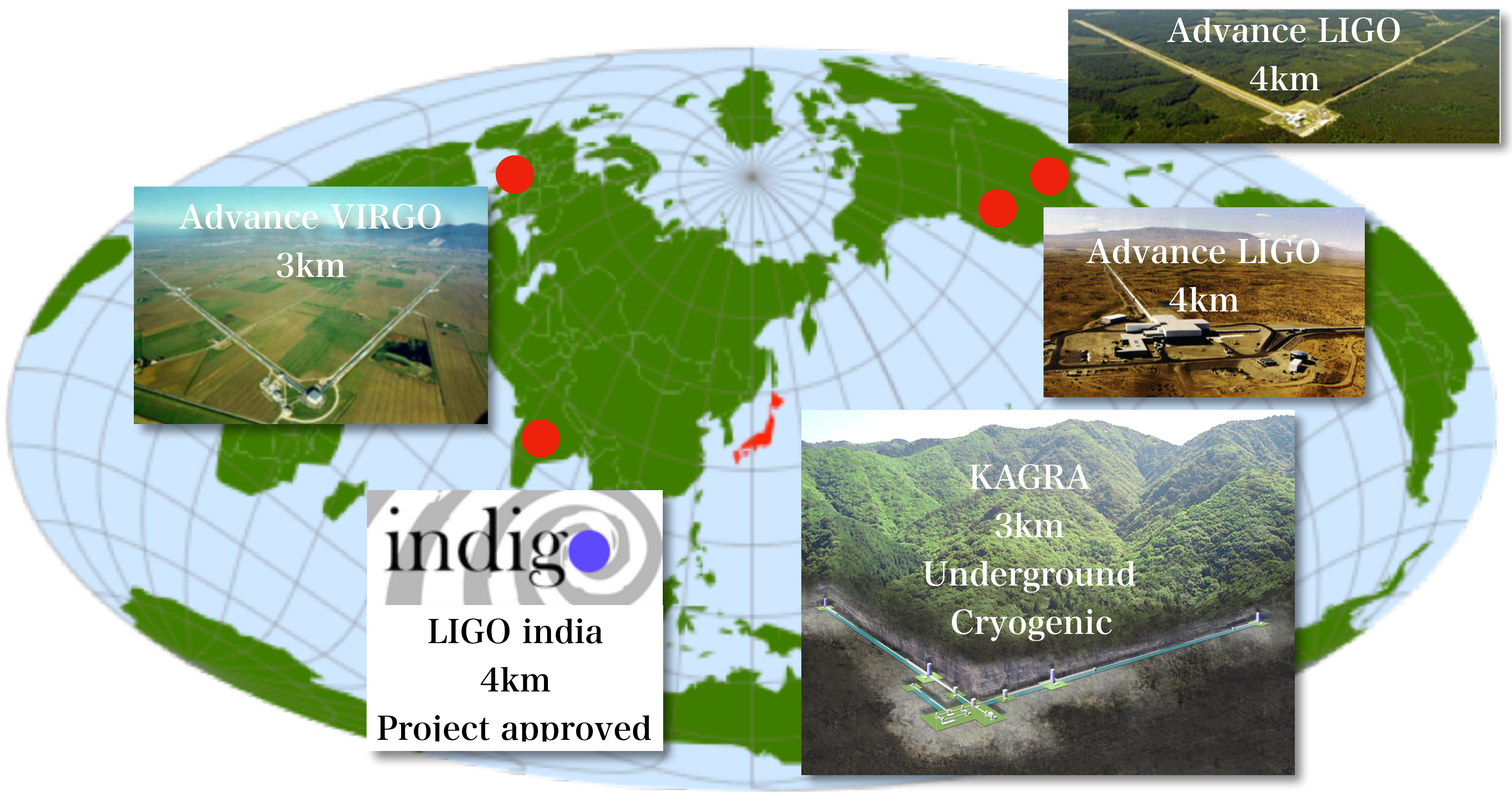
- Future upgrade plan of LIGO
- Cryogenic silicon mirror (123K)
- Observation ~2027?

KAGRA is pioneer of important concepts of the future detectors.


Pulsar Timing Array
EPTA
IPTA
SKA
Stochastic background
Supermassive binaries
Space GW Detector
Massive binaries
Ground-based GW Detector
LISA
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
Type IA supernovae
GW150914
aLIGO
KAGRA
DECIGO
Compact binary inspirals
Core collapse supernovae
Pulsars
Characteristic Strain
Frequency / Hz
10 -12
10 -14
10 -16
10 -18
10 -20
10 -22
10 -24
10 -26
10 -10
10 -8
10 -6
10 -4
10 -2
10 0
10 2
10 4
10 6

Summary

- KAGRA is a km-class interferometric GW detector in Japan.
- Use of the underground site and the cryogenic mirror technique are unique features of KAGRA.
- Installation works are done.
- Commissioning works are on going to join the observation 3 in autumn 2019.
- KAGRA will be in the global network of GW detectors with good sensitivity and then proceed GW and multi-messenger astronomy.



Fin