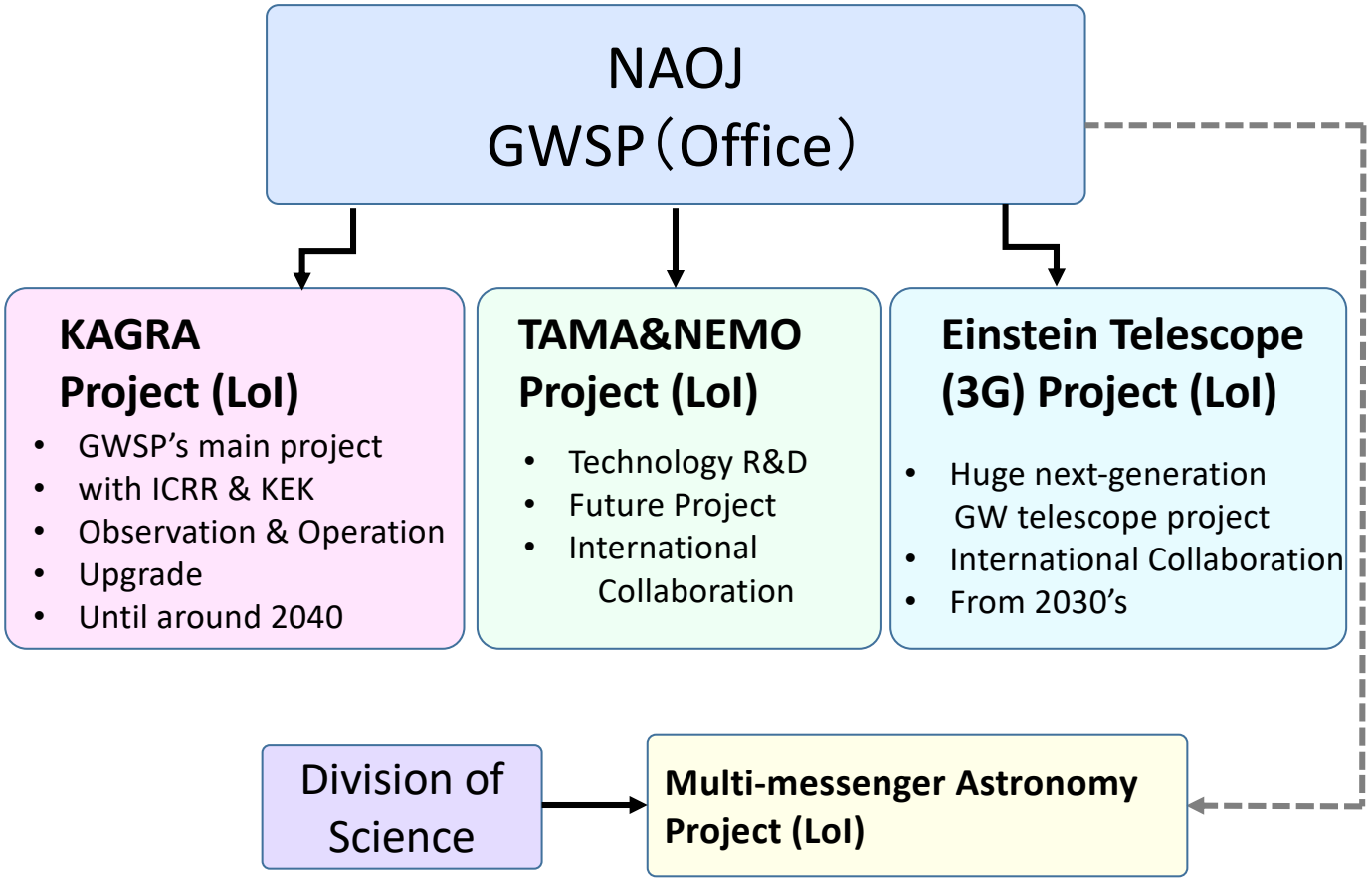
Projects in the NAOJ Gravitational Wave Science Project

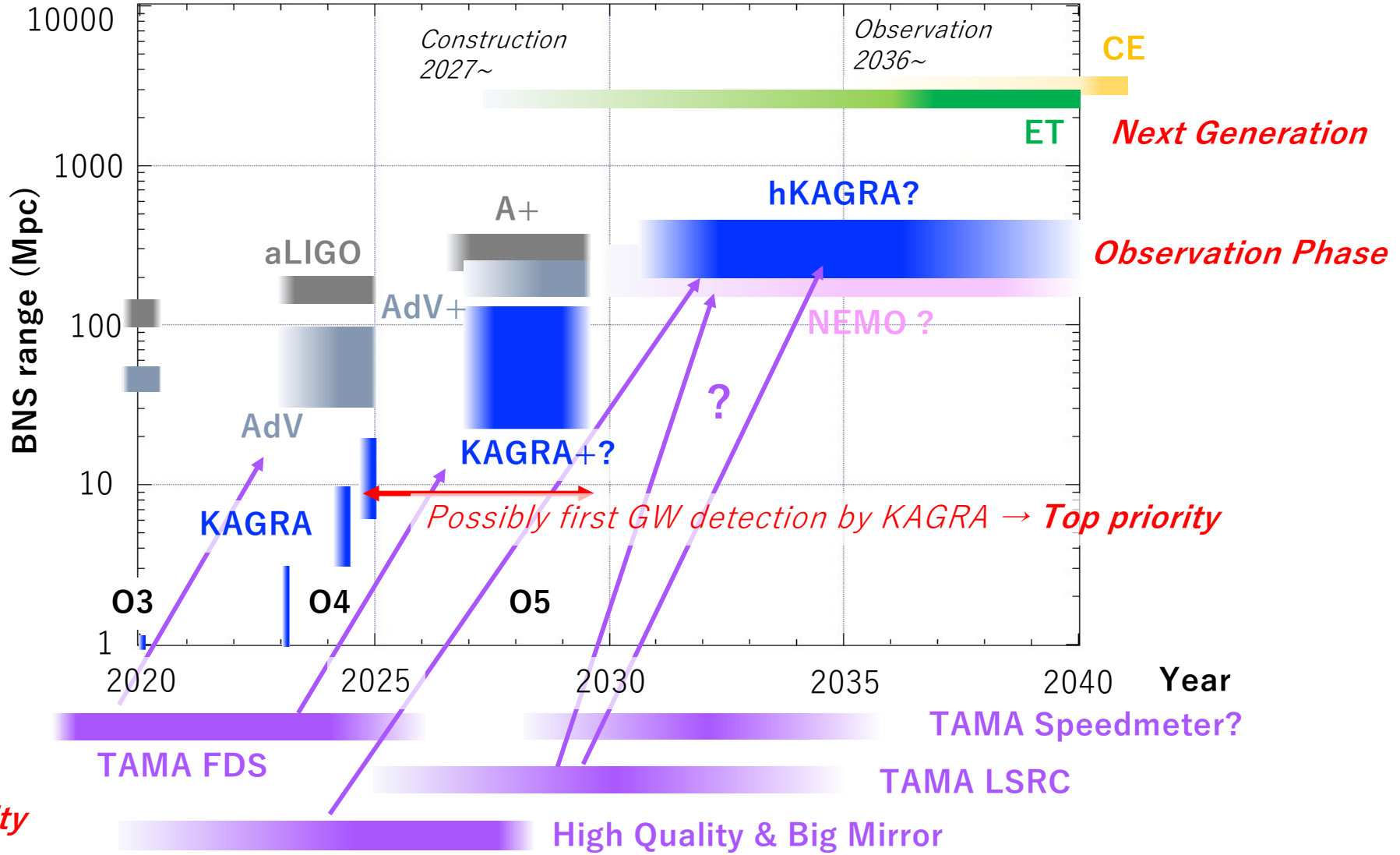
Takayuki TOMARU,
Director of GWSP

Gravitational Wave Science Project (GWSP)

→ Gravitational Wave Science Project Office



Schedule & Strategy



NAOJ GWSP's KAGRA Project

Entire KAGRA project + NAOJ GWSP's roles + NAOJ GWSP's strategies

A Frontier Project

1. Science Goals and Objectives

Science Goals

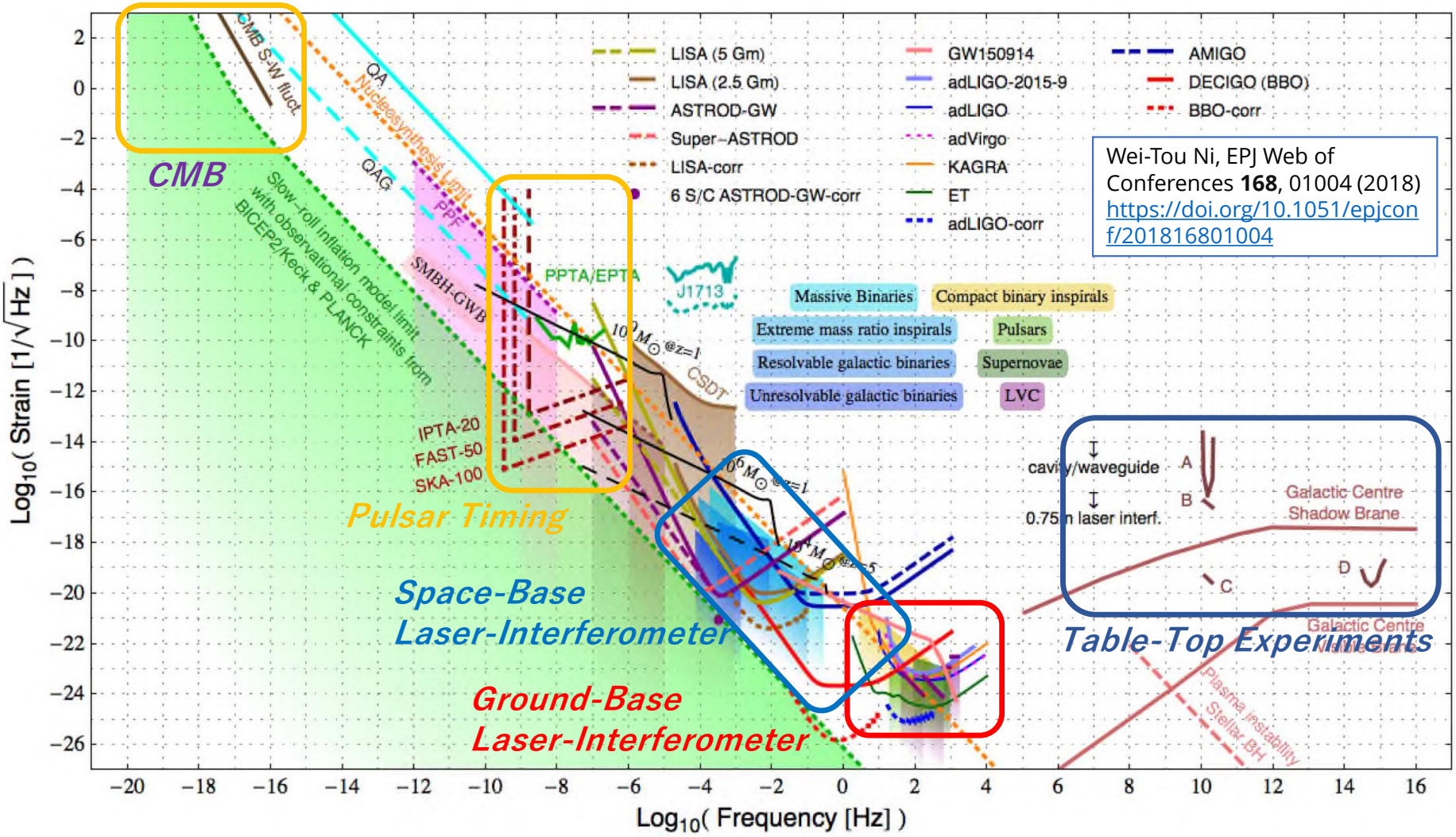
The main purpose of this research is to develop GW astronomy/physics and multi-messenger astronomy from an astronomical perspective, which can be developed using ground-based laser interferometric GW telescopes of several tens of Hz to several kHz.

Science Objectives

GW Science + Technology Development

GW Astronomy in Frequency

GW ⟺ EMW



Wei-Tou Ni, EPJ Web of Conferences **168**, 01004 (2018) https://doi.org/10.1051/epjconf/201816801004

Scientific Themes

Astronomy

- **Black-hole Astronomy**
  - Stelar mass BH
  - Mid mass BH
  - Super-massive BH
  - Distribution of BH & BH binary
  - POP-III, PBH, Dynamical Formation
  - BH spectroscopy
  - Ringdown
- **Neutron Star Astronomy**
  - Gravitational Collapse & Neutron Star formation
  - Neutron star mass, Massive NS ?
  - Equation of state of neutron
  - Starquake
  - Gamma Ray Burst
  - Distribution of NS & NS binary
- **Multi-messenger Astronomy**
  - Nucleosynthesis of heavy atoms
  - Hubble Constant
- **Cosmology**
  - Standard Siren
- **Supernova**
- **Pulsar**

Physics

- Verification of GR
  - Appliable range of GR
  - Non-linearity
  - Polarization of GW
  - Degeneration of masses and inclination angle of binary stars
- GW speed (Mass of graviton)
- Reaction of GW emission
- Quantum Gravity
- GW background (Cosmology)
  - Cosmic Inflation
  - Density of binary stars
  - Cosmological parameters
- Hadron Physics

GW Events until O3

+57 candidate in O4 @Oct.

LIGO Gallery: https://www.ligo.caltech.edu/image/ligo20211107b

What is an origin of LVK BBHs?

Scenario Selection

- Standard stars (POP I) ?
  or POP II ?

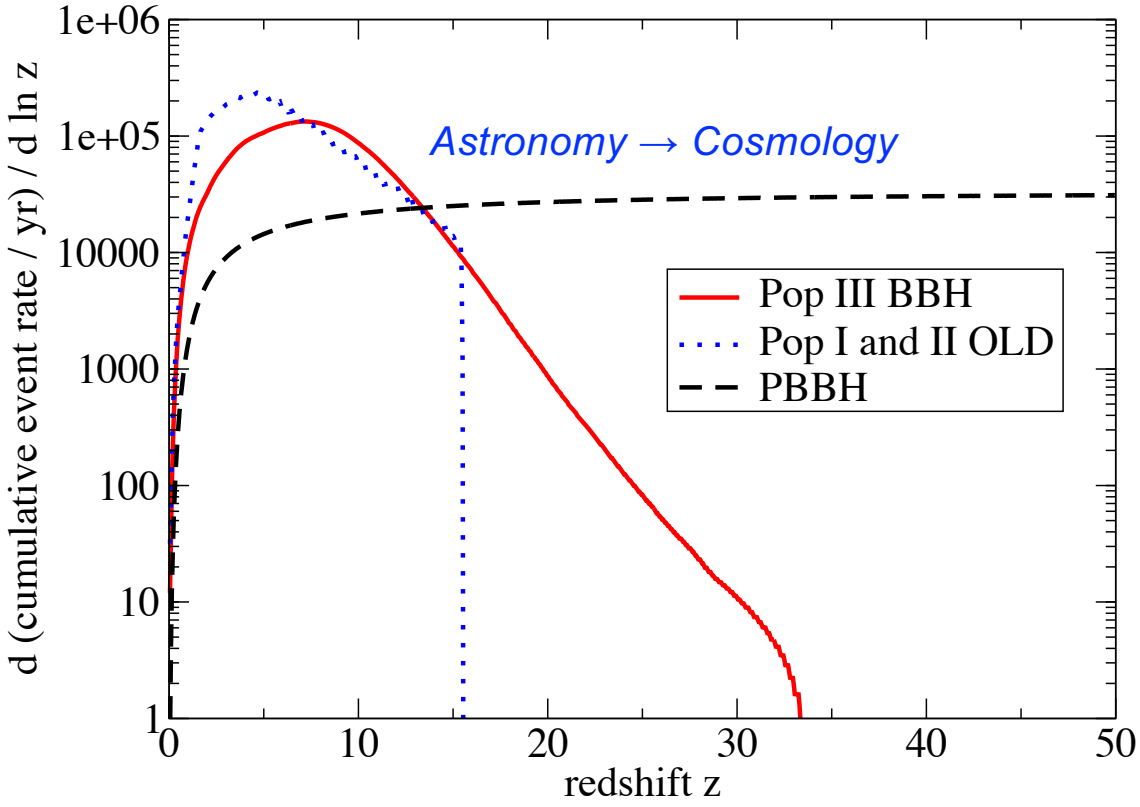
  → Our universe is too young to generate so many LVK BBH?

- POP III ?

  → Kinugawa et al. predict that binary merger of dozens-solar-mass BBHs can be observed present day.

- Primordial BBH ?

  → Quantum fluctuation at the cosmic inflation era can generate many BBHs



$z > 15$ observation is required

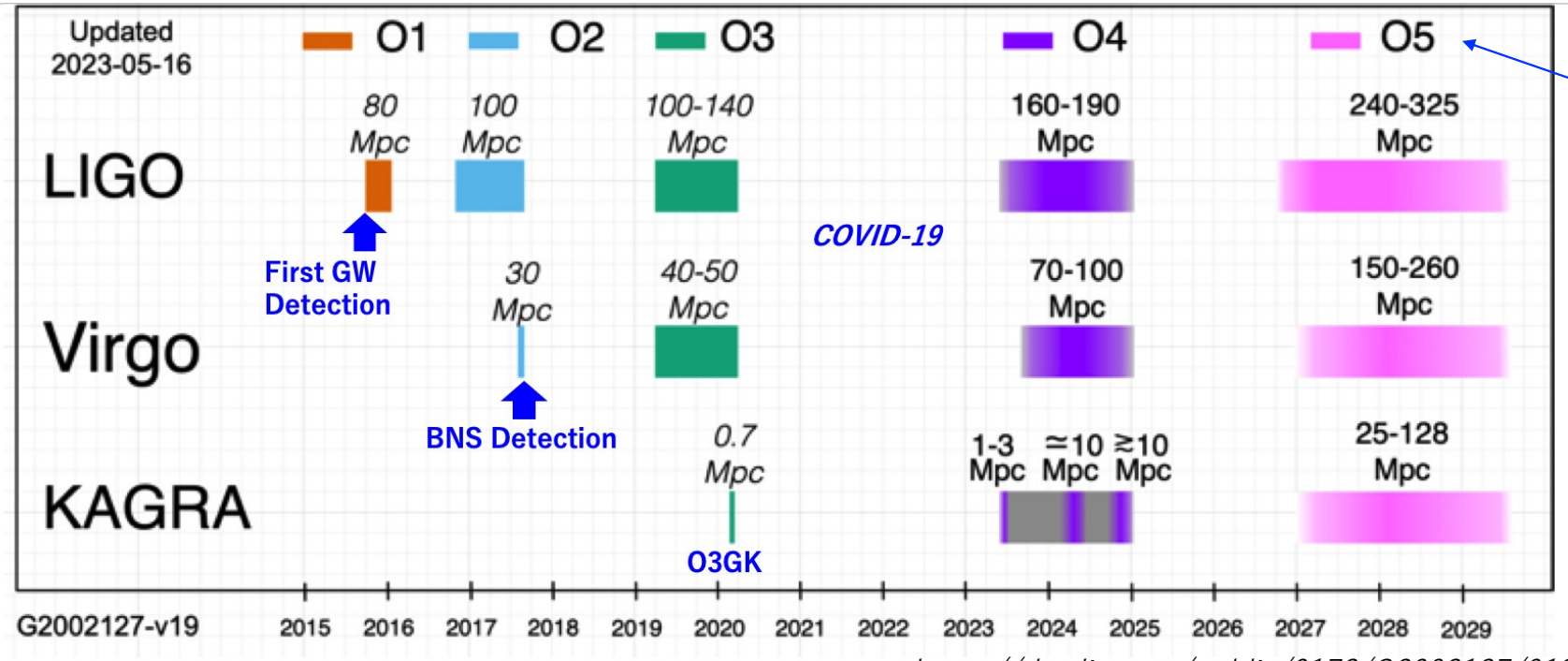
T. Nakamura, Prog. Theor. Exp. Phys. 2015, arXiv:1607.00897v2 ***[astro-ph.HE]***

2. Science Investigations, Instrumentation and Data

① International GW Observation

KAGRA collaboration
→ LIGO-Virgo-KAGRA collaboration (MoU)

← GWSP's Main Science Investigation in this roadmap



Details are not fixed yet

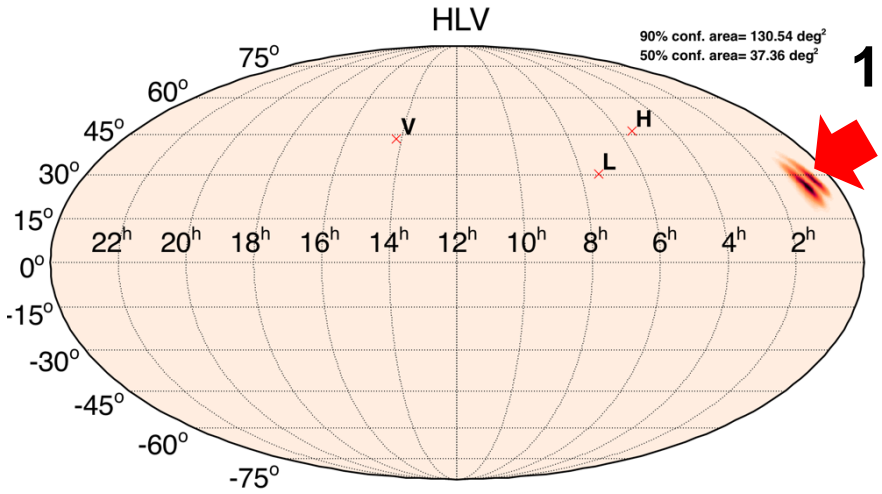
O6 and later: No discussion yet

https://dcc.ligo.org/public/0172/G2002127/019/ObsScen_timeline.pdf

Joining to international observation is the top priority for KAGRA.
This is also GWSP's top priority.

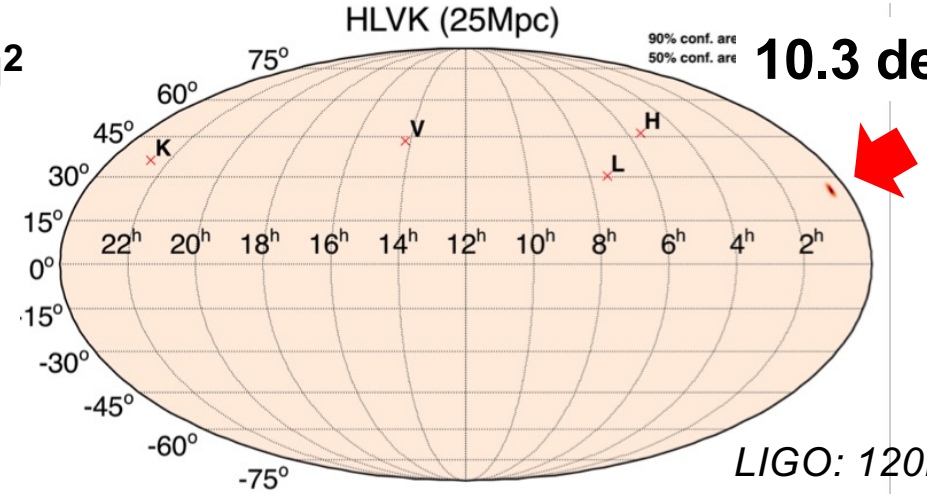
Expected Localization

Hanford-Livingston-Virgo



130 deg²

Hanford-Livingston-Virgo-KAGRA

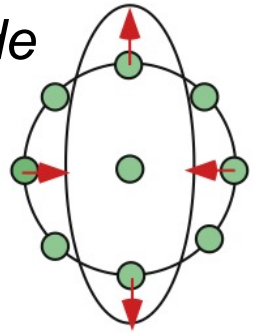


10.3 deg²

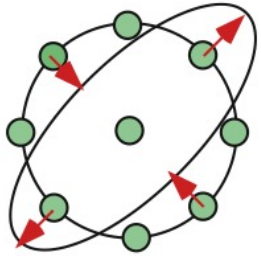
LIGO: 120Mpc
VIRGO: 60Mpc
KAGRA: 25Mpc

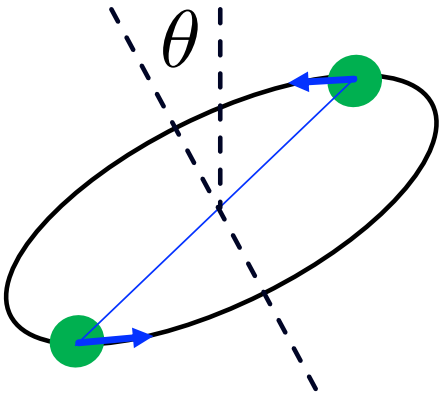
GW Polarization

+ mode



× mode





With more than four telescopes, we can identify GW polarization and can know inclination angle of binary orbit.

Current Status & Plans of KAGRA

KAGRA joined O4a from May 2023 for a month with 1.3Mpc sensitivity

→ We aim to improve the sensitivity of 3~10Mpc in O4b (from spring 2024)

O4b commissioning works are largely delayed by many troubles.

→ Need to select to-do-items

→ Quick shift to interferometer commissioning is required.

Problems: No sufficient budget, no sufficient human-resources, no sufficient time …
And we can not identify real noises without real interferometer operation.

Note *Virgo also has much troubles and its sensitivity is still 30Mpc (half of O3).*
They decided to join O4 from this Dec. even with lower sensitivity.

Risk

- KAGRA budget can be terminated and GW astronomy in Japan can be disappeared.
- Without KAGRA and Virgo, event localization will be very poor and astronomy community can not fix follow-up observation area.

② Data Analysis

Present GWSP staffs: Hardware experts,
No data analysis experts

→ NAOJ can not lead GW astronomy

→ **Risk**

Accumulated Data in KAGRA

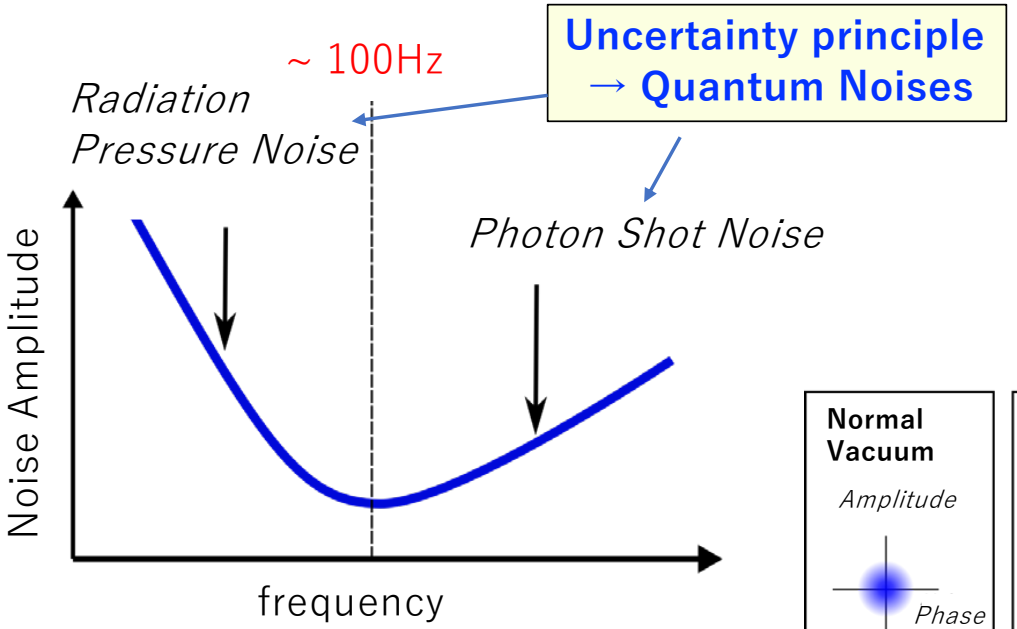
650TB/yr
>2PB @2022

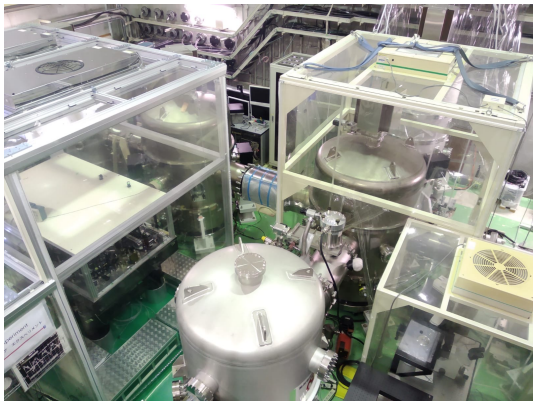
Proposal

- Hiring an expert of GW data analysis and computing (Associate Prof. class)
- **GRID Computing + 1000 CPU cores**
  - LIGO-Virgo share GW data analysis on Open Science GRID
  - LV demand KAGRA to provide 5000 cores on the GRID
  - Very small contribution to the LV GRID framework from KAGRA, only 1000 from Taiwan
  - We wish to have initiative of GRID and data analysis framework to show NAOJ's visibility.

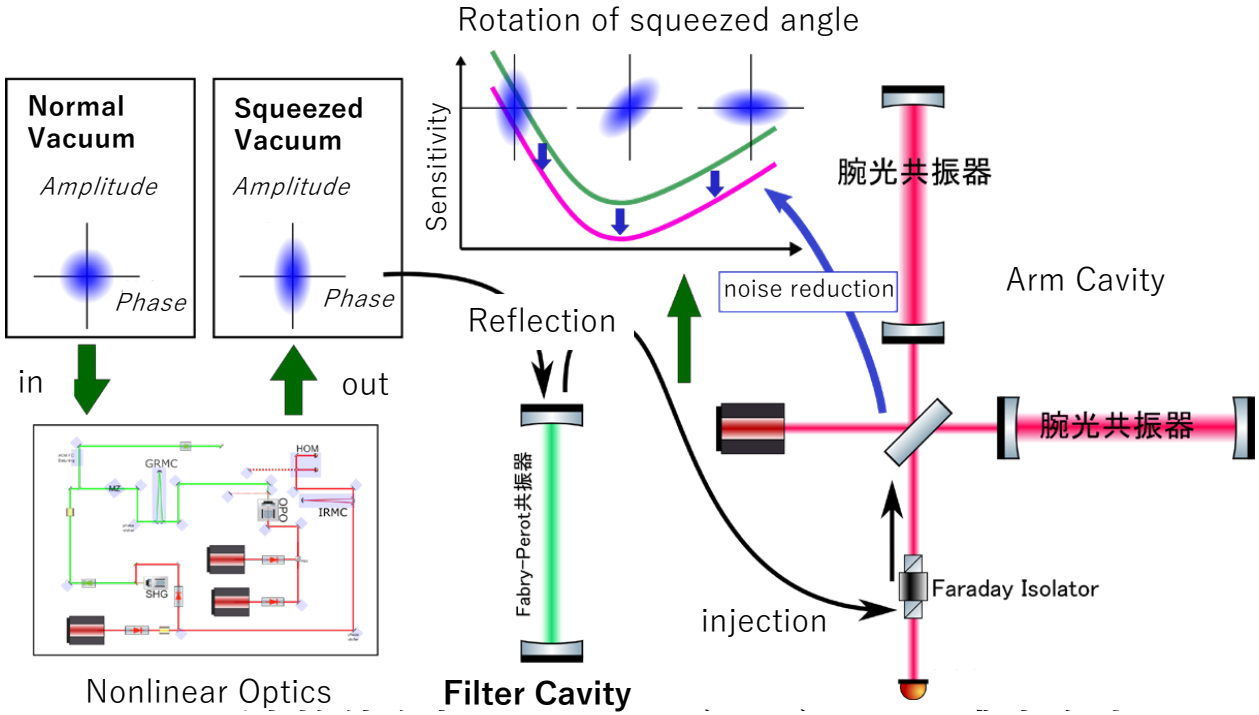
KAGRA's CPU

③ Frequency Dependent Squeezing for KAGRA



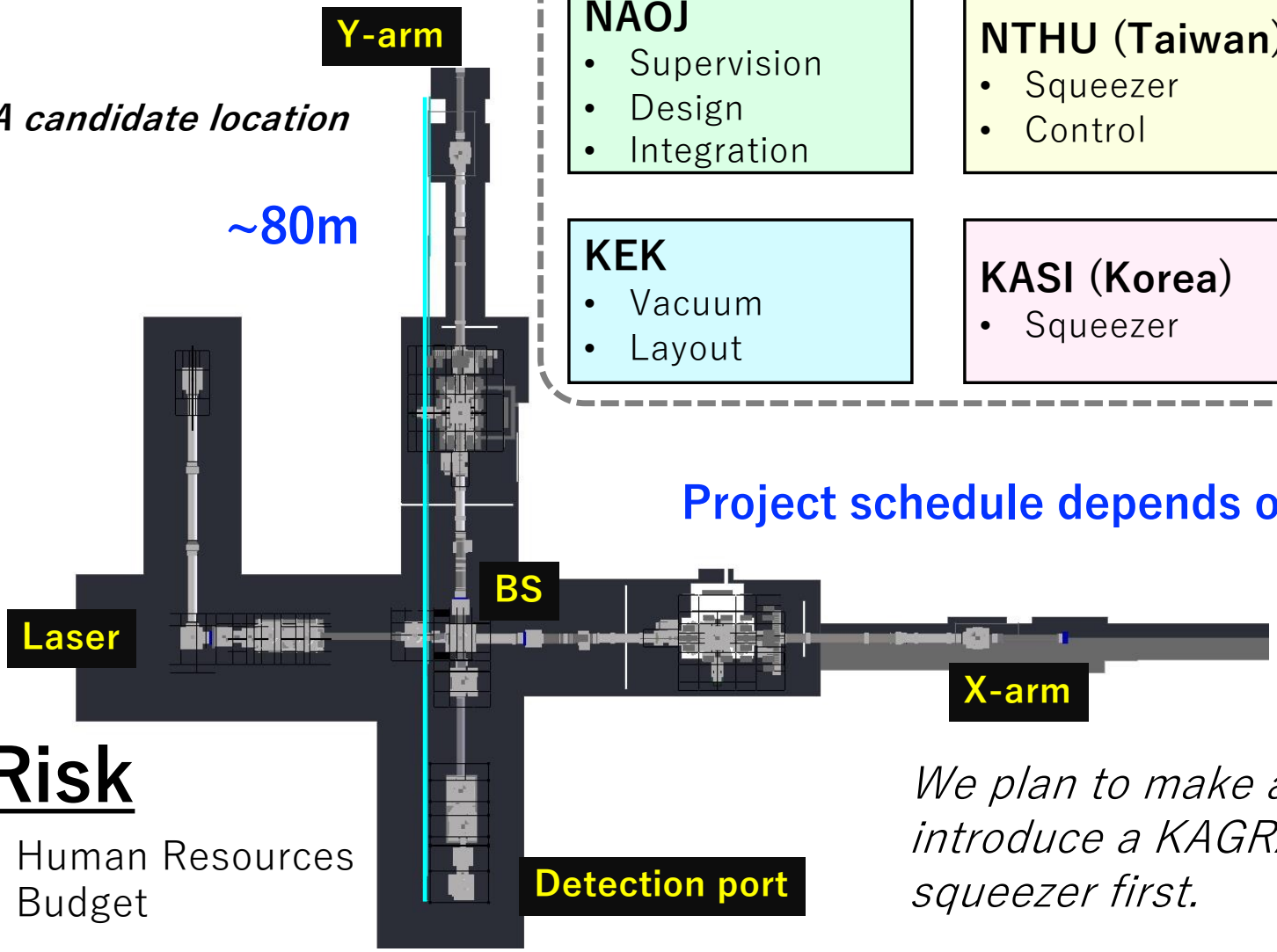


TAMA300
@NAOJ



The NAOJ GWSP demonstrated the FDS at 100Hz range the first in the world.
This technique has been already introduced in Virgo/LIGO.

KAGRA FDS



KAGRA FDS team

NAOJ
- Supervision
- Design
- Integration

NTHU (Taiwan)
- Squeezer
- Control

KEK
- Vacuum
- Layout

KASI (Korea)
- Squeezer

We plan to construct KAGRA FDS by external budget.

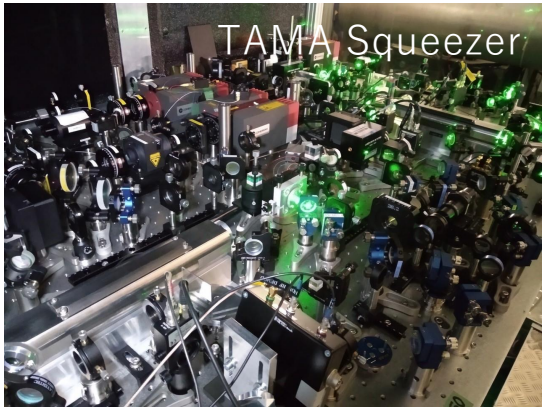
- *NTHU acquired budget*
- *KASI has budget*
- *NAOJ/KEK could not acquire Kakenhi budget*

Project schedule depends on the budgetary situation.

Risk

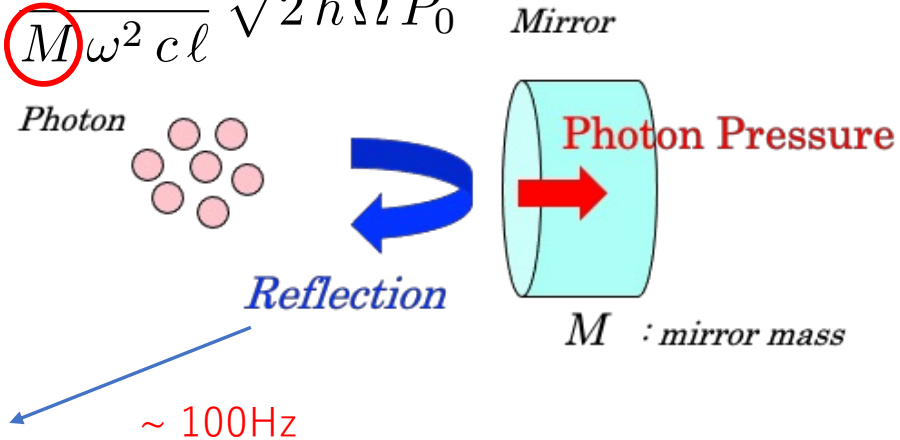
- Human Resources
- Budget

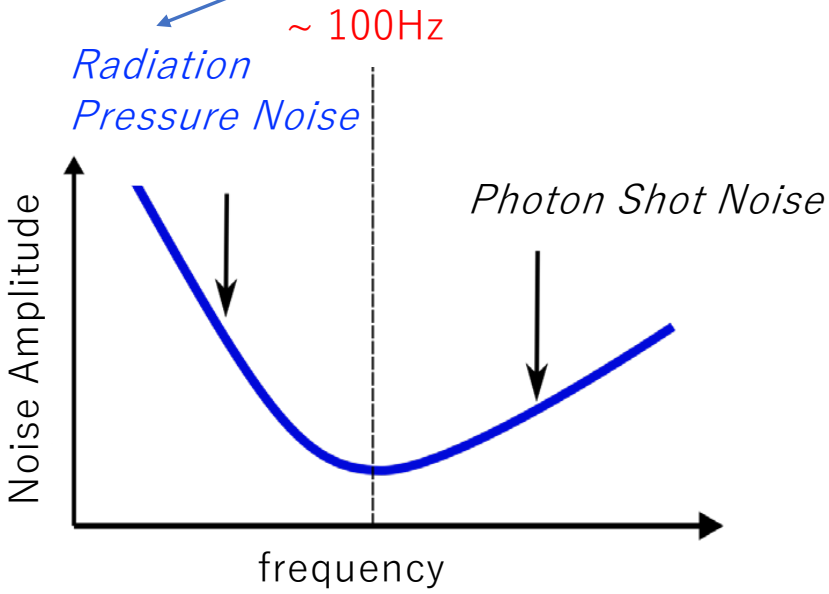
We plan to make and introduce a KAGRA squeezer first.



④ Development of Large Sapphire Mirrors

$$\delta\tilde{h}_{rp} = \frac{2}{M\omega^2 c\ell}\sqrt{2\hbar\Omega P_0}$$





Combination of FDS and heavy mirror is critical to reduce “quantum noise”.

Required Items

- Large crystal growth (40-100kg)
- Small optical absorption (<20ppm/cm)
- Small birefringence
  ($\Delta n \equiv n_e - n_o < 10^{-6}, \theta < 5^\circ$)
- Small defects & small optical scattering
- Super Polish
  (surface figure < ~nm, roughness < sub Å)
- Multi-layer coating with high mechanical Q

Large Sapphire Mirror team

NAOJ
- Supervision
- Evaluation
- Integration

iLM (France)
- Crystal growth (in house)

ICRR
- Procurement

KASI (Korea)
- Crystal growth
- Evaluation

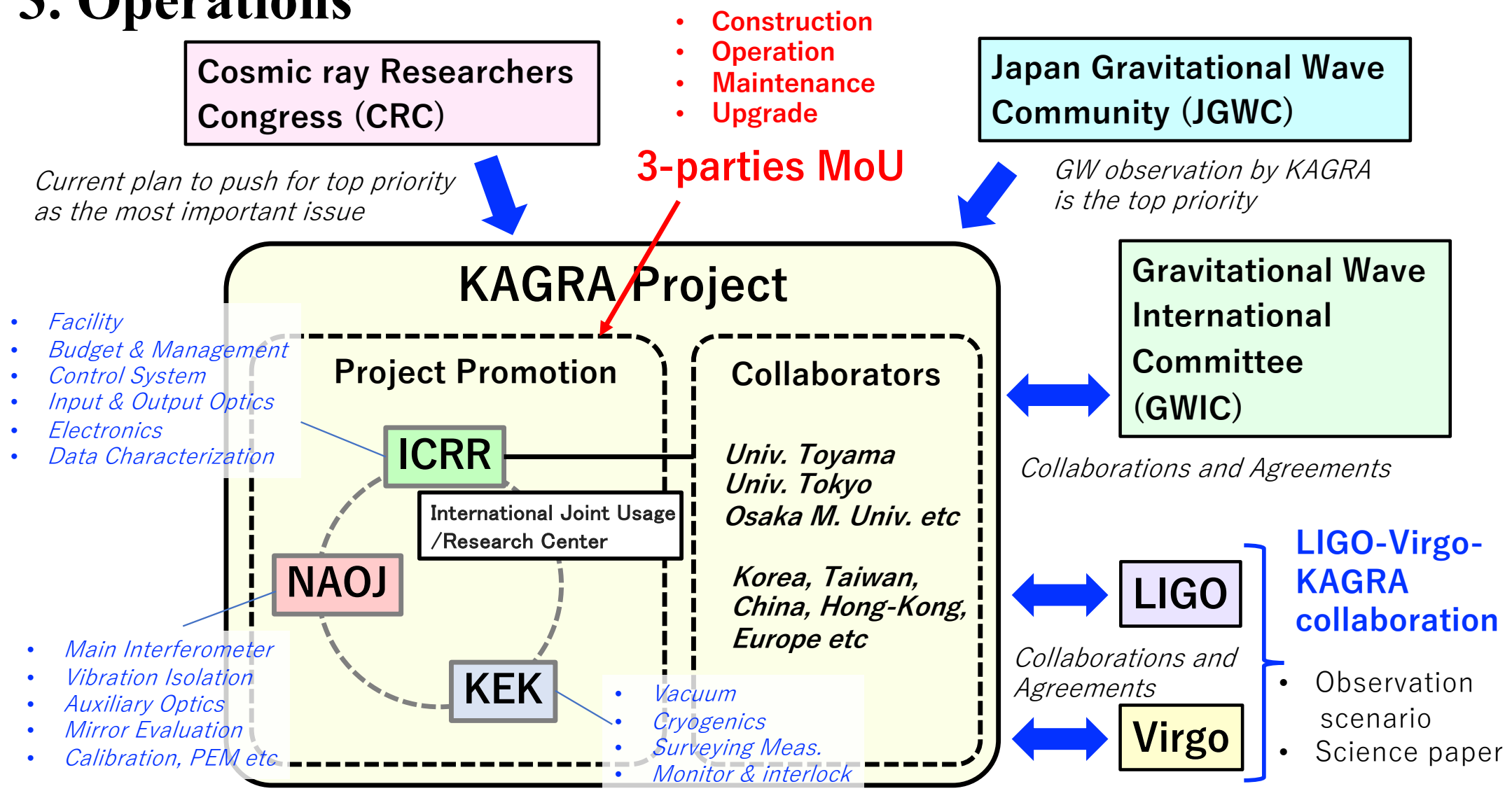
Birefringence Map

Optical Absorption Map

Risk

- Need trial to growth large sapphire crystal
- Nobody knows origin of optical absorption of sapphire at 1064nm wavelength

3. Operations



4. Key Technologies, and Issues

① International GW Observation: Top Priority

- Noise hunting ← Nobody knows noise sources. Steady noise hunting is required. Time!
- Replacement of two ITMs before O5 (in progress) ← Maybe OK, but very tight schedule
- Hardware Maintenance ← Hard budgetary situation…

② Data Analysis

- Data Analysis & GRID Computing ← We don't have data analysis & computing experts.
- 1000 core CPU ← Budget & long-term maintenance

③ Frequency Dependent Squeezing for KAGRA ← *Wide-band sensitivity improvement*

- Squeezer development ← Technically OK, but no budget and no human power
- Filter Cavity ← Technically OK, but no budget and no human power

④ Development of Large Sapphire Mirrors ← *Low frequency sensitivity improvement*

- Large crystal growth ← The iLM constructed a large furnace. Try & Error. Time!
- Small optical absorption ← Nobody knows its origin. This is a big uncertainty.

11. Risks

① If KAGRA don't join International GW Observation with more than 25Mpc sensitivity:

- The KAGRA project can be terminated.
- Promises in the LVK are broken and trust of Japan is lost.
- LIGOIndia starts

② Data Analysis

- NAOJ can not lead GW astronomy. Only hardware contribution
- The KAGRA can not provide sufficient CPU to LVK in GRID frame.
  → NAOJ can lead GW data management

③ Frequency Dependent Squeezing for KAGRA

- We will lose technological advantage as a FDS pioneer.
- No improvement of sensitivity in principle
- We will lose Taiwanese and Korean friends…

④ Development of Large Sapphire Mirrors

- No improvement of sensitivity in principle, in particular lower frequency range

5. Threshold Science Mission

① International GW Observation

- **More than25Mpc BNS sensitivity at O5** to give impact of localization improvement by KAGRA
- 80% Duty cycle

② Data Analysis

- Hiring an expert of GW data analysis and computing

③ Frequency Dependent Squeezing for KAGRA

- Development and implementation of Squeezer to KAGRA to reduce photon shot noise

④ Development of Large Sapphire Mirrors

- Development of 40-100kg sapphire mirror substrates
- Small sapphire crystals with 20ppm/cm in optical absorption at 1064nm wavelength

8. Scientific Traceability Matrix

Science goals	Science objectives	Investigations		Instruments		Data Requirements
		Physical parameters	Observables	Design Parameters	Requirement	
Foundation of GW astronomy and Multi-messenger astronomy	Black-Hole Astronomy	Mass, Spin, Luminosity Distance, Number density	GW waveform	128Mpc BNS range	More than 25Mpc BNS sensitivity @05	Provision of 5000 CPU cores to LVK in GRID
	Multi-messenger astronomy using binary neutron star mergers	Mass, Luminosity Distance, Number density	GW waveform	128Mpc BNS range	More than 25Mpc NBS sensitivity @05	
		Inclination angle of orbit	Polarization	LVK network	More than 4 detectors @O5	
		EM wave, Neutrino	Luminosity, Spectrum, Energy, Arrival Time…	J-GEM (Subaru etc.), Rubin, ALMA, Ice-CUBE, SK/HK, Fermi…	Wide FOV, Various wavelength, Various detectors	

7. Project Organization

6. Cost Estimation