Gravitational Wave Astronomy

KMI Colloquium @Nagoya University, Nov. 27, 2013

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JGW-G1302016-v1

Outline

- Gravitational wave
- Laser interferometer detector
- Science obtained so far
- KAGRA
- DECIGO
- Summary

Gravitational wave

- **Einstein Equation**

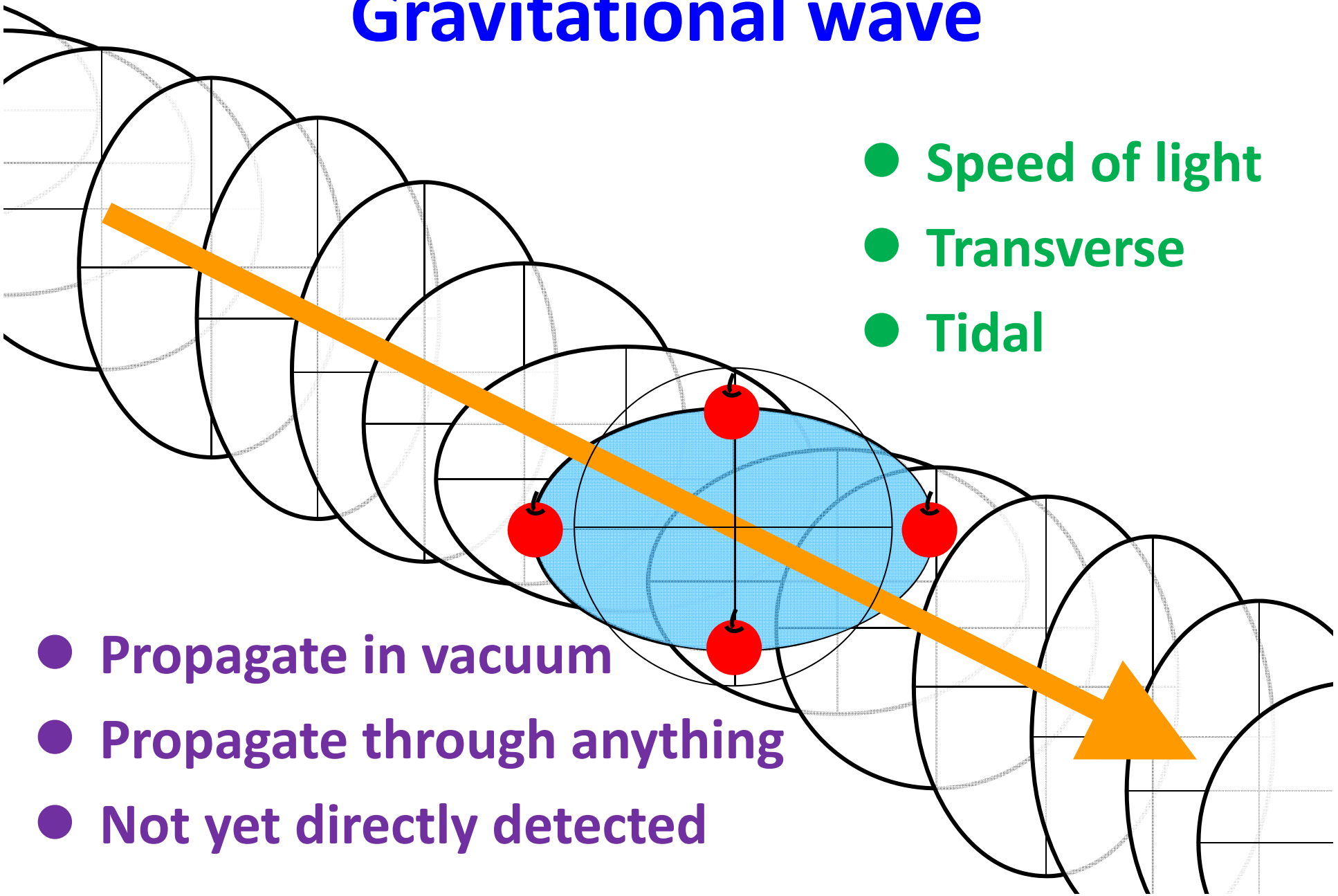
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\kappa T_{\mu\nu}$$

- **For a small perturbation 'h', a wave equation is derived**

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$

Gravitational wave

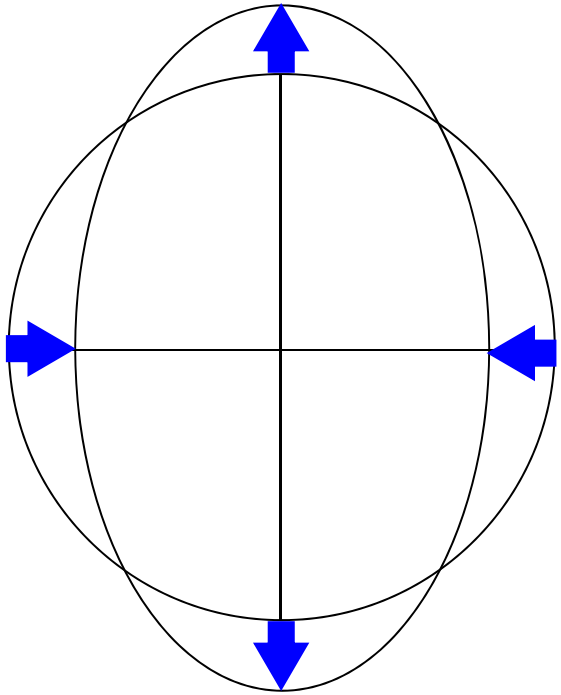


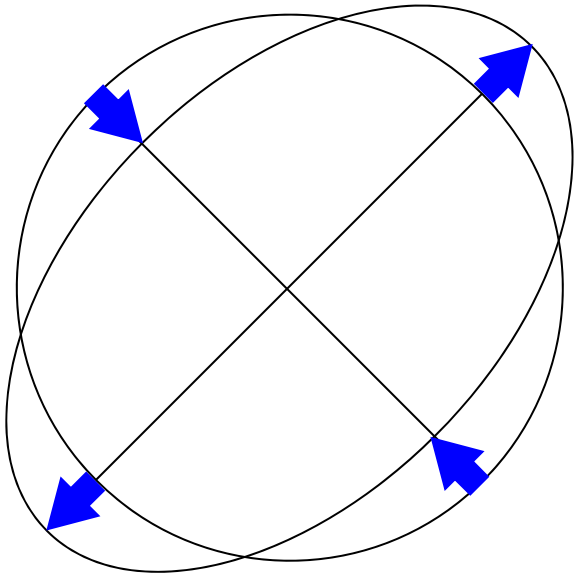
- Speed of light
- Transverse
- Tidal

- Propagate in vacuum
- Propagate through anything
- Not yet directly detected

Polarization

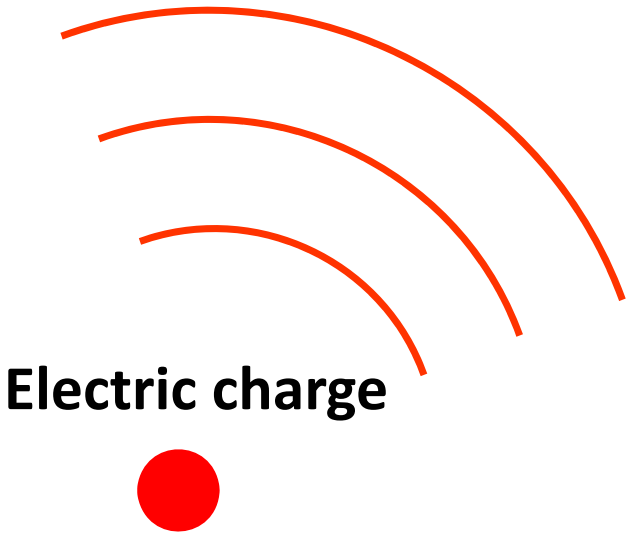
$$h_+ = h \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad h_\times = h \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$





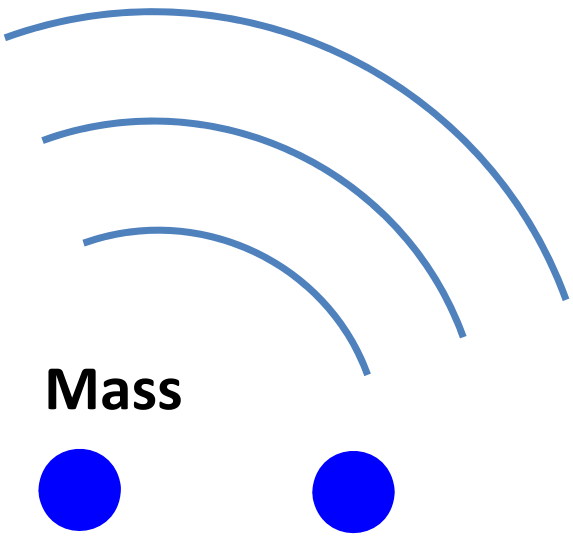
What produces GWs?

Electromagnetic wave



Dipole radiation

Gravitational wave



Quadrupole radiation

GW exists!

- Hulse & Tayler's observation on PSR 1913+16
- Orbit period decreased due to GW emission
- Nobel prize in1993

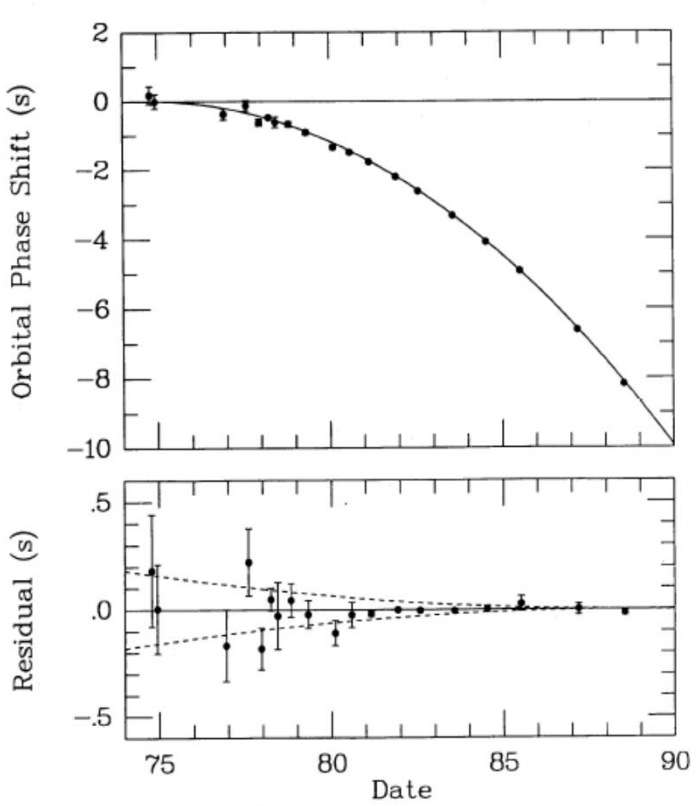


FIG. 5.—*Top:* Cumulative shift of the times of periastron passage relative to a nondissipative model in which the orbital period remains fixed at its 1974.78 value. *Bottom:* Differences between the locally measured periastron times and those expected according to the DD(1) parameter set. Dashed curves illustrate differential trends that would be expected (relative to epoch 1988.54) if the rate of orbital decay $\dot{P}_b$ were 2% larger or 2% smaller.

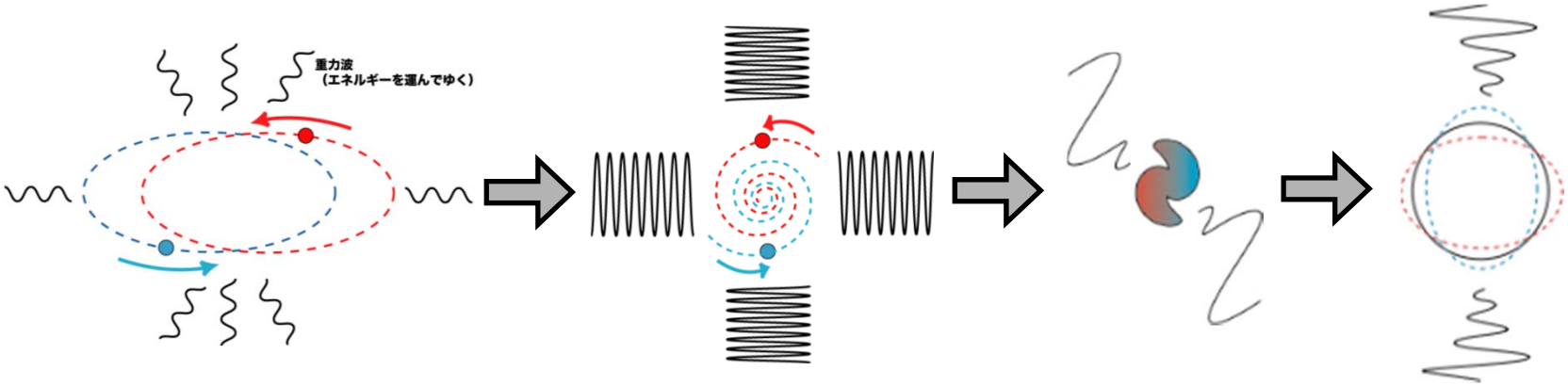
Taylor et al., ApJ.345(1989) p435

Emission of gravitational wave

1. Coalescence of binary neutron star
2. Supernova
3. Coalescence of binary black hole

CG／KAGAYA

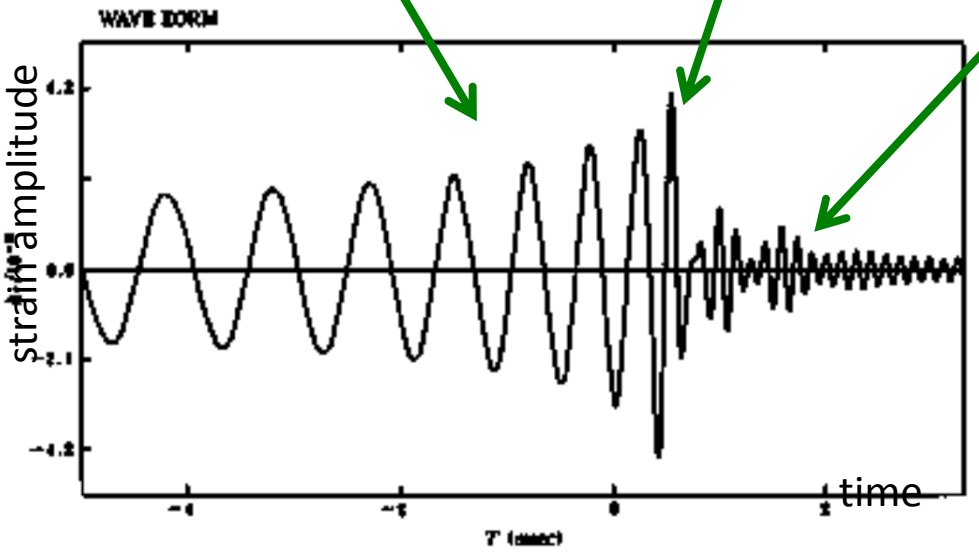
Neutron star binary coalescence



inspiral phase

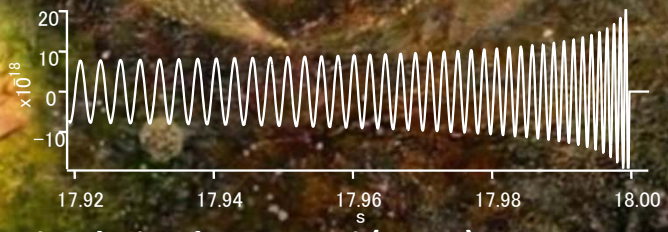
merger

Black hole quasi-normal mode



Sound of chirp signals

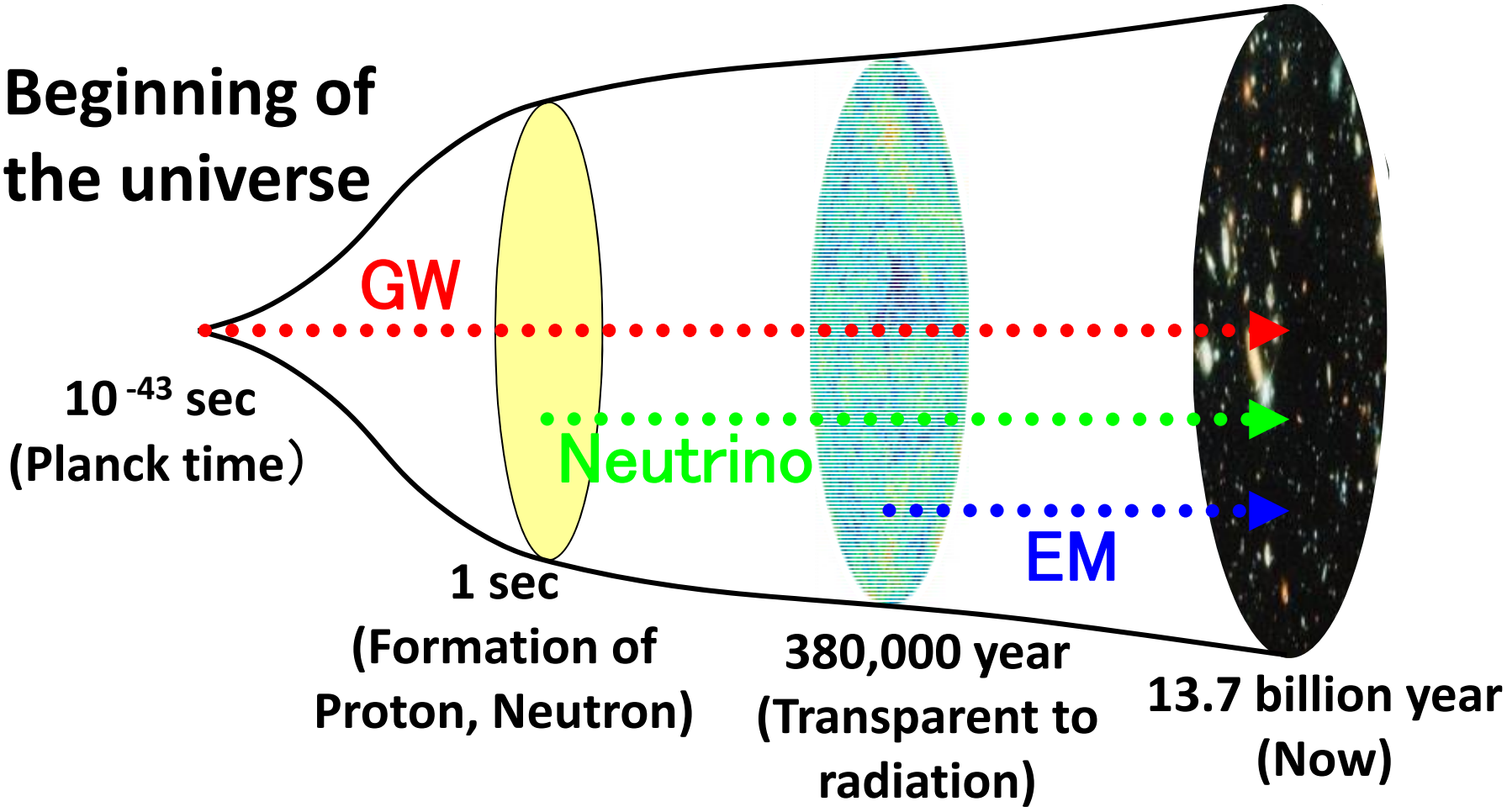
- NS-NS inspiral
- BH-BH (10 solar mass) inspiral
- Whole universe (optimistic)



Simulation by Tatsumi (NAOJ)

Illustration by Sora

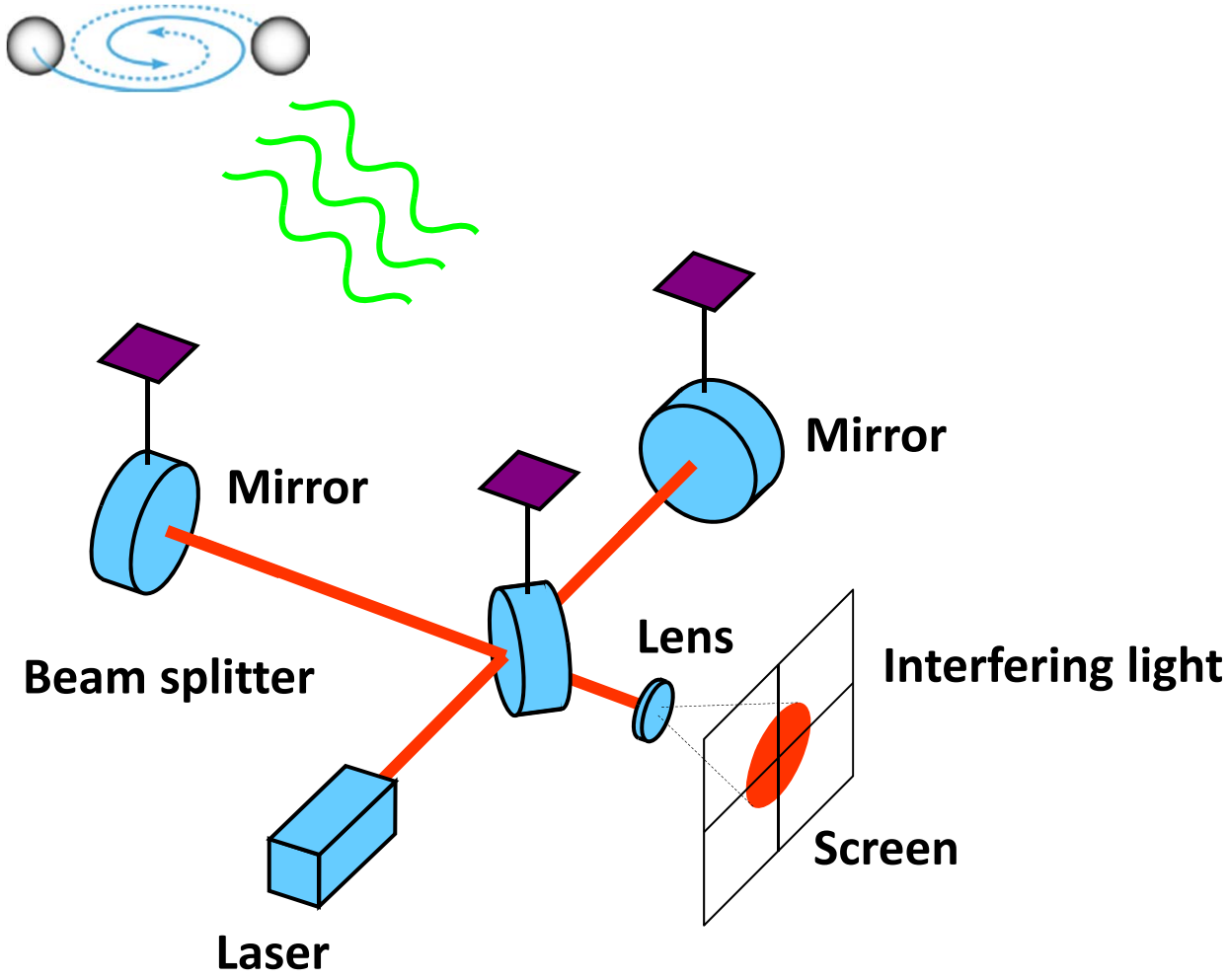
Beginning of the Universe



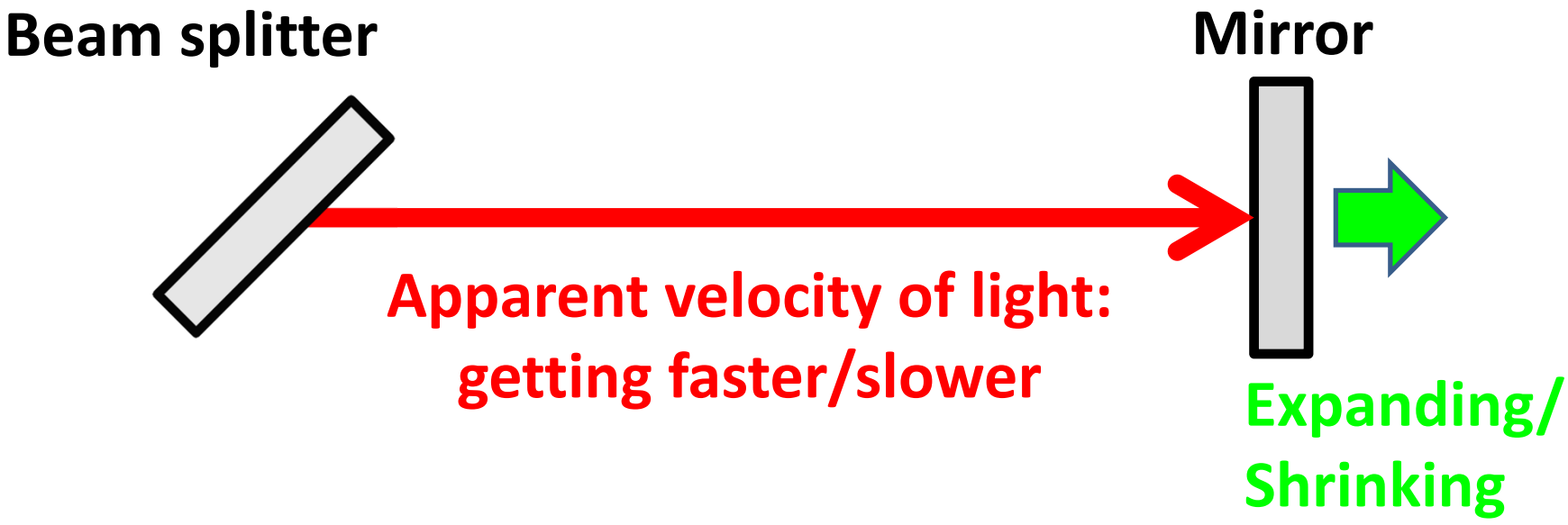
Extra dimensions

- **Gravitational waves could leak into extra dimensions.**
- **If we find that the observed amplitude of GW is weaker than the amplitude expected by general relativity, it could indicate the evidence of the existence of extra dimensions.**

Michelson interferometer



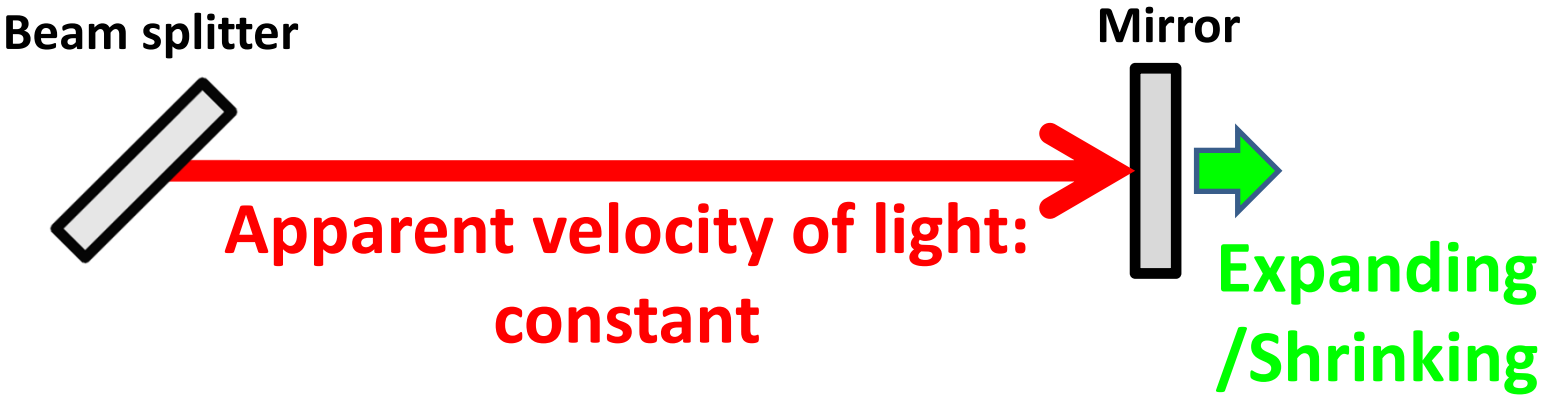
Can we really measure it?



Aren’t the two effects canceled out?

Yes, we can!

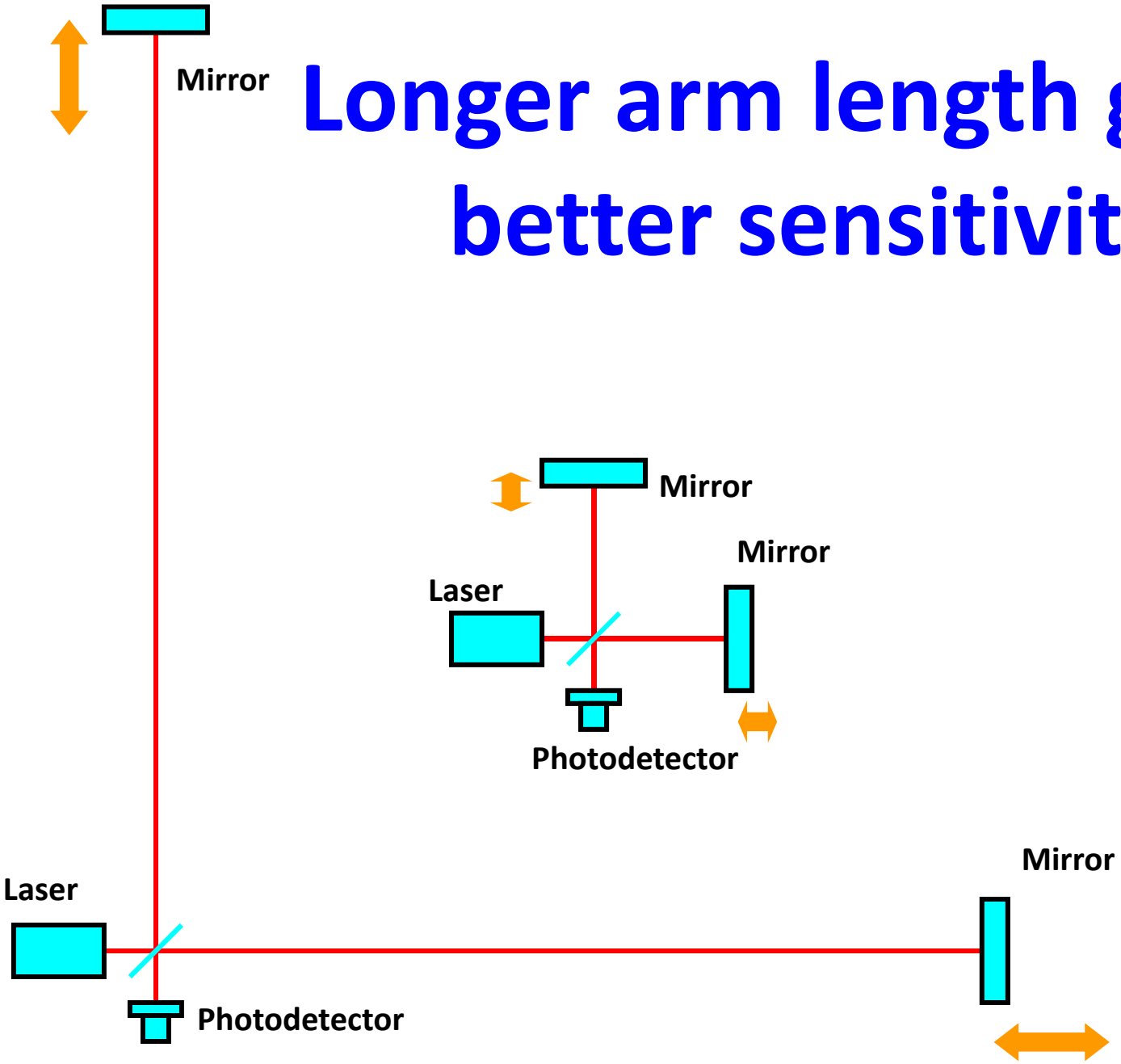
(1) Local Lorentz frame



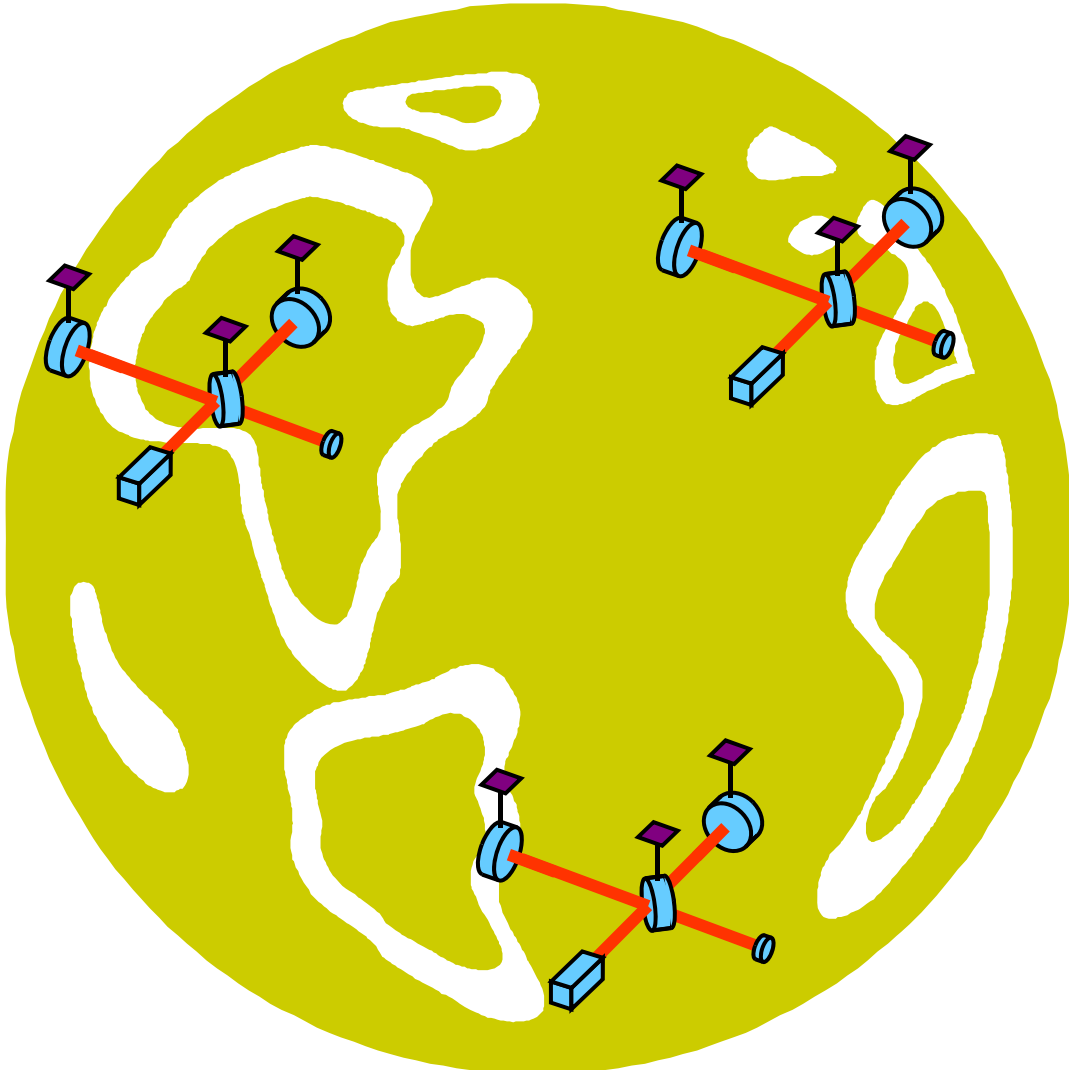
(2) Transverse Traceless gauge

In either coordinate, the travel time of light changes.

Longer arm length gives better sensitivity

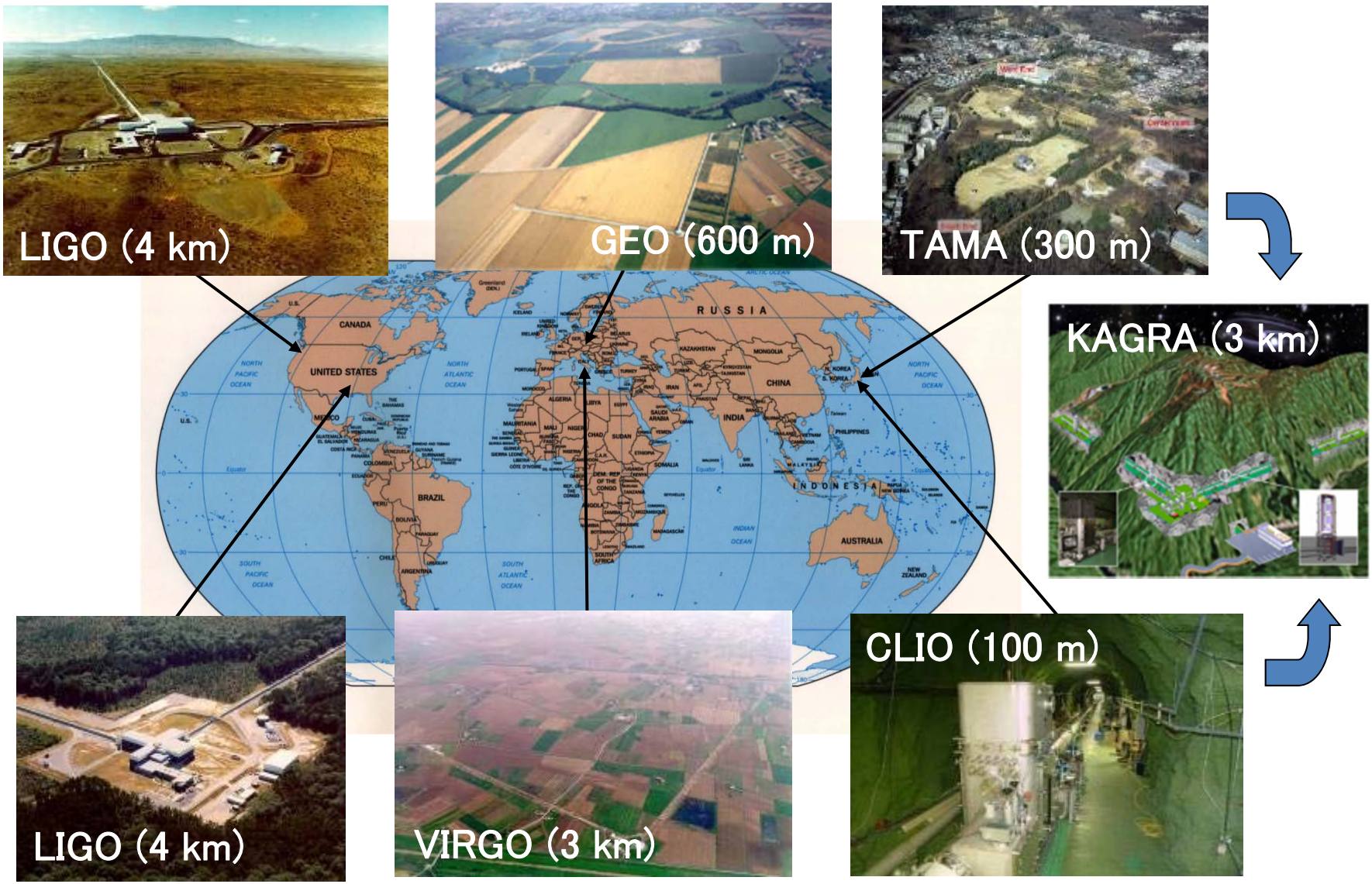


Direction of source

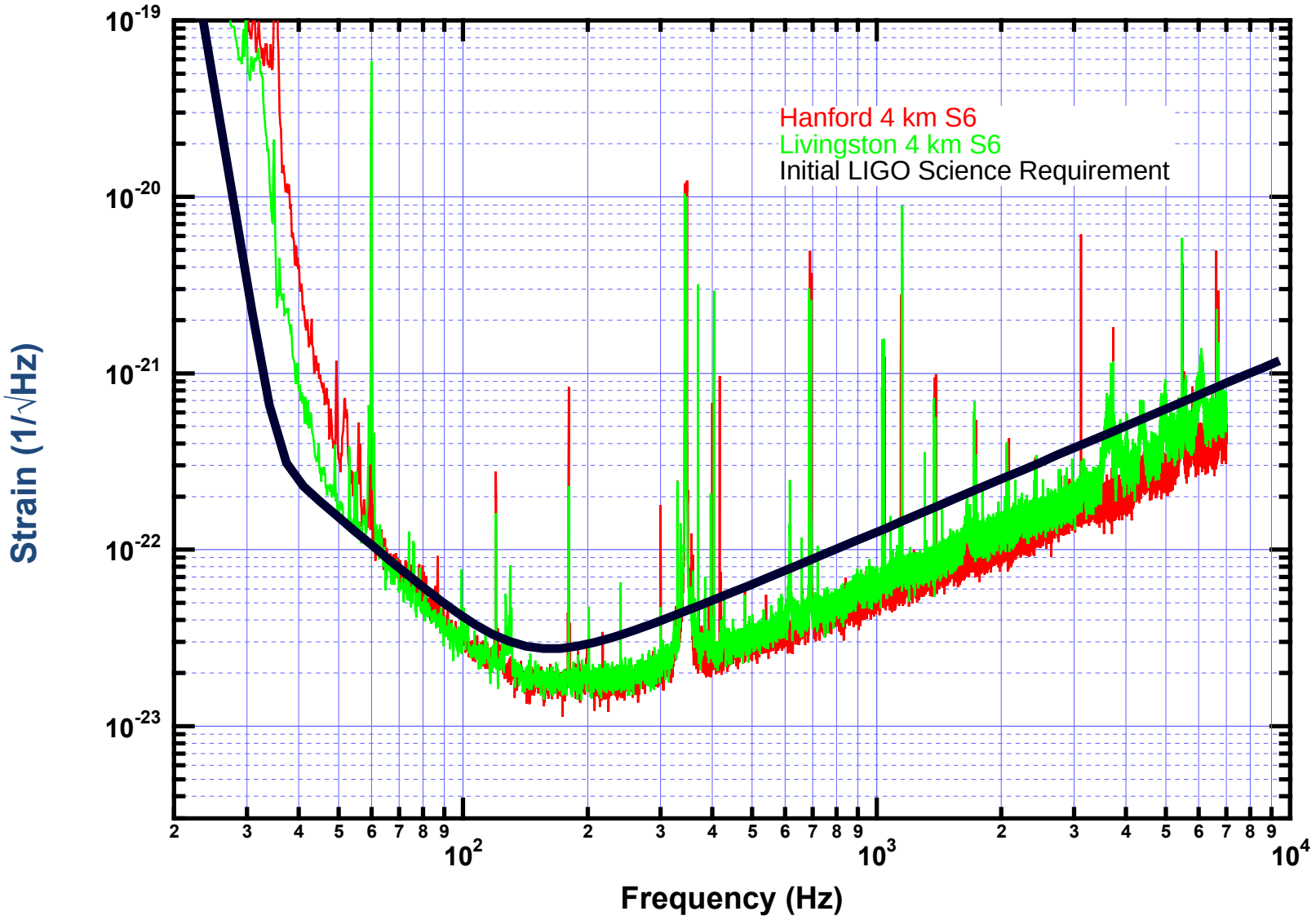


Difference in arrival time

Detectors in the world



Sensitivity of enhanced LIGO



Astrophysics reach

- **We have not yet detected GWs**
- **It is not surprising given the expected GW signals**
- **Yet, it is surprising that we have not yet got any surprise!**

GRB 070201

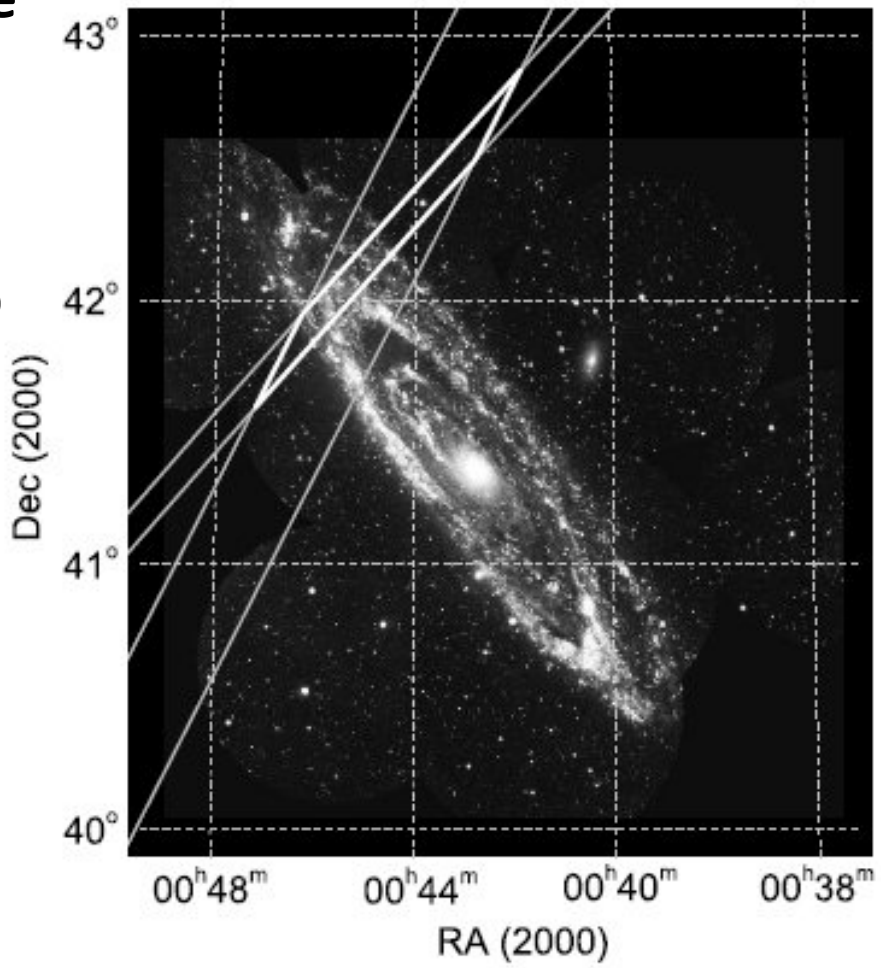
(Short) GRB 070201 was found to be originating in the direction that includes M31

but

No GW signal was detected by LIGO

Binary merger in M31 scenario was excluded at >99% level

- **Most likely giant magnetar flare**
- **Significant scientific result**
- **Start of synergy between GW and other astronomy**



Abbott B, et al., Astrophys. J., **681** (2008) 1419

Crab Pulsar

Spin down rate gives the upper limit of GW emitted from Crab pulsar

No GW signal was detected by LIGO

GW energy upper limit < 4% of spin down limit

- **Significant scientific result**

Abbott B, et al., ApJ Lett., **683** (2008) 45

Stochastic background

Set the upper limit for stochastic GW background coming from the beginning of the Universe.

$\Omega_{GW} < 6.9 \times 10^{-6}$

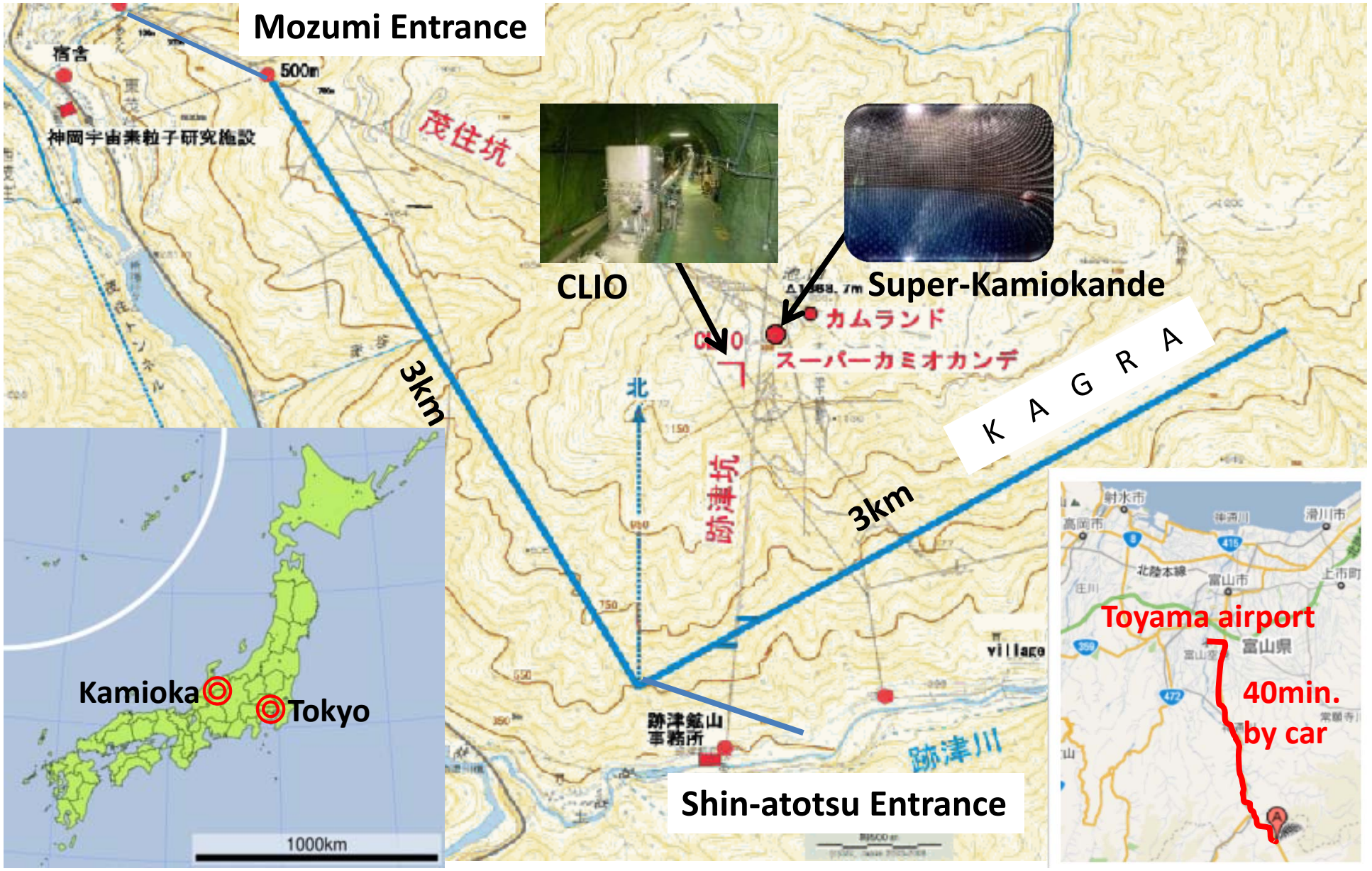
Better than the upper limit set by Big Bang Nucleosynthesis and observation of microwave background

Set some constraints for super string theory and the evolution model of the early Universe

Abbott B P, et al., Nature, **460** (2009) 990

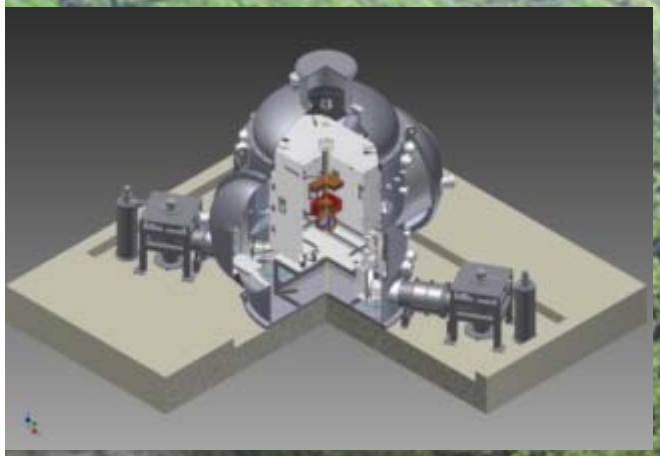

KAGRA
KAGRA

Location (Kamioka)



Key features of KAGRA

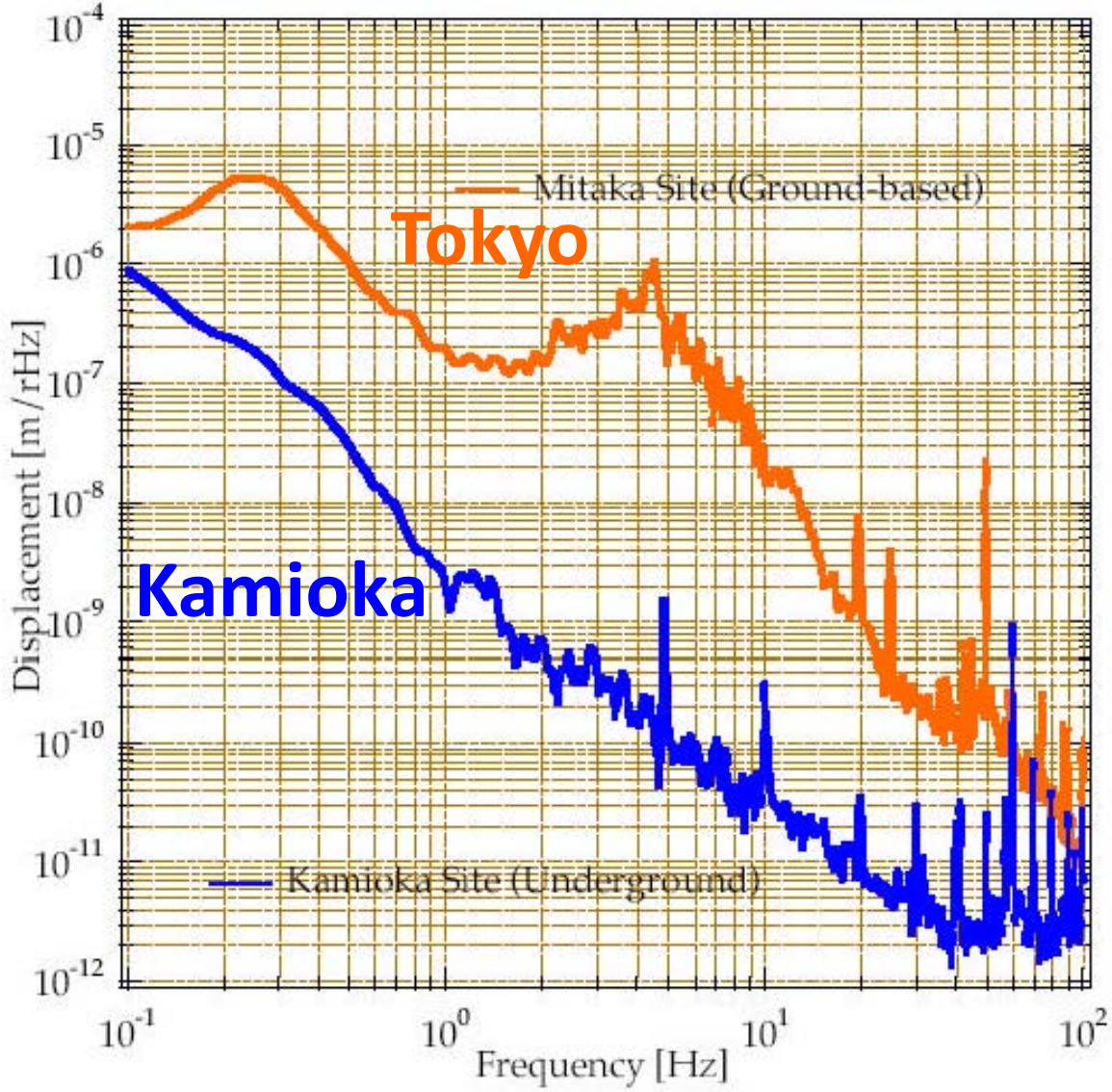
Cryogenic Mirror



Underground

Technologies crucial for the 3rd-generation detectors; KAGRA can be regarded as a 2.5-generation detector.

Ground motion in Kamioka mine



Hard rock of Hida gneiss
(5 [km/sec] sound speed)

Vibration isolation system

Two-layer structure was chosen to avoid the resonances of the structure.

2nd floor

Chamber

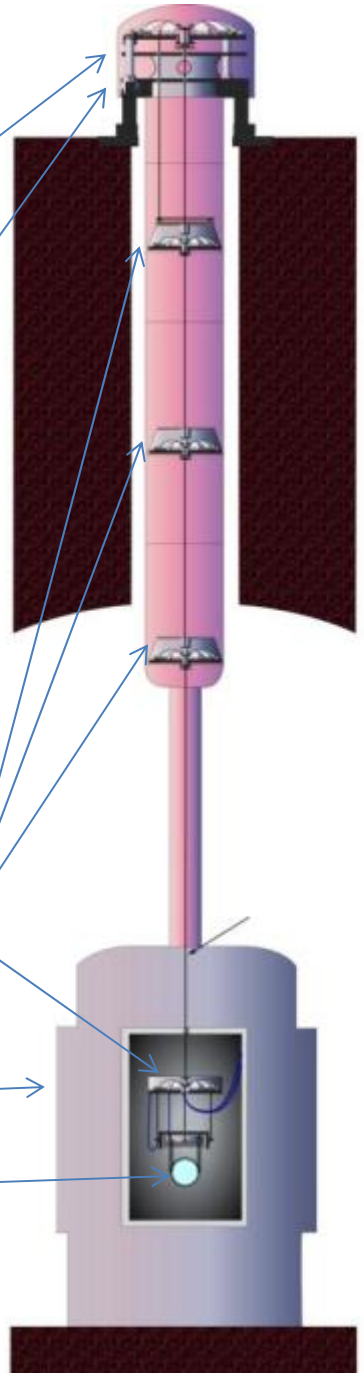
Inverted pendulum

Geometrical antispring filter

Cryostat

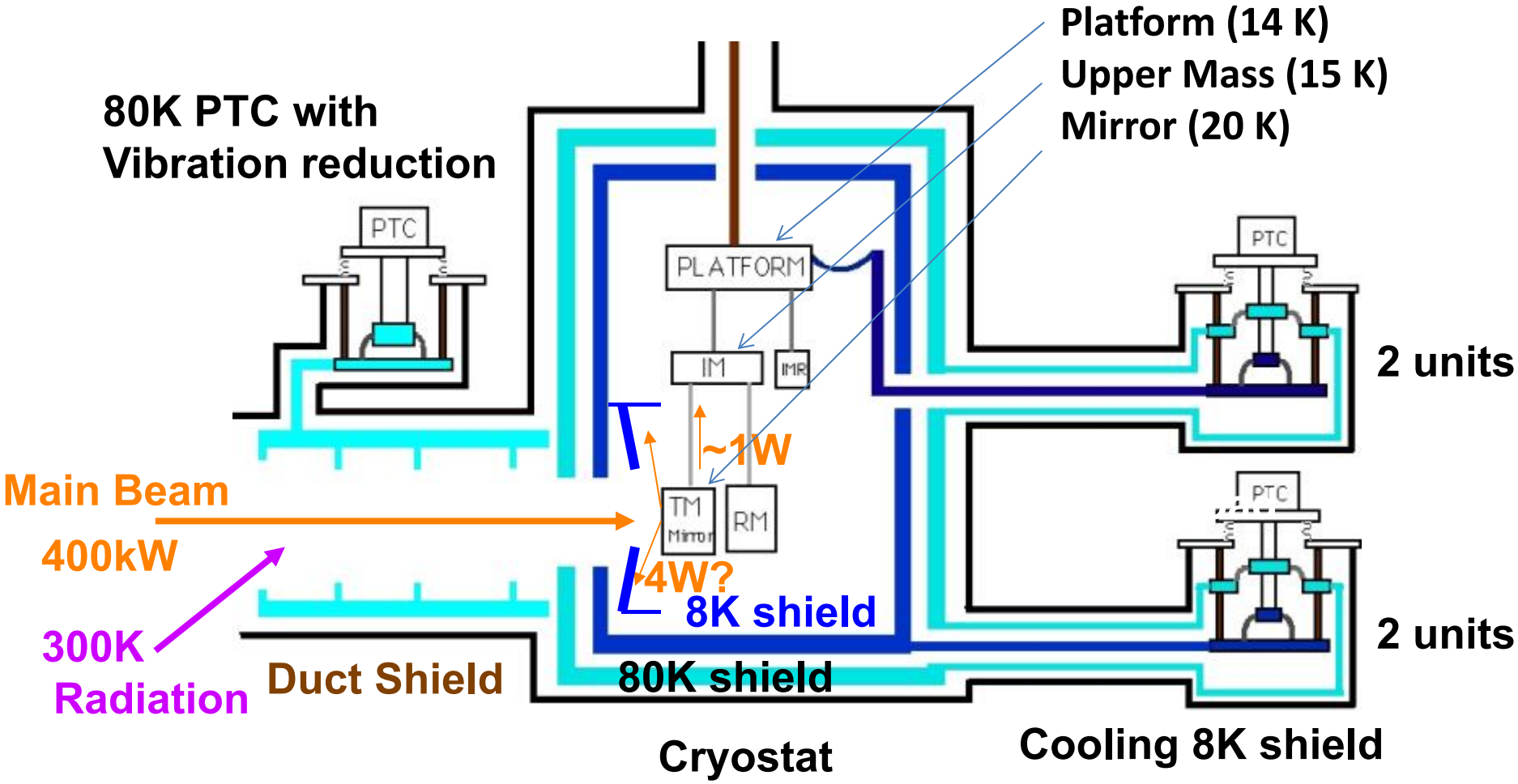
Mirror

1st floor

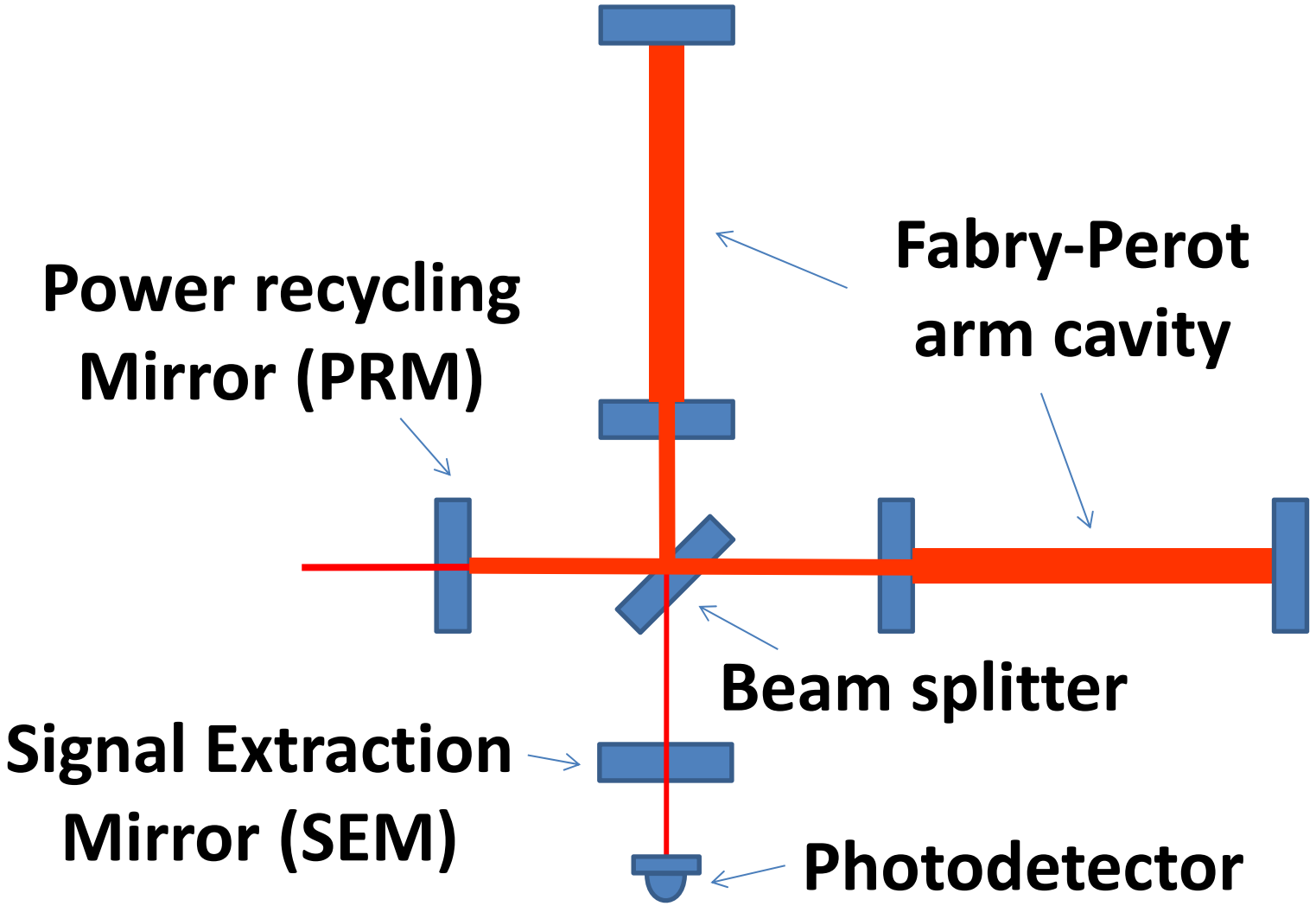


Tunnel (3D movie)

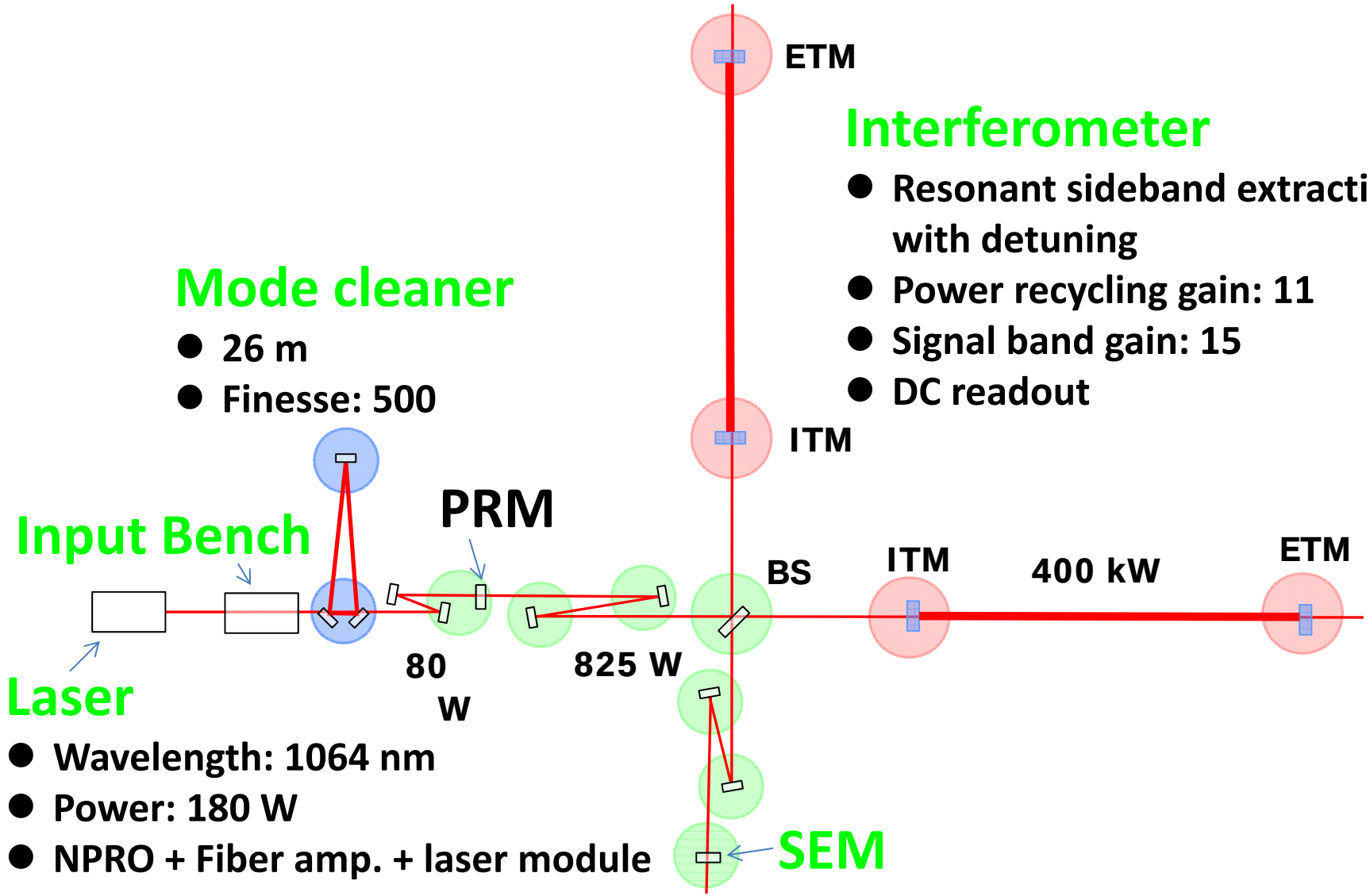
Cryogenics System



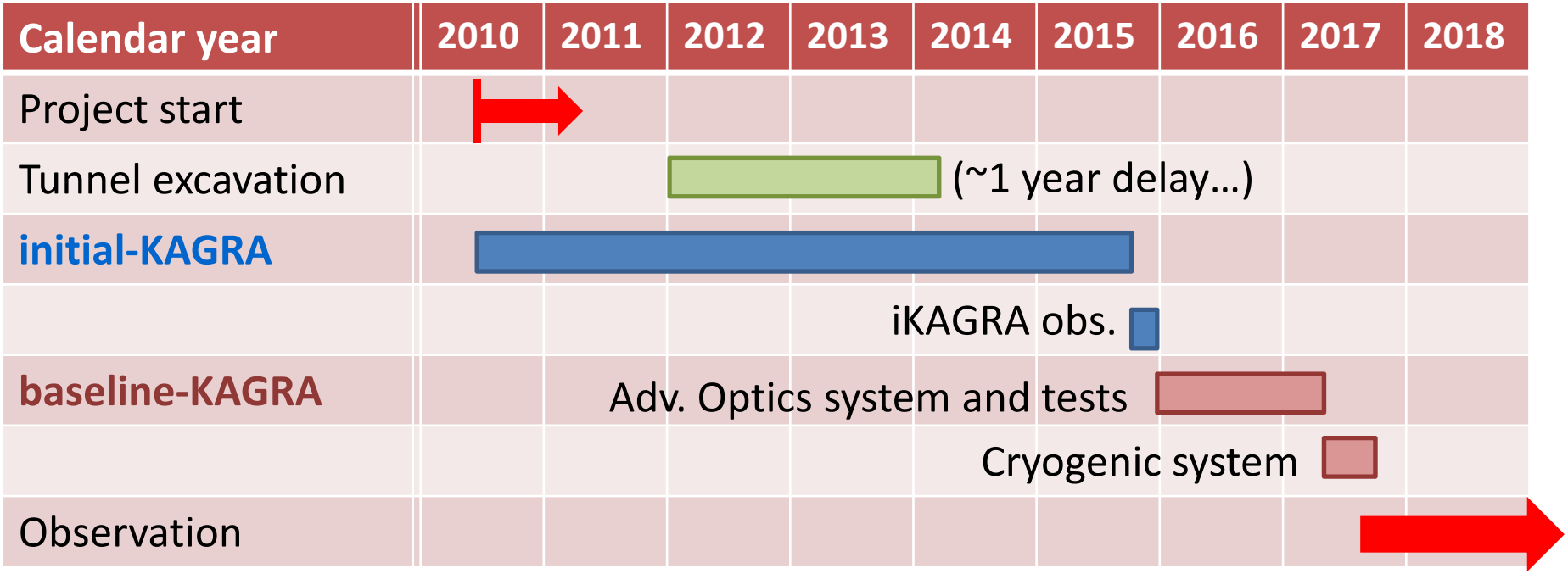
Resonant Sideband Extraction (RSE) interferometer



Optical configuration



Schedule of KAGRA



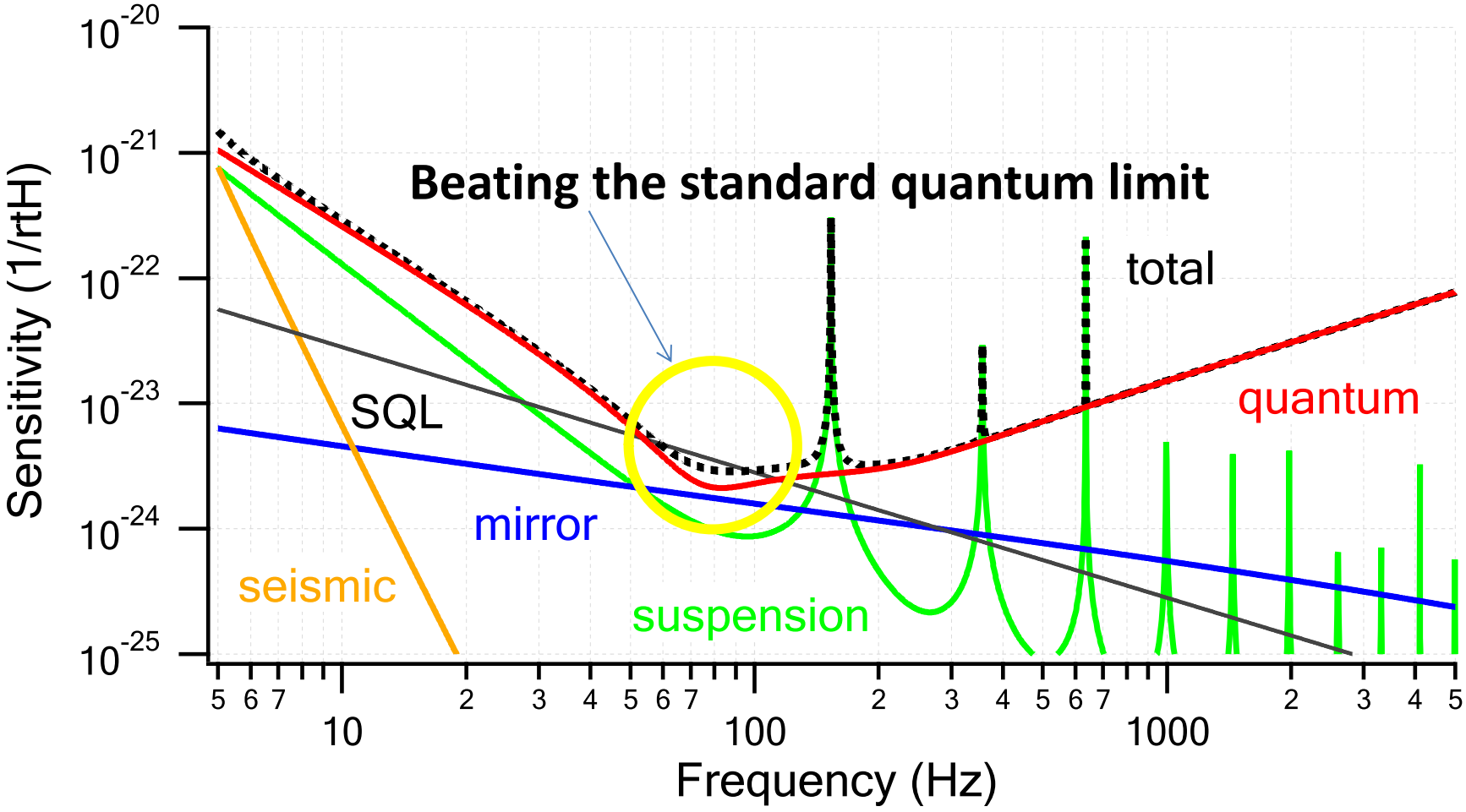
iKAGRA

- Fabry-Perot Michelson interferometer
- Room temperature
- Simple seismic isolation system

bKAGRA

- Resonant sideband extraction with detuning
- Cryogenic temperature
- Advanced seismic isolation system

Target Sensitivity of KAGRA



Expected event rate for NS-NS coalescence

Inspiral range: 176 Mpc
(the same definition as LIGO/Virgo)

Assuming Inspiral rate per galaxy

$$118^{+174}_{-79}\,\mathrm{Myr}^{-1}$$

Expected event rate $9.8^{+14}_{-6.6}\,\mathrm{yr}^{-1}$

Tunnel excavation

Mozumi Entrance

New-Atotsu Entrance

Blasting (Movie)

Water (Movie)

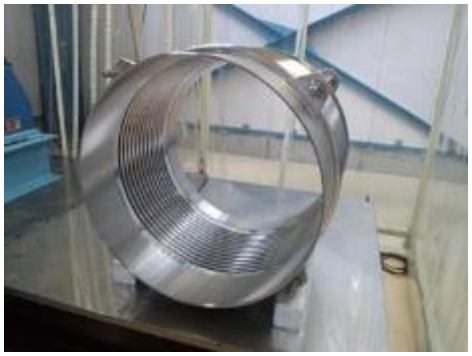
Water (Movie)

Beam tubes

12m, Φ800mm beam tubes for 3km x 2 arms:

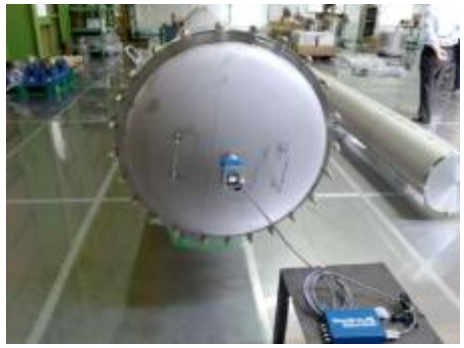
Delivered in 2012

Press to form a beam tube



Bellows for each beam tube

Baking at MIRAPRO Co.
Noda/MESCO, Kamioka



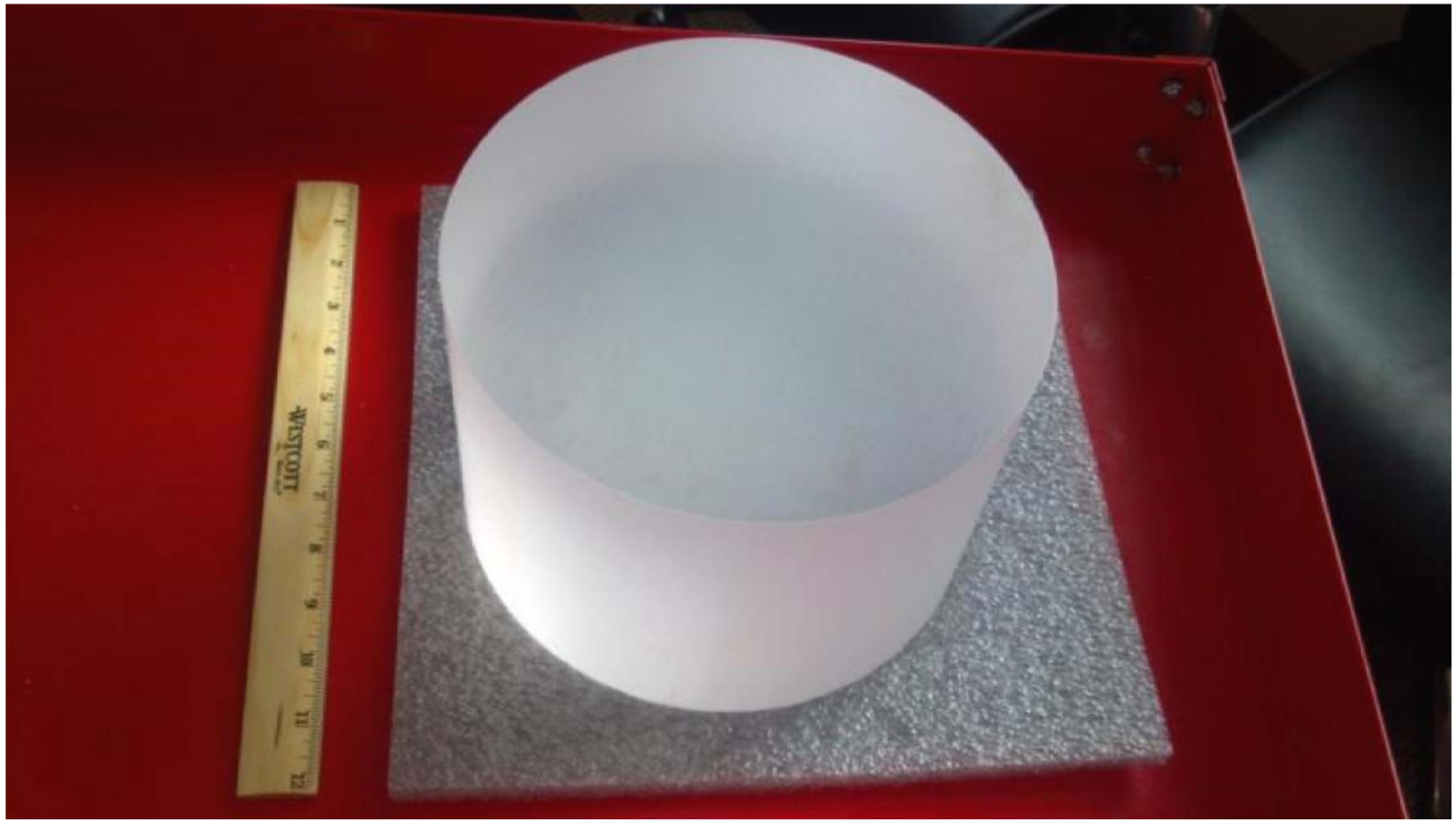
Test at MIRAPRO Co. Noda

Transportation to Kamioka

Cryostat construction and test

Construction and cooling tests were finished!

Sapphire Mirror

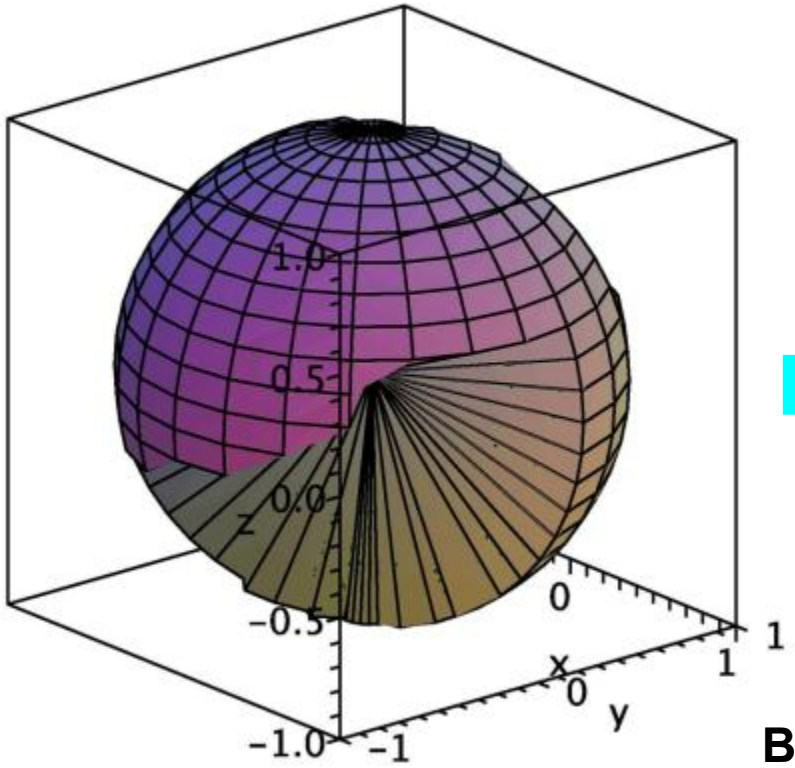


Two Sapphire substrates have been delivered.
(Φ220mm, t 150mm, c-axis)

KAGRA in network

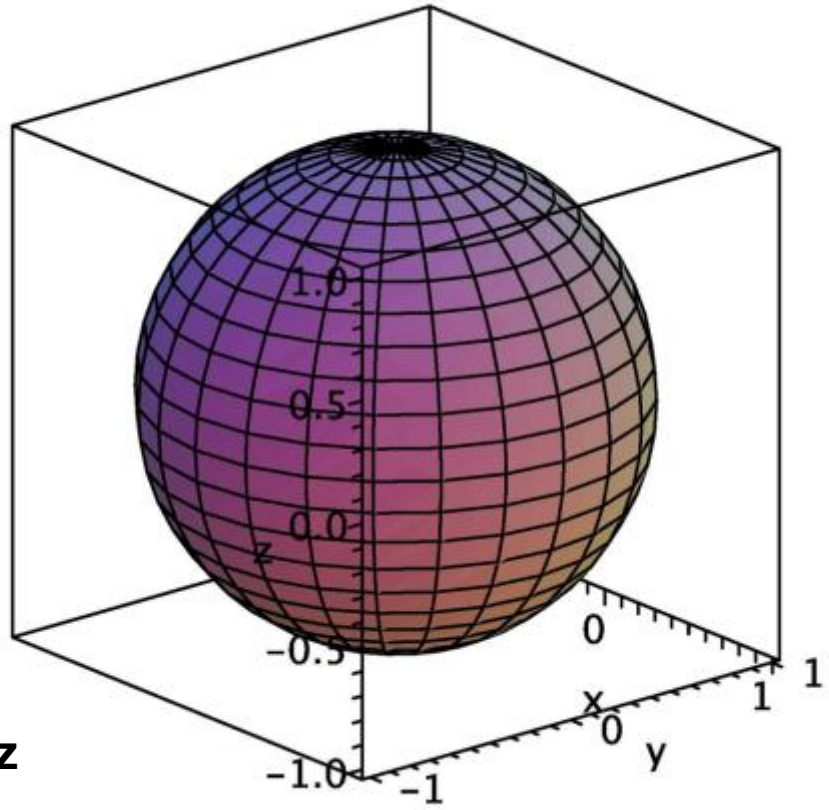
LIGO(H)+LIGO(L)+Virgo

- Coverage at 0.5 M.S.: 72%
- 3 detector duty cycle: 51%

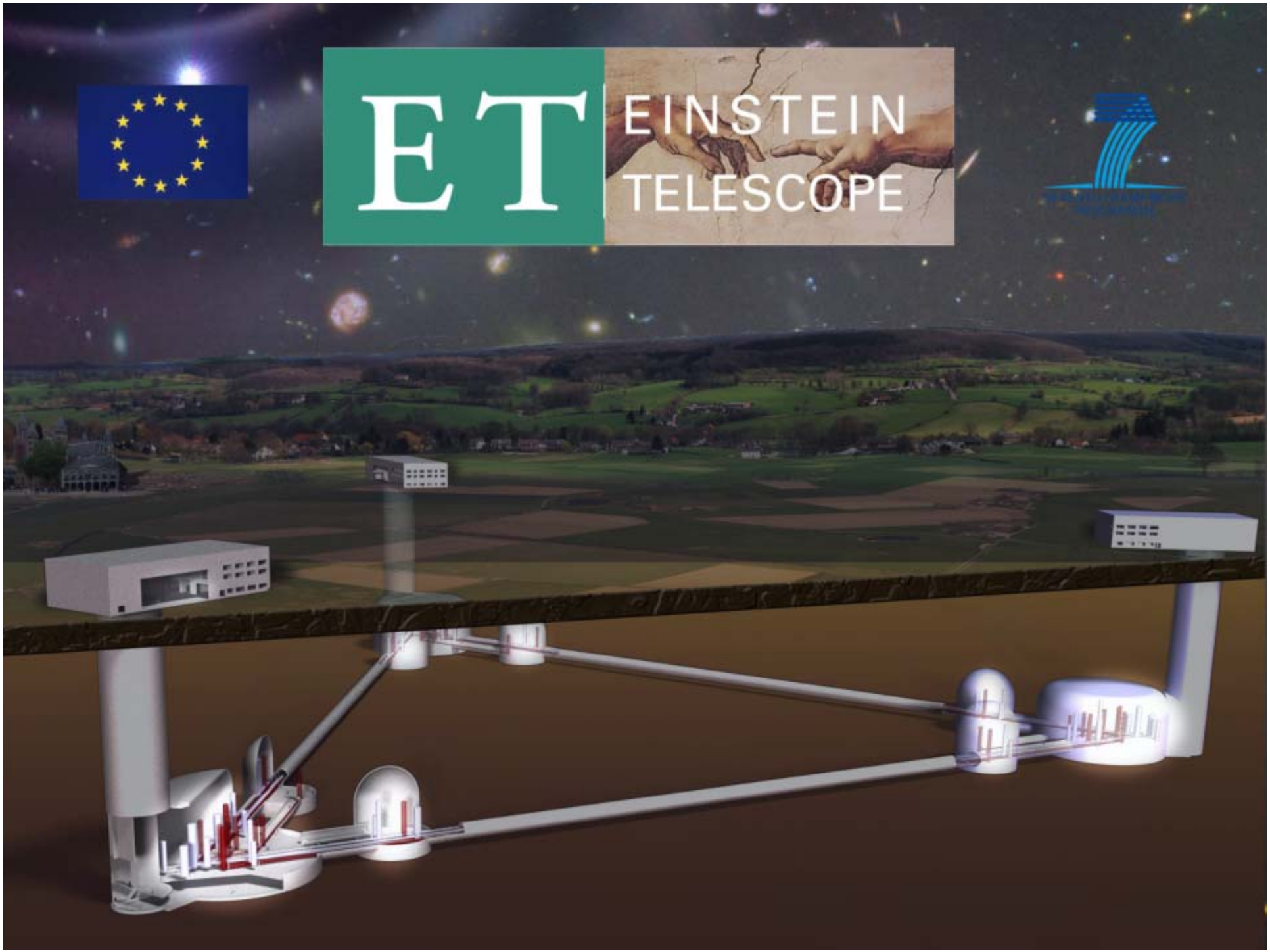


LIGO(H)+LIGO(L)+Virgo+KAGRA

- Max sensitivity (M.S.): +13%
- Coverage at 0.5 M.S.: 100%
- 3 detector duty cycle: 82%



B. F. Schutz

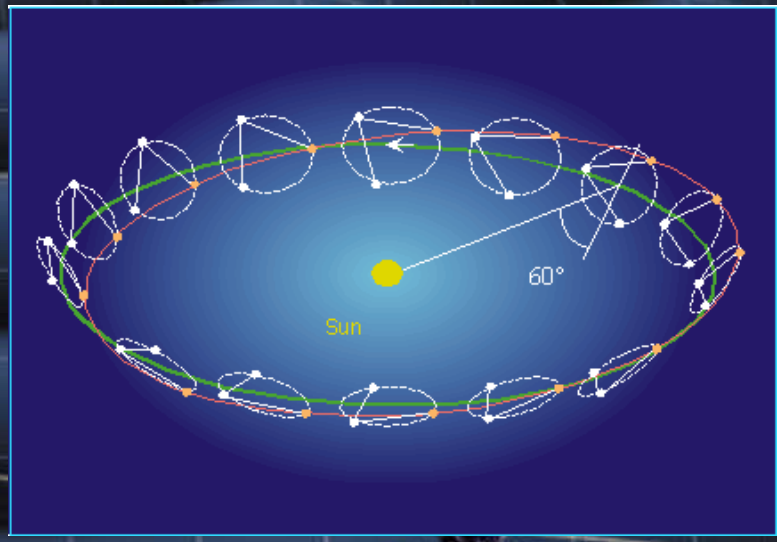

ET
EINSTEIN
TELESCOPE

Laser Interferometer in Space

- **Signal increased**
  - Due to longer interaction between GW and light
  - Cancellation of signals at higher frequencies
- **Noise reduced**
  - Lower seismic noise and gravity gradient noise

Sensitivity improved
at lower frequencies

eLISA



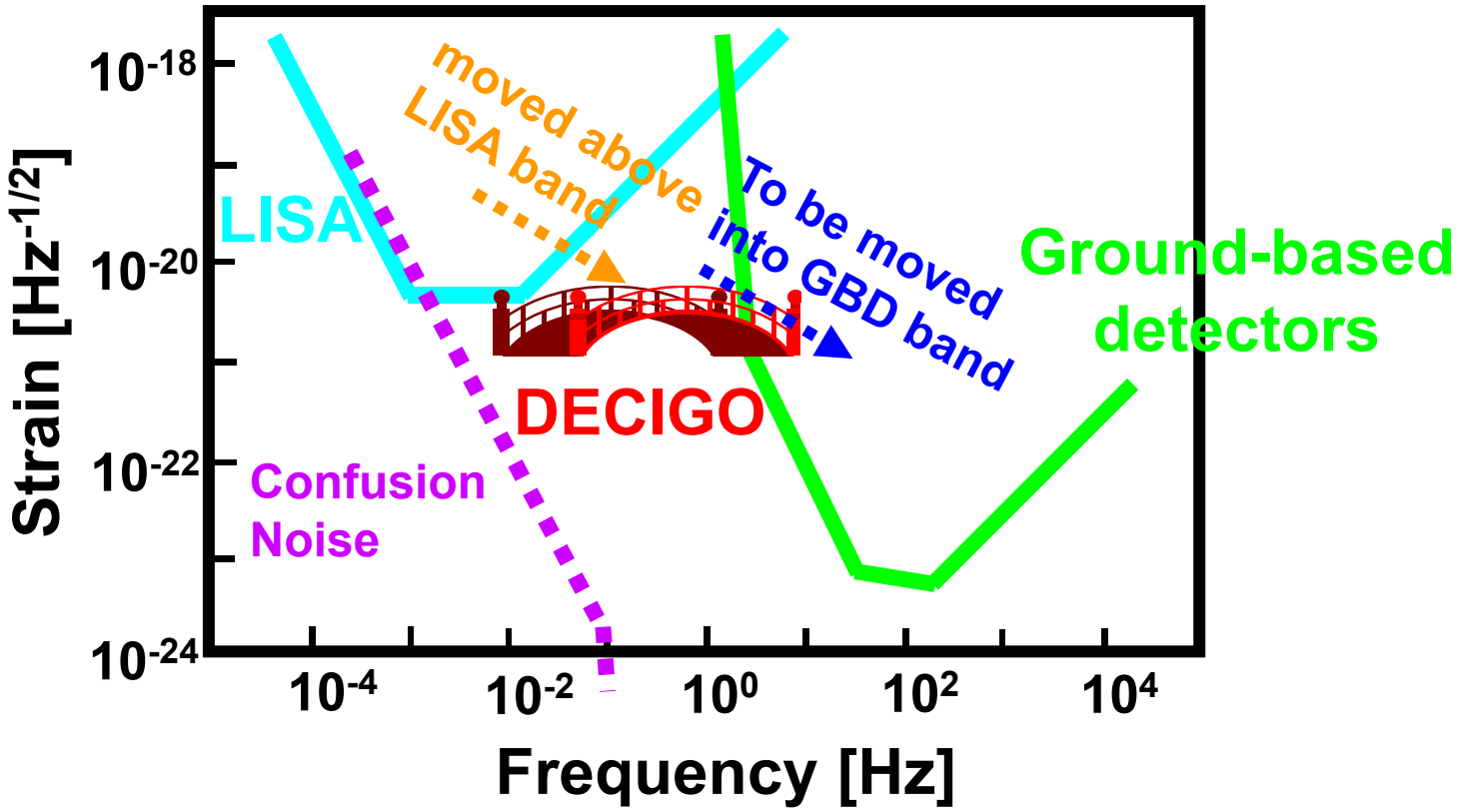
LISA project

Illustration Sora

What is DECIGO?

***Deci*-hertz Interferometer *G*ravitational Wave *O*bservatory**

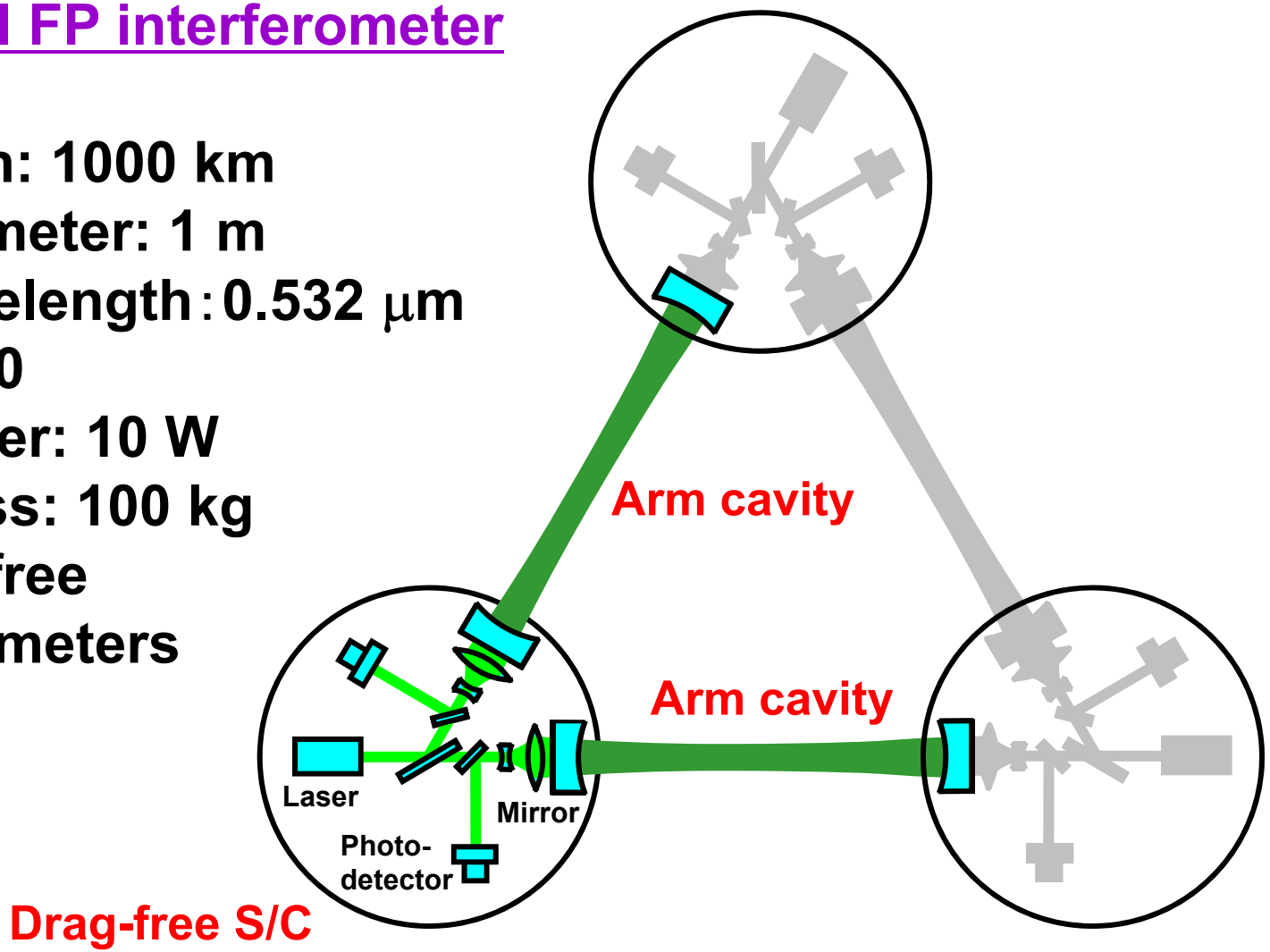
- **Bridges the gap between LISA and ground-based detectors**
- **Low confusion noise -> Extremely high sensitivity**



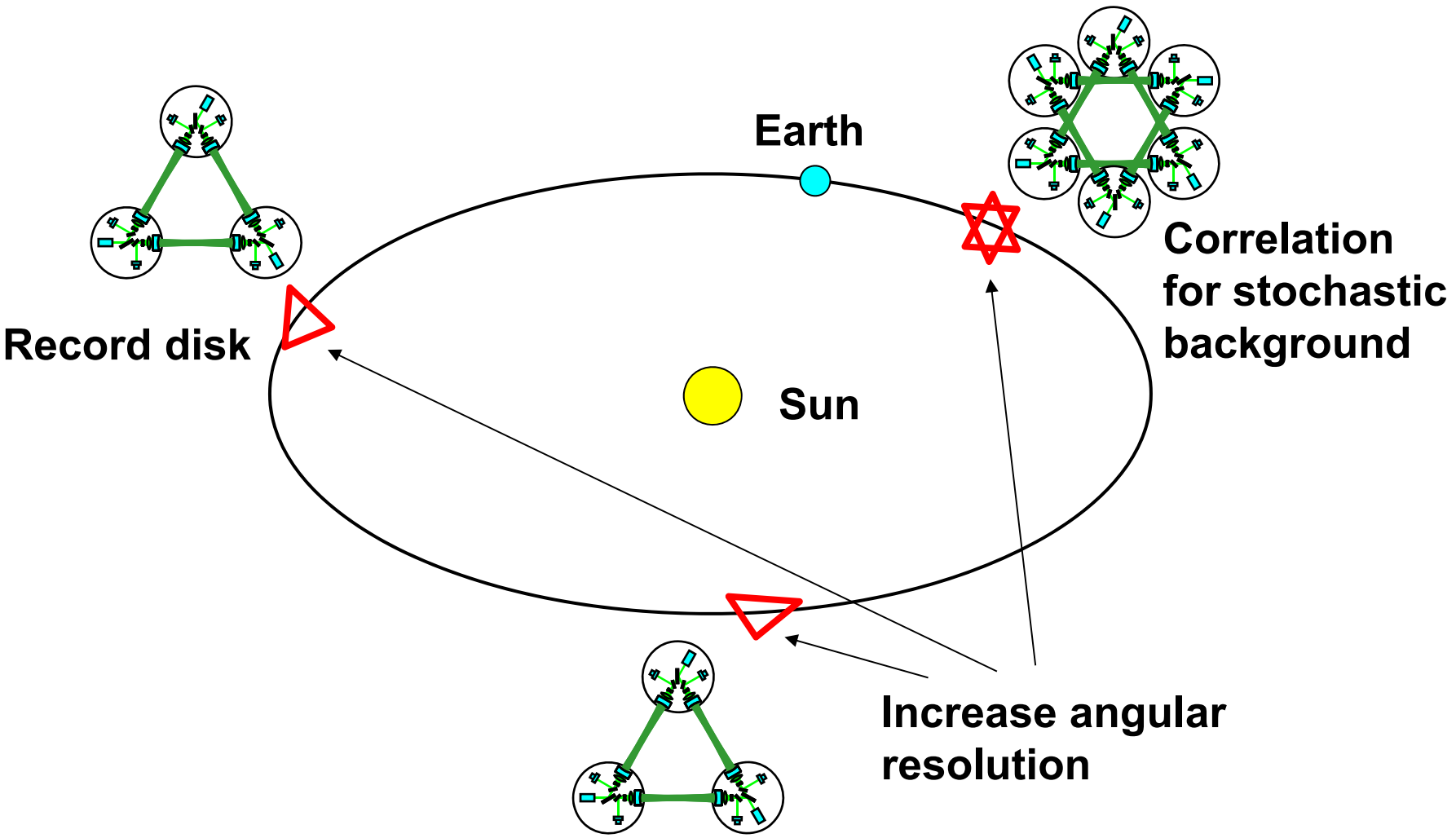
Pre-conceptual design

Differential FP interferometer

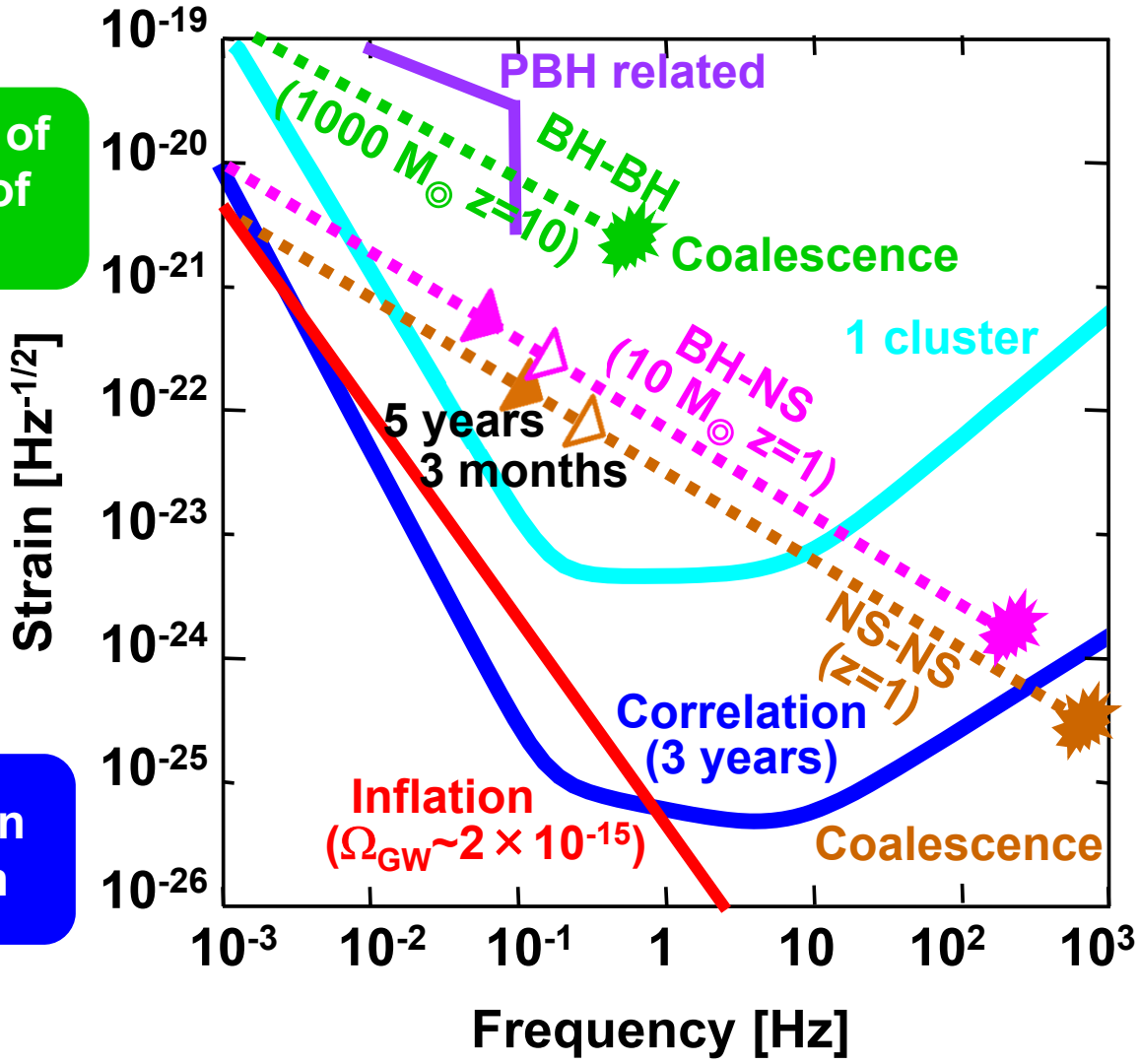
Arm length: 1000 km
Mirror diameter: 1 m
Laser wavelength : 0.532 μm
Finesse: 10
Laser power: 10 W
Mirror mass: 100 kg
S/C: drag free
3 interferometers



Orbit and constellation (preliminary)



Sensitivity and Science of DECIGO



Mechanism of formation of giant BH

Observation of inflation

Search for dark matter

Saito, Yokoyama 2009

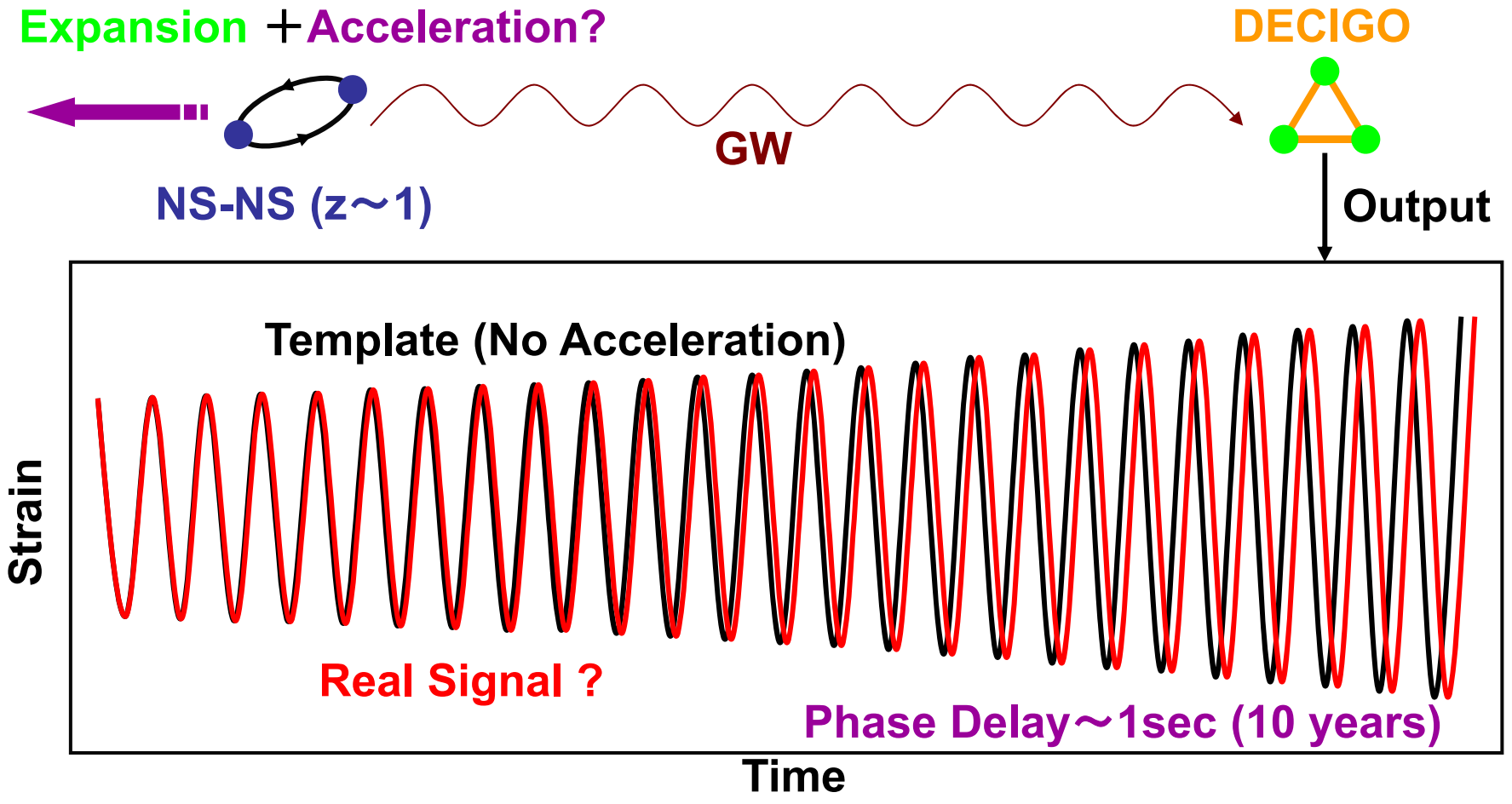
Verification of general relativity

Yagi, Tanaka 2009

Measurement of acceleration of expansion

Seto, Kawamura, Nakamura 2004

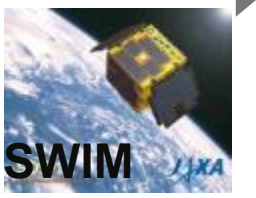
Acceleration of Expansion of the Universe

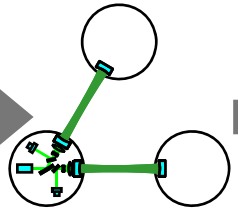


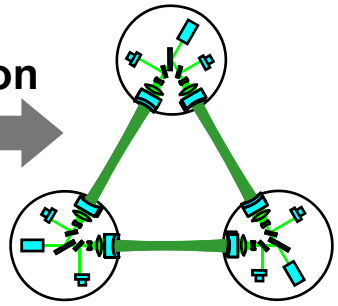
Seto, Kawamura, Nakamura, PRL 87, 221103 (2001)

Roadmap (should be updated)

	2009	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Mission	R&D Fabrication						DICIGO Pathfinder			R&D Fabrication			Pre-DECIGO			R&D Fabrication				DECIGO	
Objectives	Test of key technologies									Detection of GW w/ minimum spec. Test FP cavity between S/C						Full GW astronomy					
Scope	1 S/C 1 arm									3 S/C 1 interferometer						3 S/C, 3 interferometer 3 or 4 units					







Dawning of Gravitational Wave Astronomy is near!

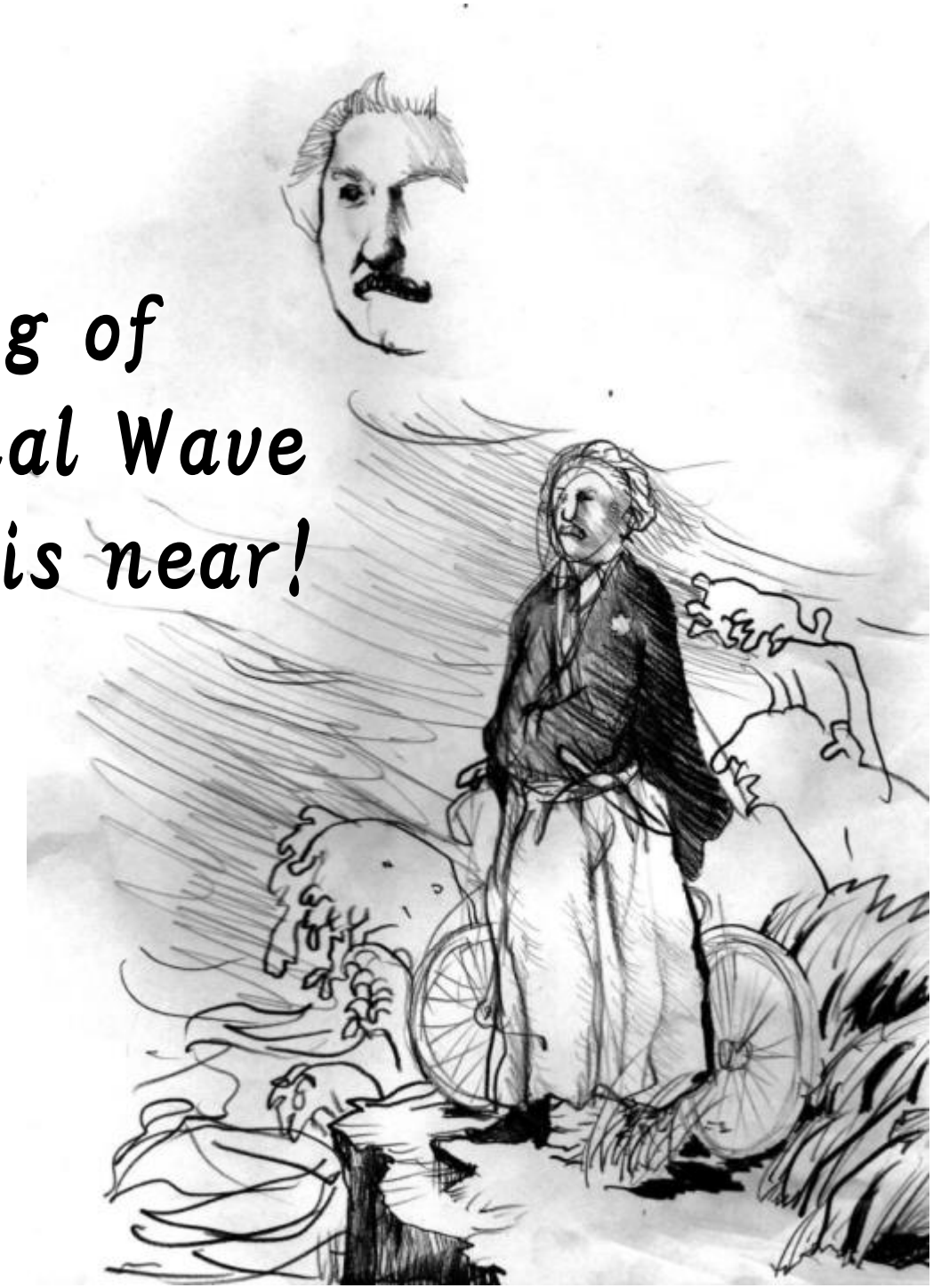
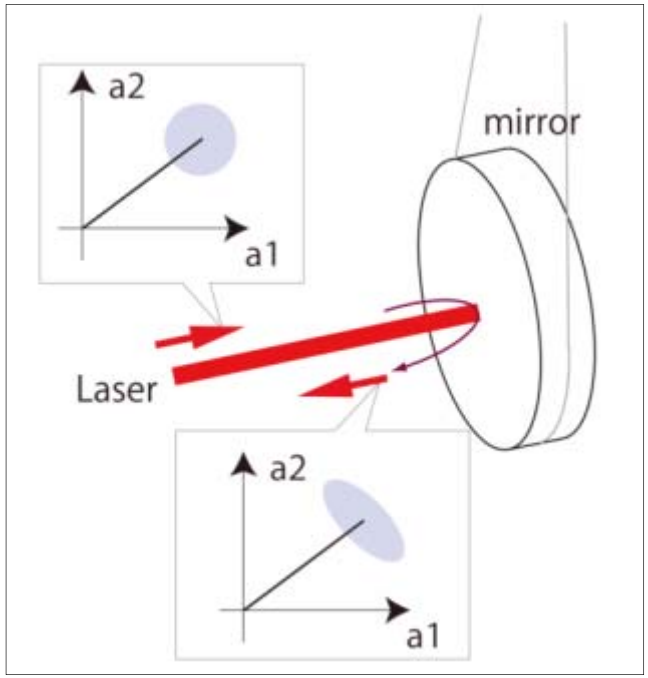


Illustration:
Sora

Ponderomotive squeezing

Incident light: (Amplitude fluctuations) + (Phase fluctuations)



Reflected light: (Original amplitude fluctuations)

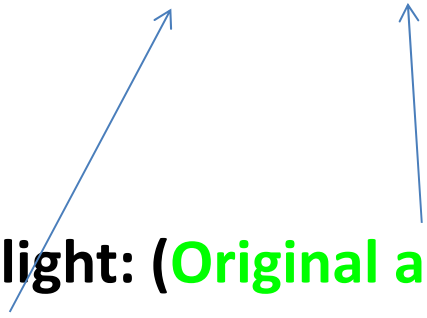
+ (Phase fluctuations caused by the original amplitude fluctuation)

+ (Original phase fluctuations)

Ponderomotive squeezing

Incident light: (Amplitude fluctuations) + (Phase fluctuations)

Can be Cancelled out with homodyne detection



Reflected light: (Original amplitude fluctuations)

+ (Phase fluctuations caused by the original amplitude fluctuation)

+ (Original phase fluctuations)