Journey toward Gravitational Wave Astronomy

IPMU Seminar

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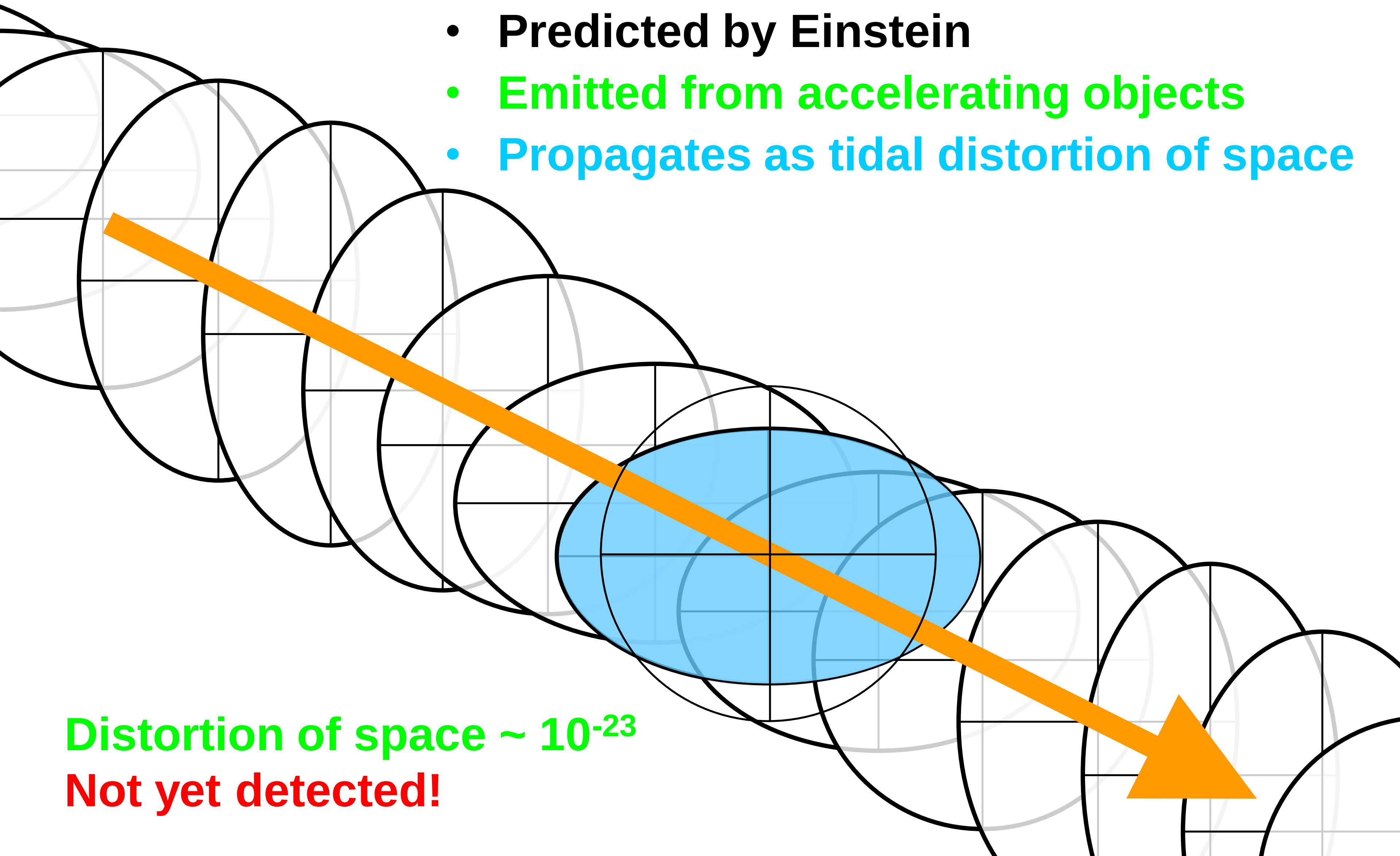
Sora

Outline

- Gravitational wave, detection, current status
- Space gravitational wave antenna DECIGO
- Advanced technologies for 3rd generation GW detectors
  - Displacement-noise free interferometer
  - Juggling interferometer
- Summary

Gravitational wave

- **Predicted by Einstein**
- **Emitted from accelerating objects**
- **Propagates as tidal distortion of space**

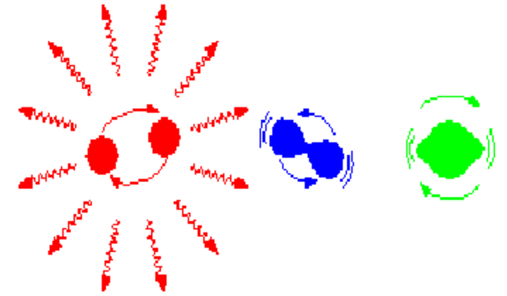


Distortion of space ~ 10^{-23}

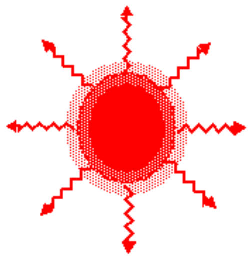
Not yet detected!

Astrophysical Sources of Gravitational Waves

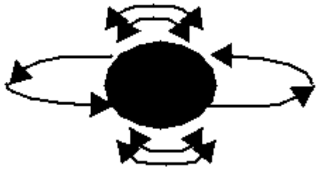
Coalescing compact binaries
(neutron stars, black holes)



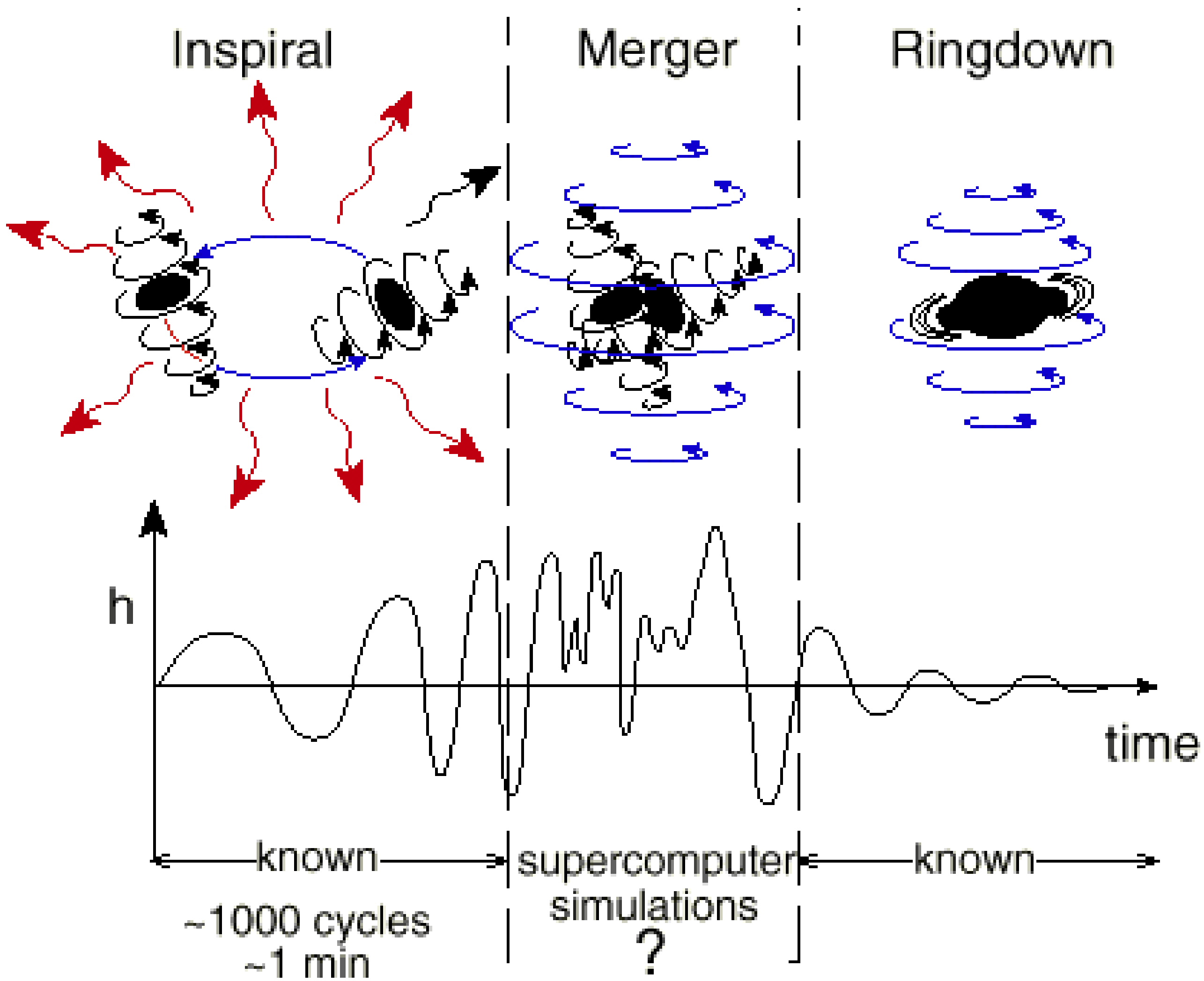
Non-axi-symmetric
supernova collapse



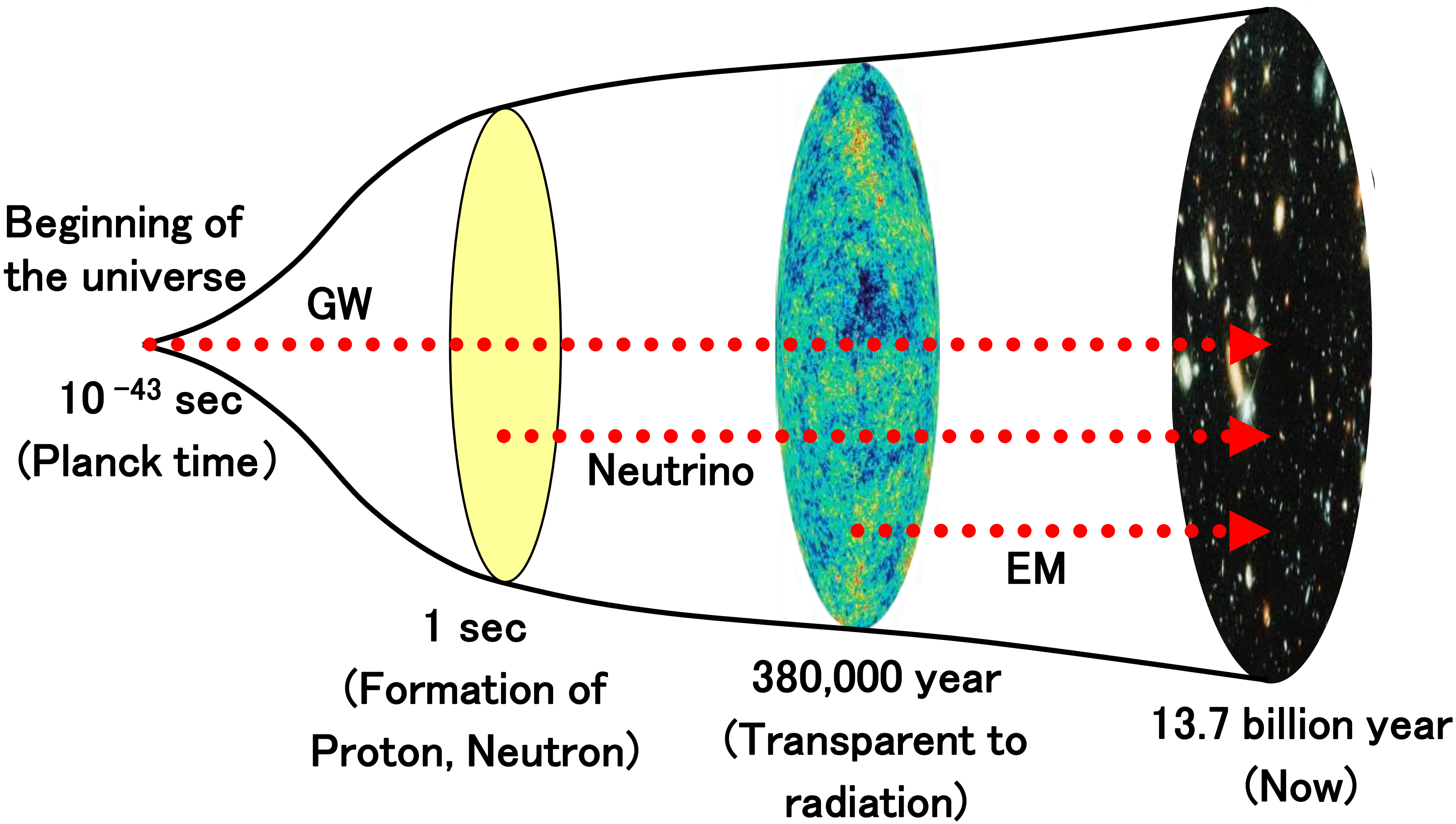
Non-axi-symmetric pulsar
(rotating, beaming
neutron star)



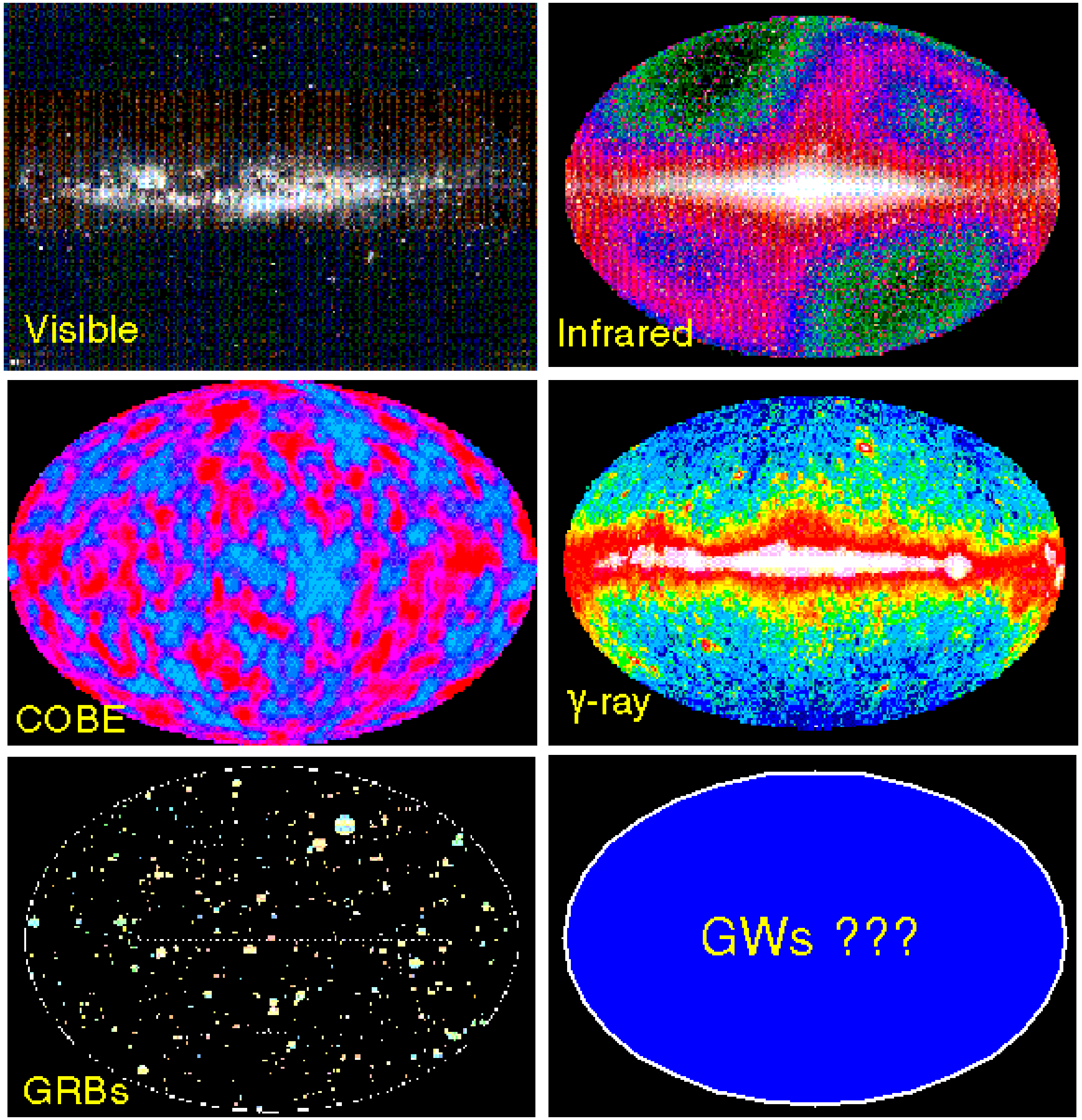
GWs from coalescing compact binaries



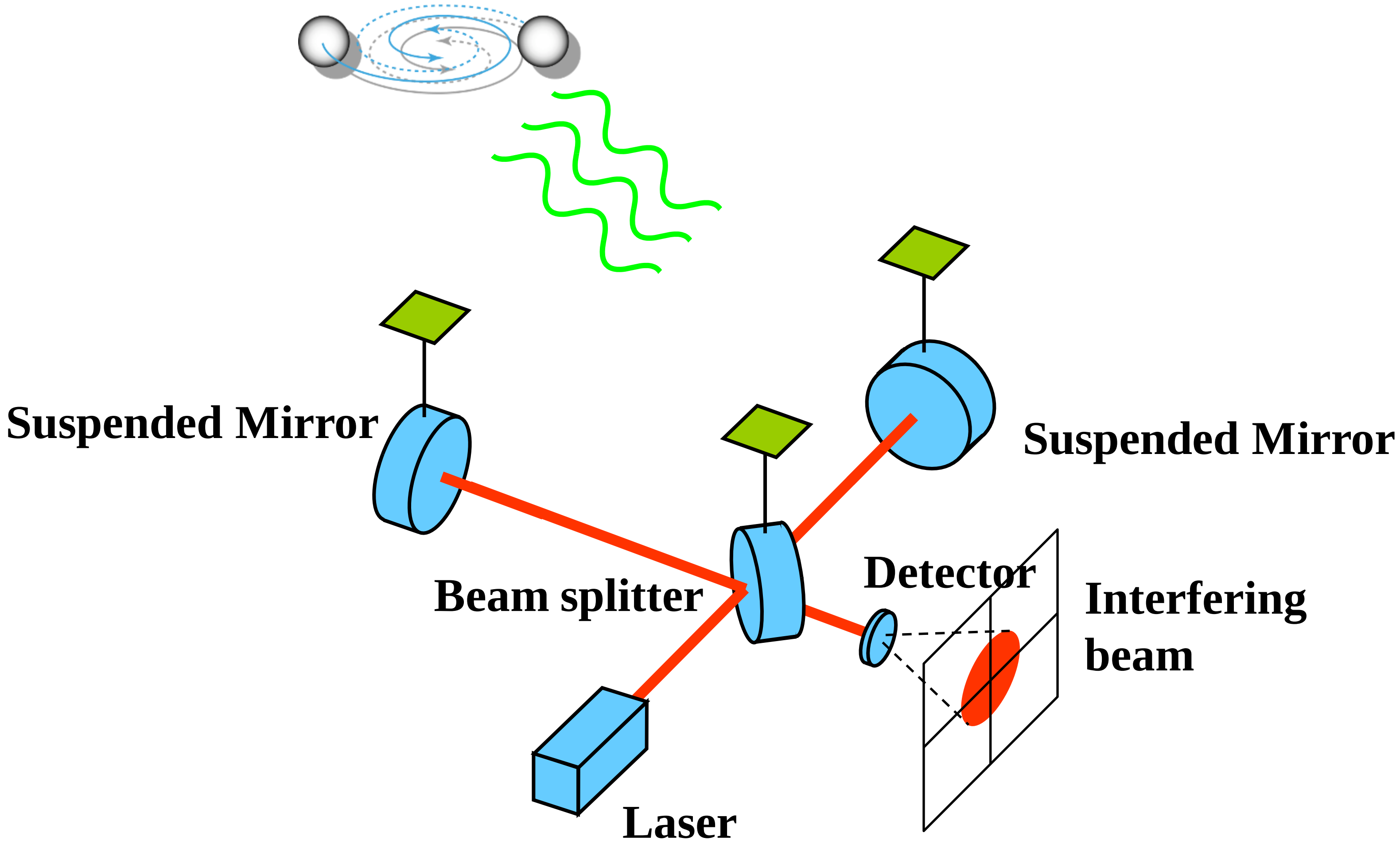
Beginning of the universe



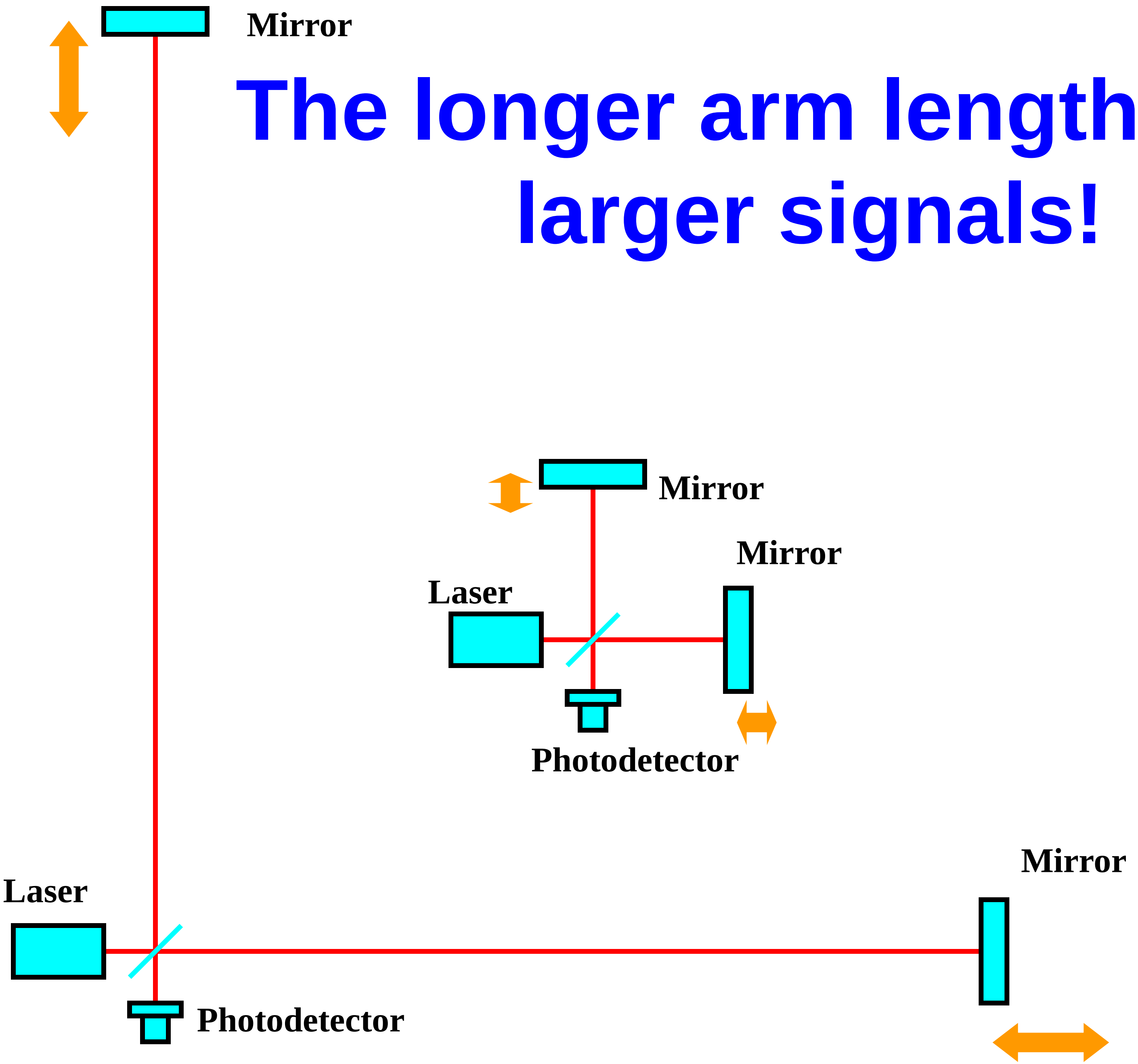
Gravitational wave astronomy



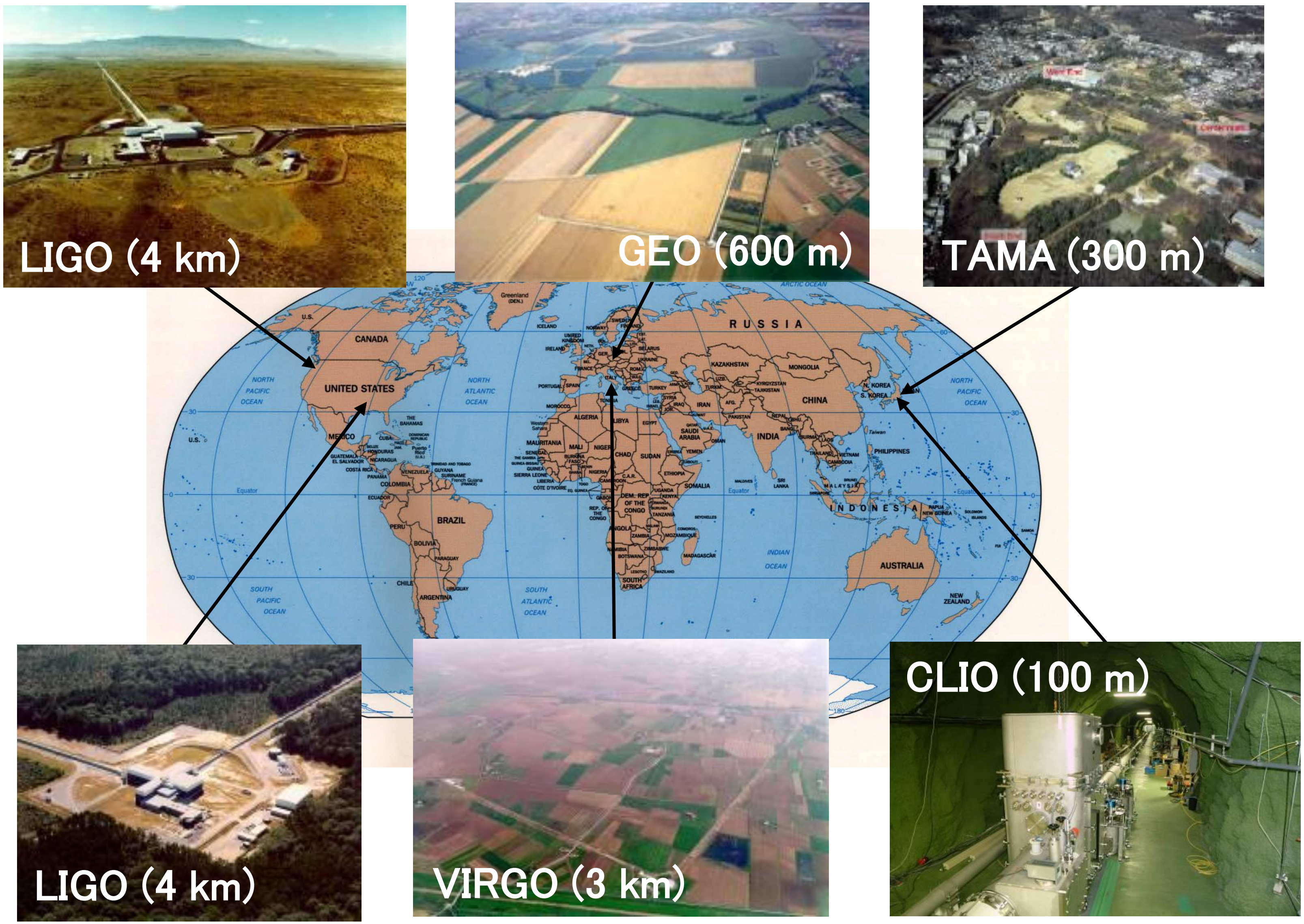
Detection of GW
by laser interferometer



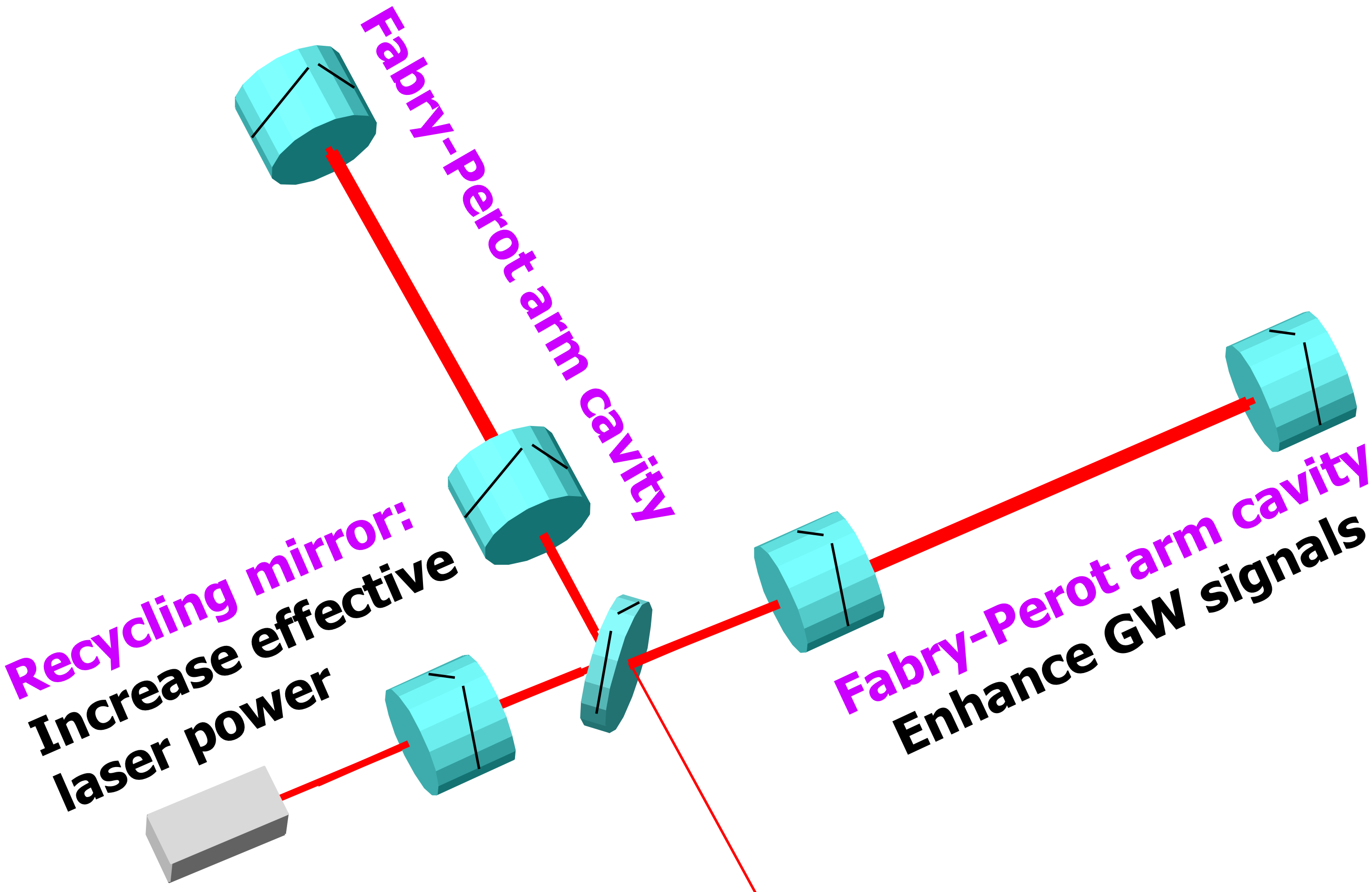
The longer arm length gives larger signals!



Large-scale detectors

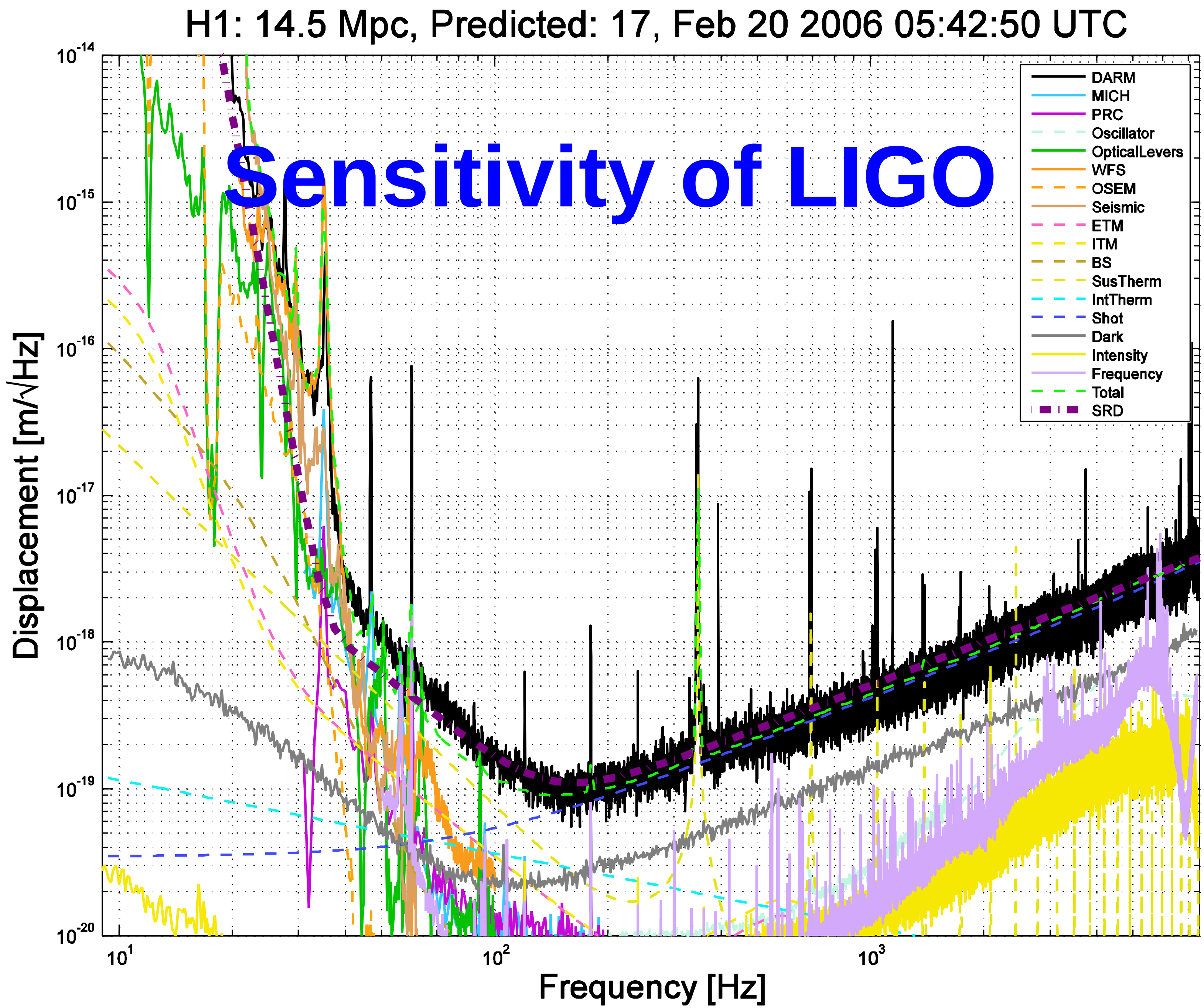


Standard optical configuration

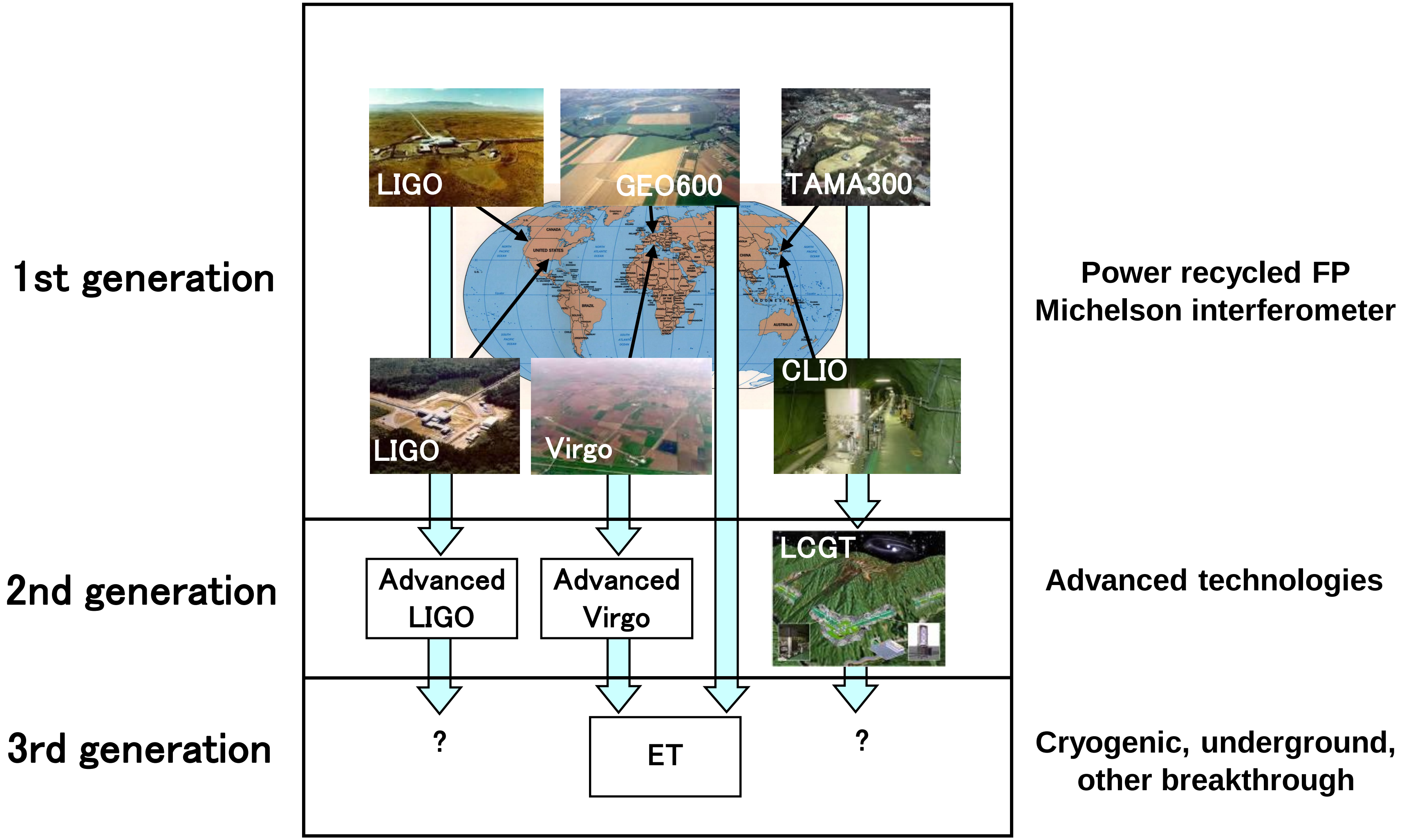



LIGO

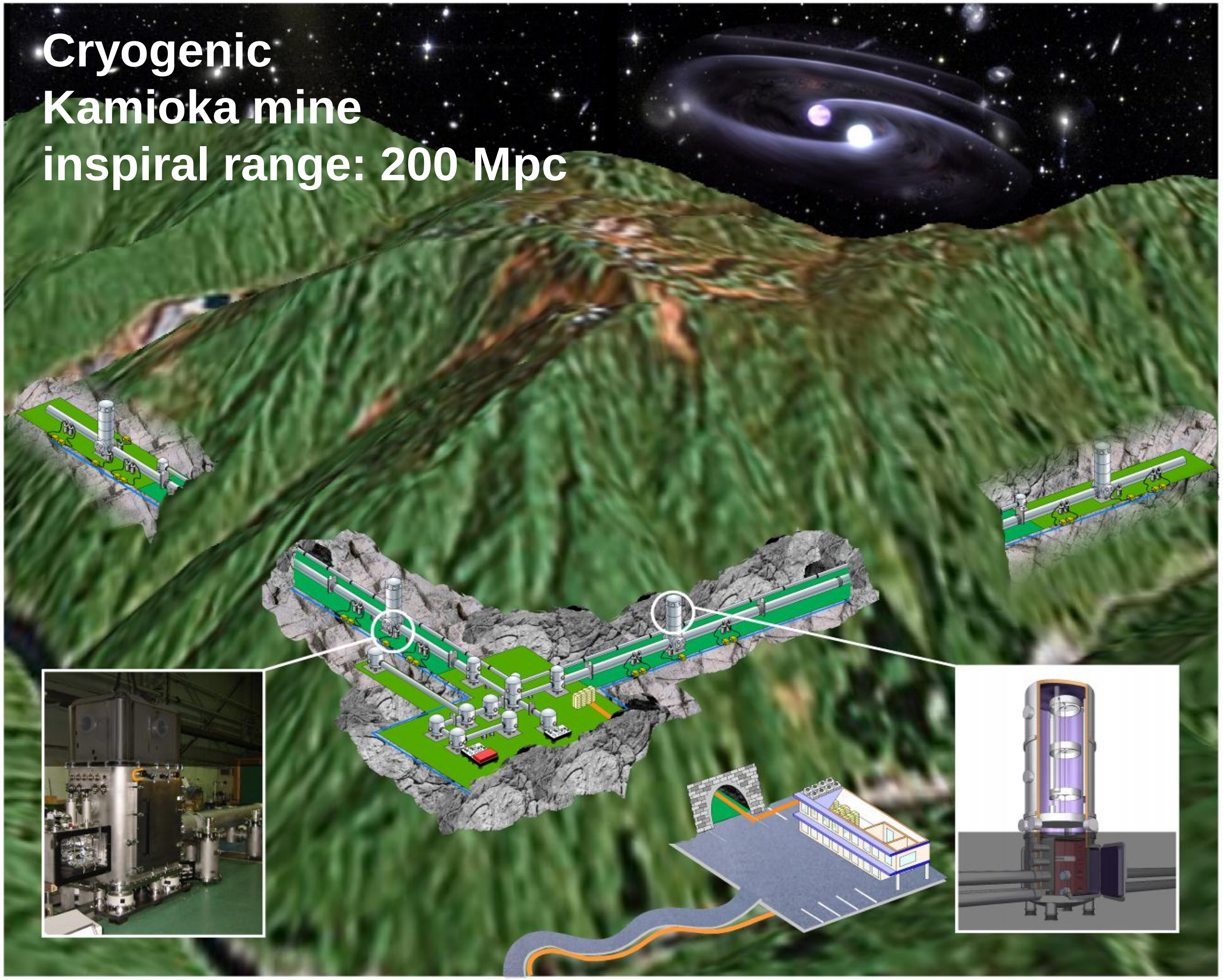
Sensitivity of LIGO



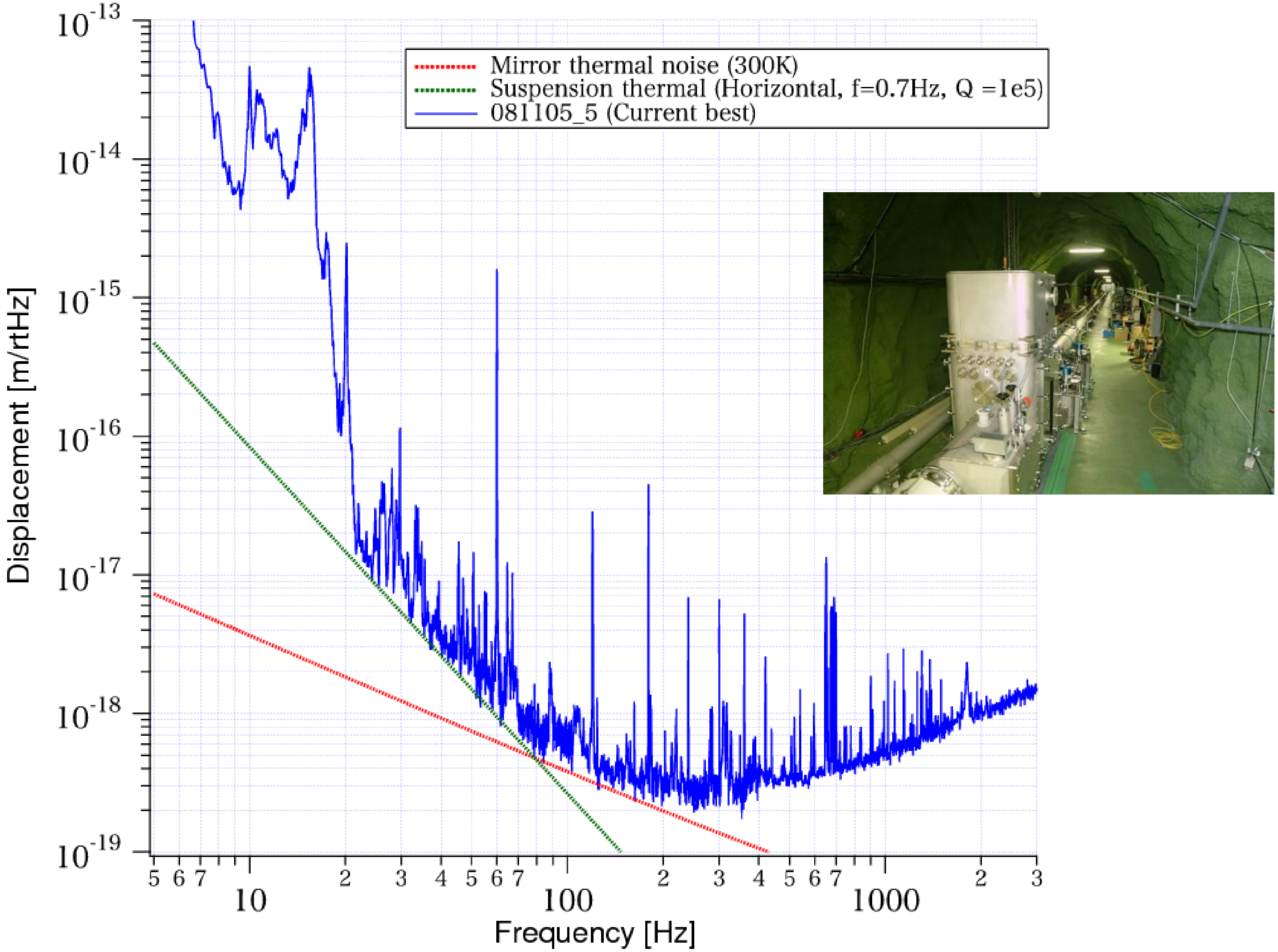
2nd generation and 3rd generation



LCGT



Sensitivity of CLIO



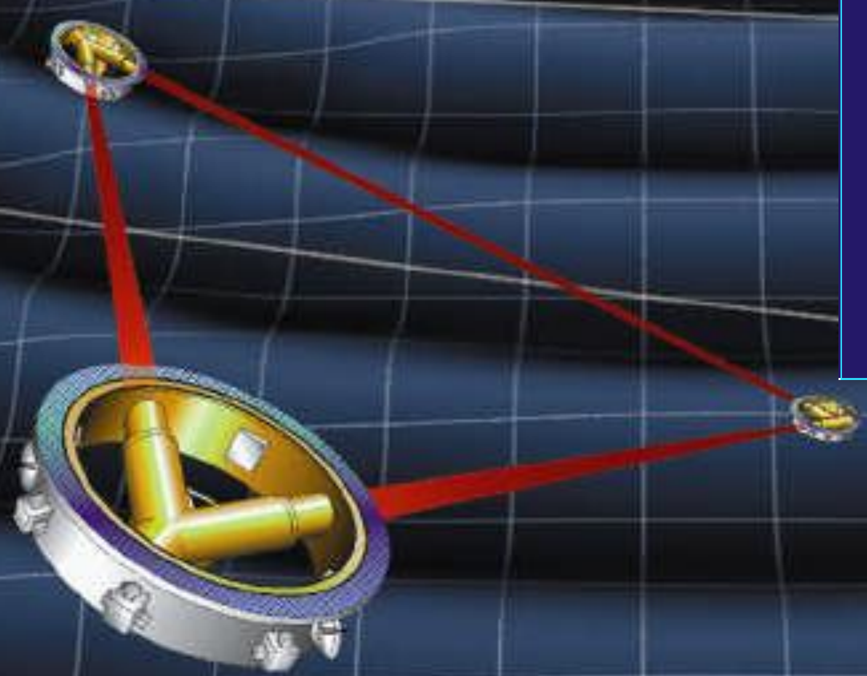
Space antenna

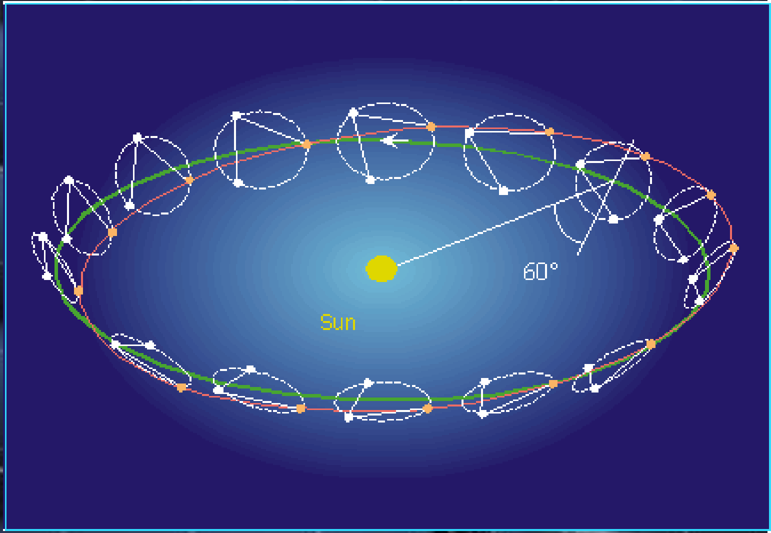
- Long arm length
- No seismic noise

- Better sensitivity at low frequencies

LISA

- Arm length: 5,000,000km
- Frequency range: 1 mHz – 0.1 Hz
- Target Source: White dwarf binary, Giant BH coalescence
- Optical configuration: Light transponder





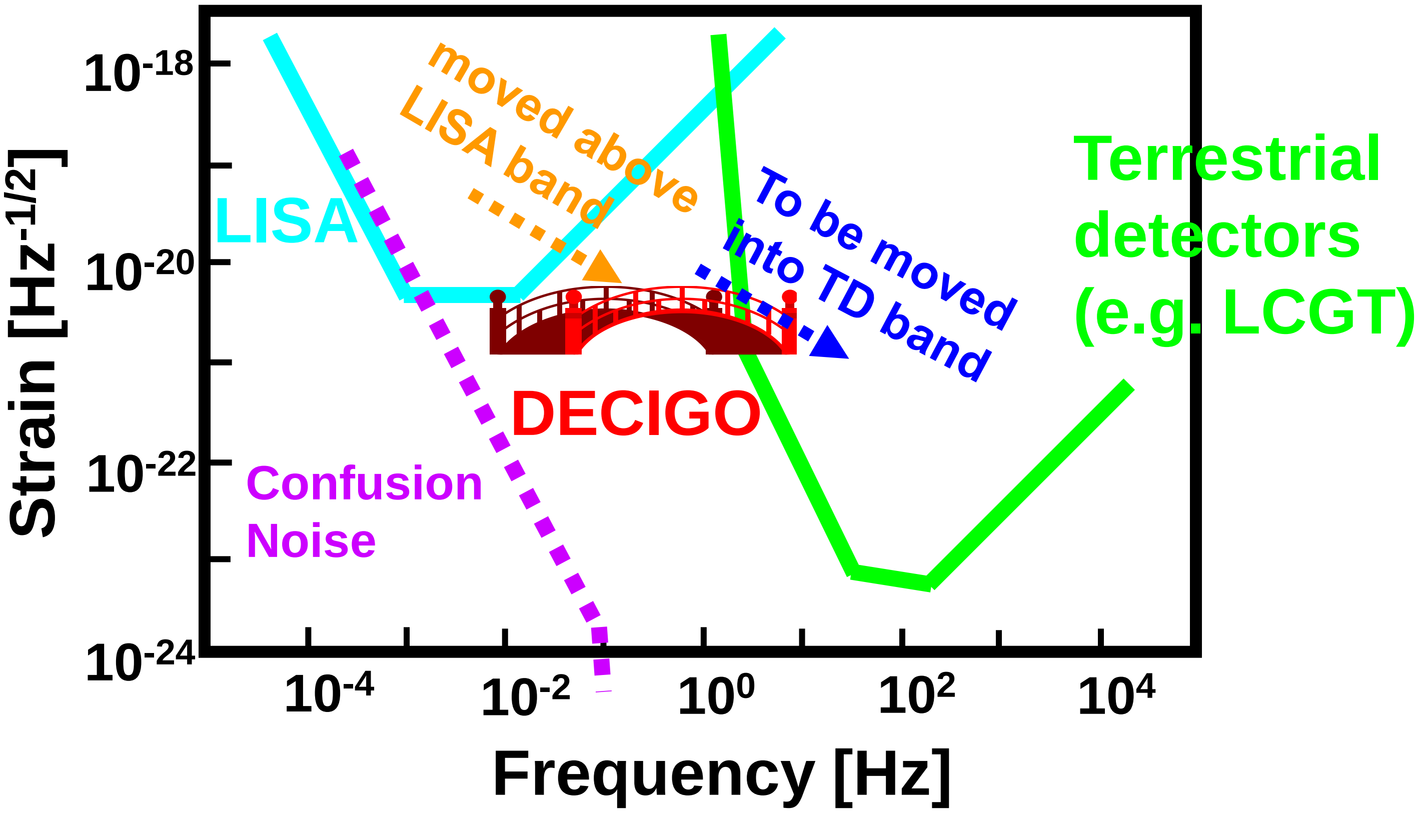
LISA project

What is DECIGO?

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

(Kawamura, et al., CQG 23 (2006) S125-S131)

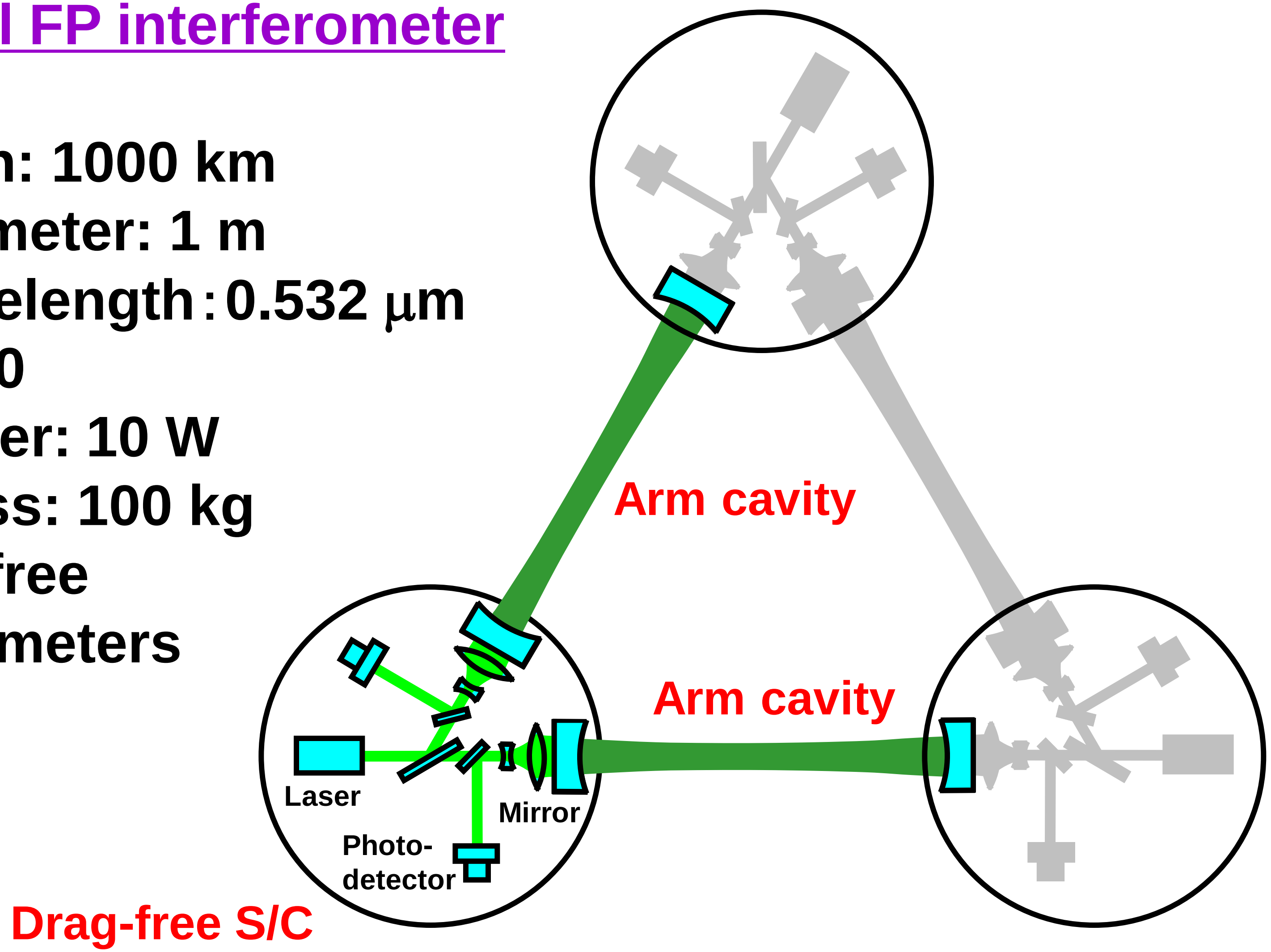
- **Bridges the gap between LISA and terrestrial detectors**
- **Low confusion noise -> Extremely high sensitivity**



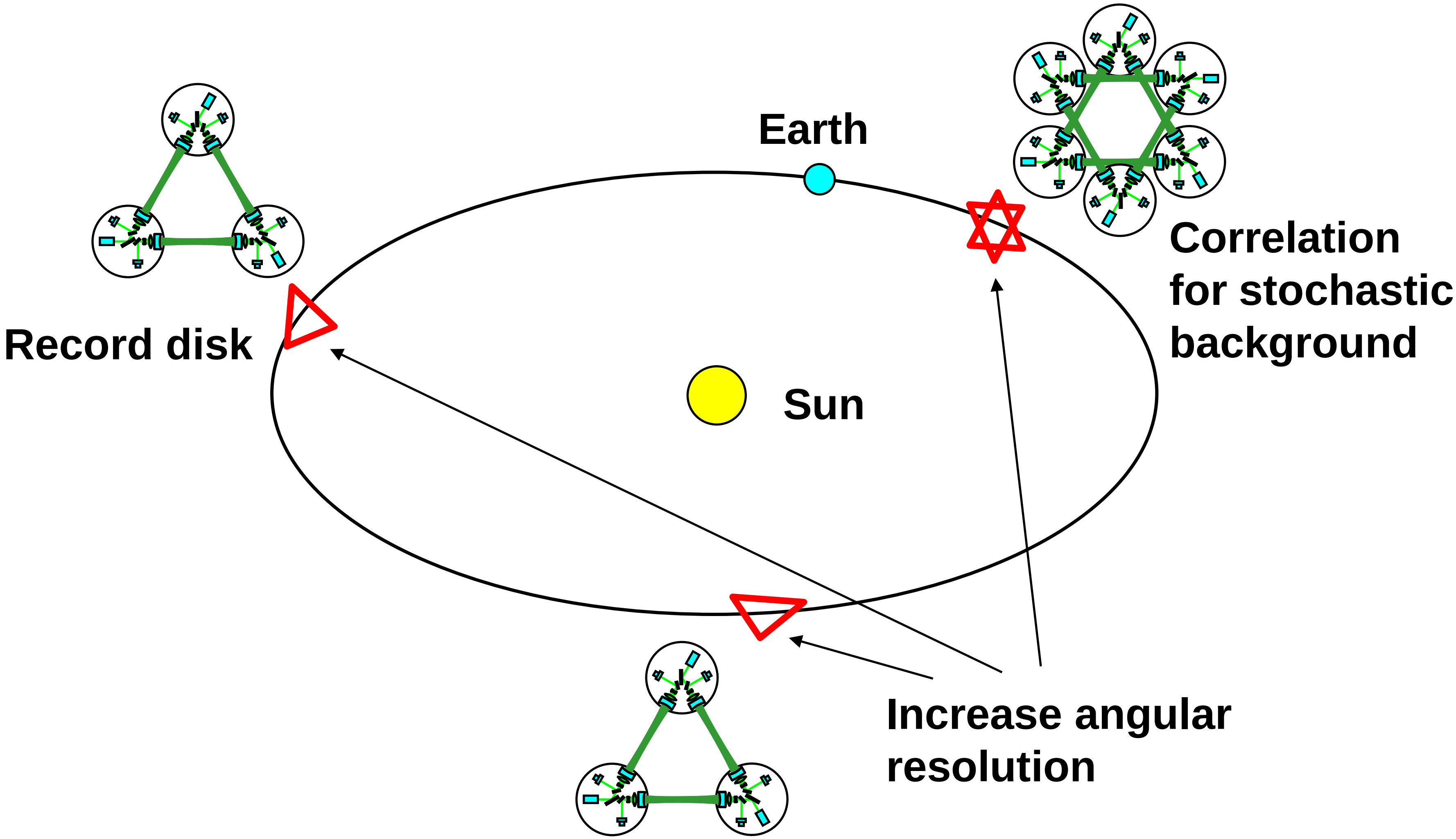
Pre-conceptual design

<u>Differential FP interferometer</u>

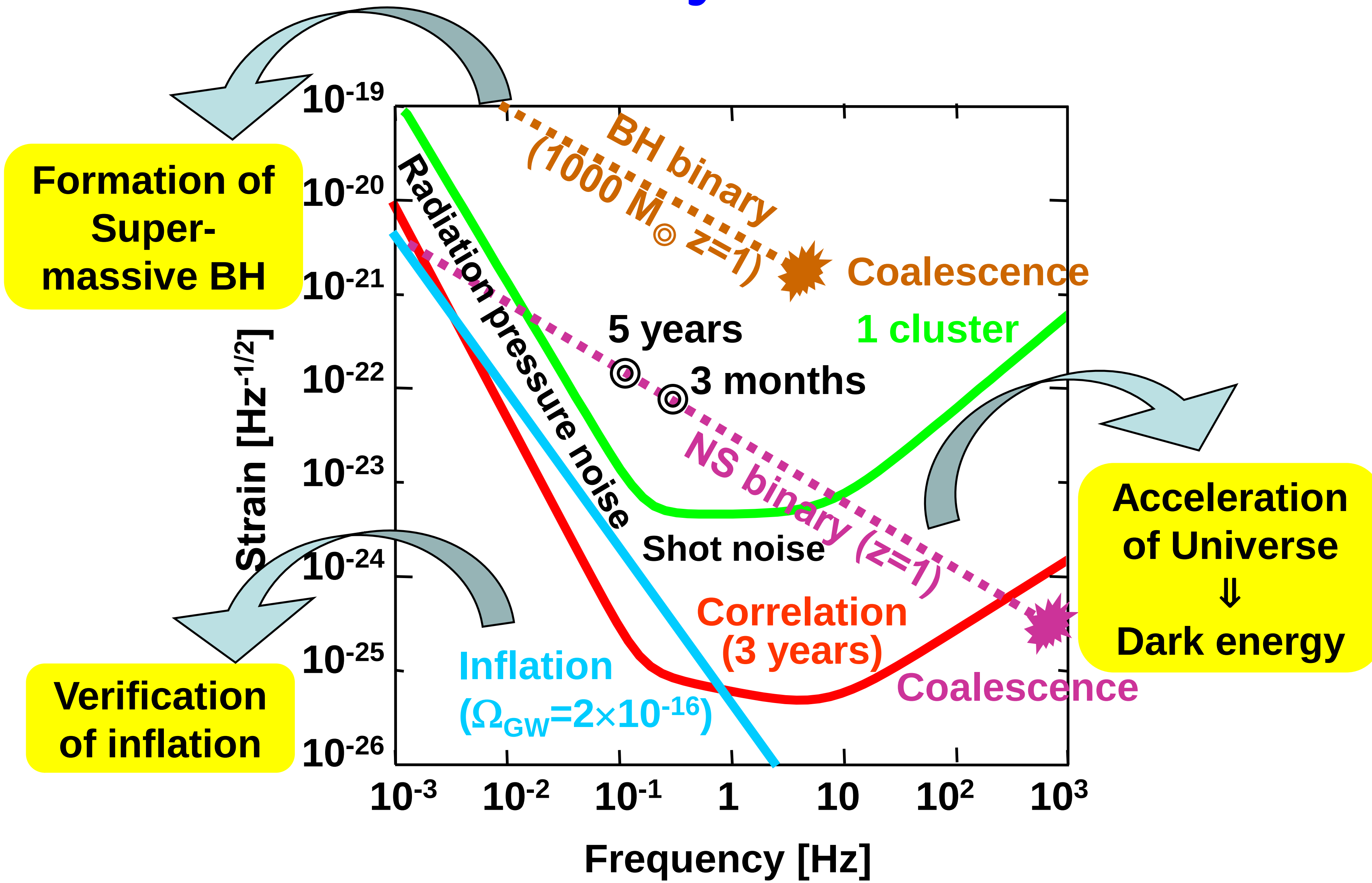
Arm length: 1000 km
Mirror diameter: 1 m
Laser wavelength：0.532 μm
Finesse: 10
Laser power: 10 W
Mirror mass: 100 kg
S/C: drag free
3 interferometers



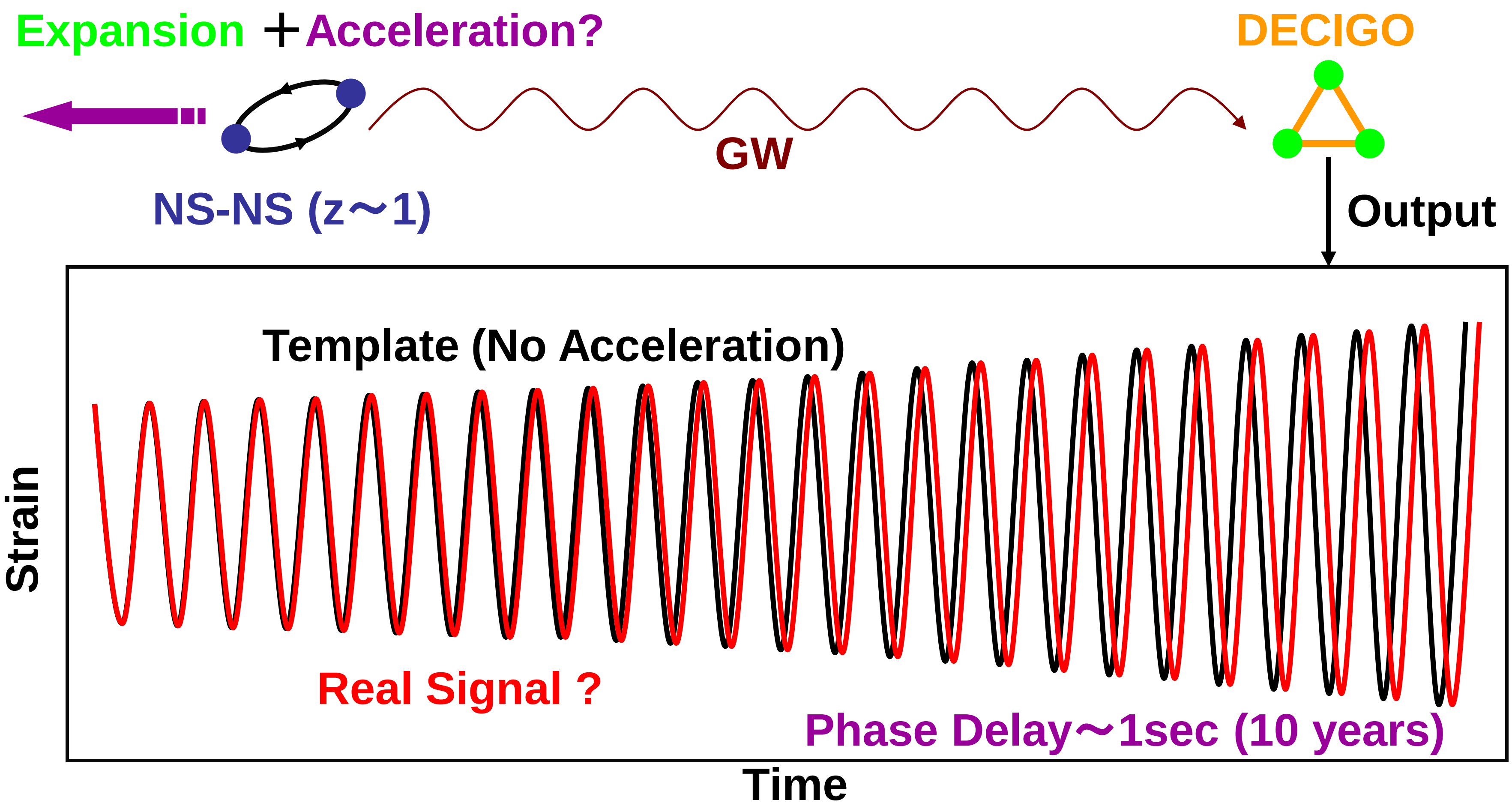
Orbit and constellation (preliminary)



Science by DECIGO



Acceleration of Expansion of the Universe

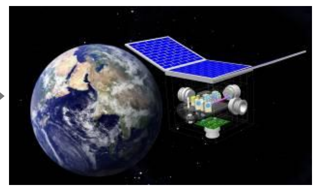
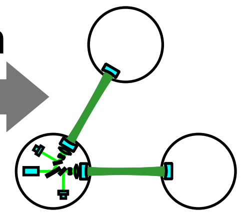
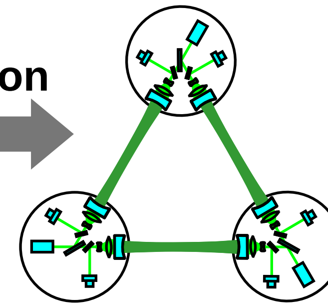


Seto, Kawamura, Nakamura, PRL 87, 221103 (2001)

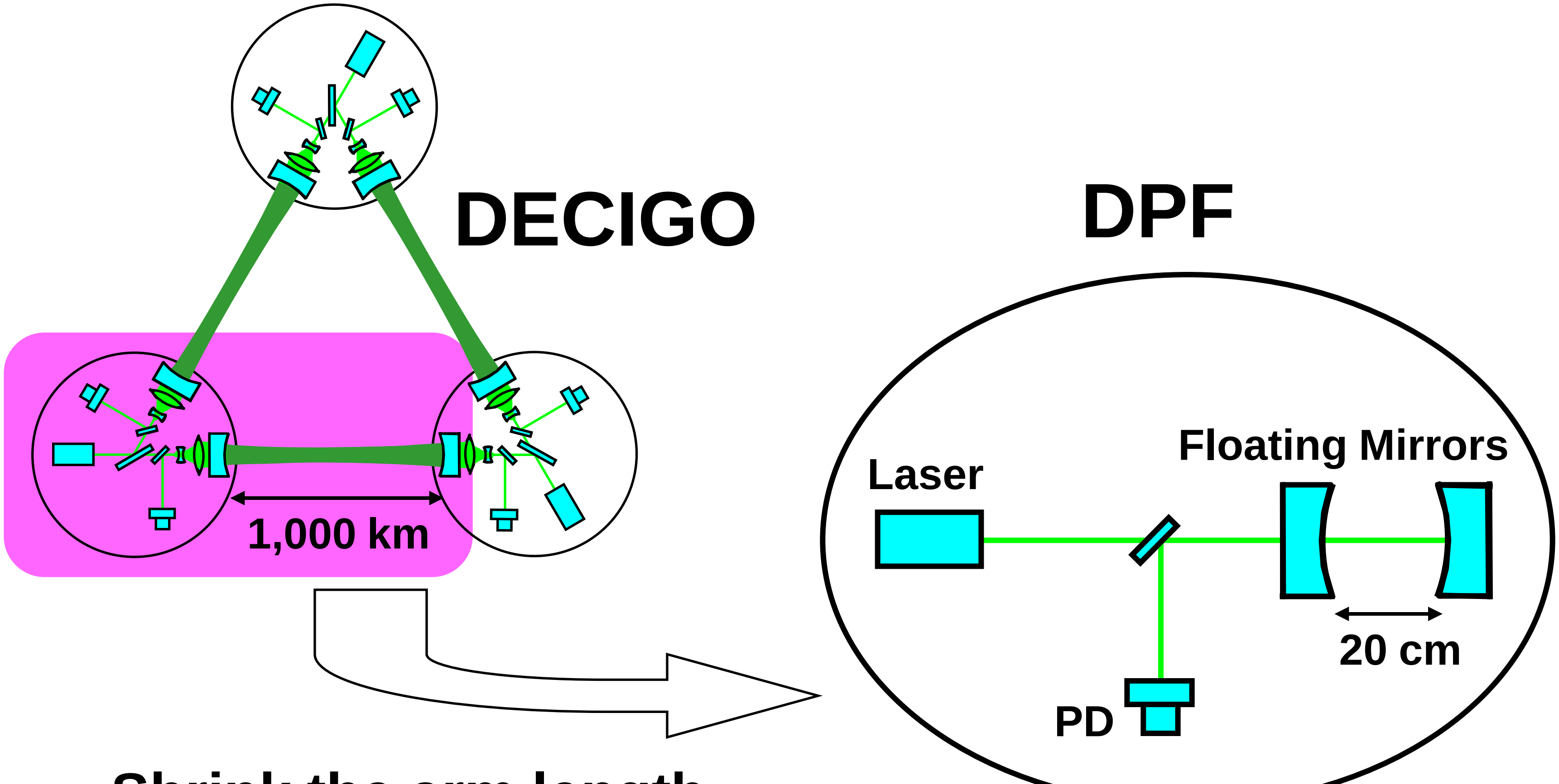
Requirements

- Acceleration noise should be suppressed below radiation pressure noise
  - Force noise: DECIGO = LISA/50
    (Acceleration noise in terms of h: 1, Distance: 1/5000, Mass: 100)
  - Fluctuation of magnetic field, electric field, gravitational field, temperature, pressure, etc.
- Sensor noise should be suppressed below shot noise.
  - Phase noise: DECIGO = LCGT × 10
    (Sensor noise in terms of h: 1, storage time: 10)
  - Frequency noise, intensity noise, beam jitter, etc.
- Thruster system should satisfy range, noise, bandwidth, and durability.

Roadmap

	2007	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Mission	R&D Fabrication					 DICIGO Pathfinder (DPF)			R&D Fabrication			 Pre-DECIGO			R&D Fabrication			 DECIGO		
Objectives	Test of key technologies Observation run of GW								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					

DECIGO Pathfinder (DPF)



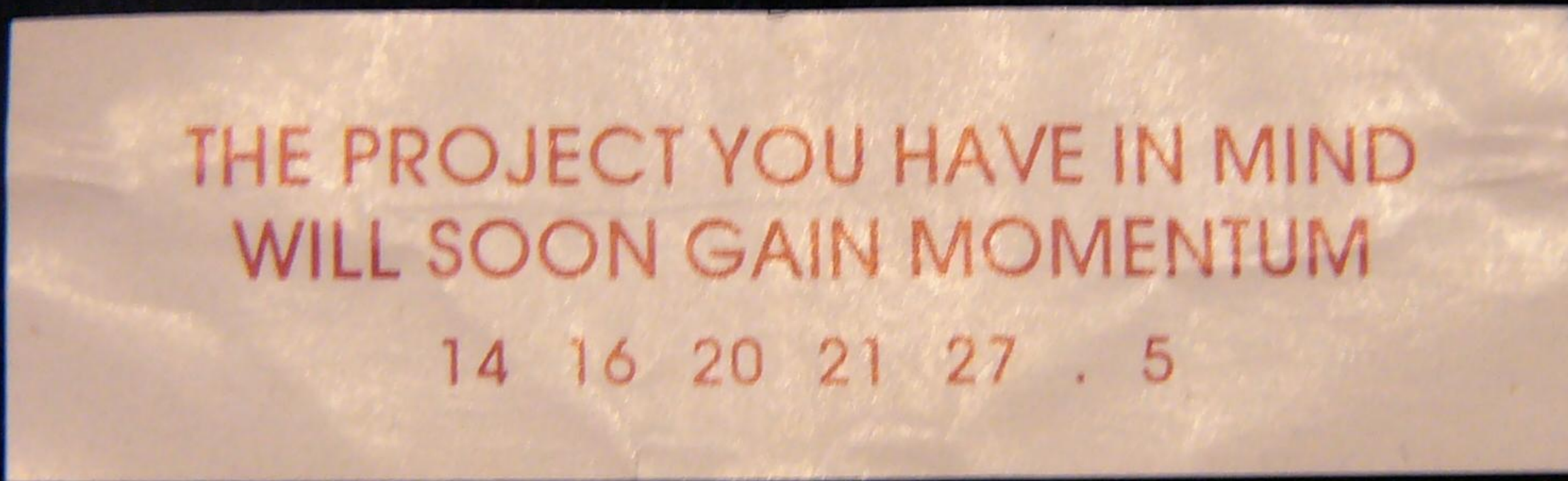
Drag-free S/C

Shrink the arm length
from 1,000 km to 20 cm

Fortune Cookie

June 2007, LIGO PAC meeting @ Pasadena

Fortune Cookie



June 2007, LIGO PAC meeting @ Pasadena

We gained momentum!

DPF was selected as one of the important mission candidates for small science satellite series run by JAXA/ISAS.

JAXA's Small satellite series

Plan to launch 3 small satellites by the year 2015
using next-generation solid rocket booster
Reduce time and cost
by means of 'Standard bus system'

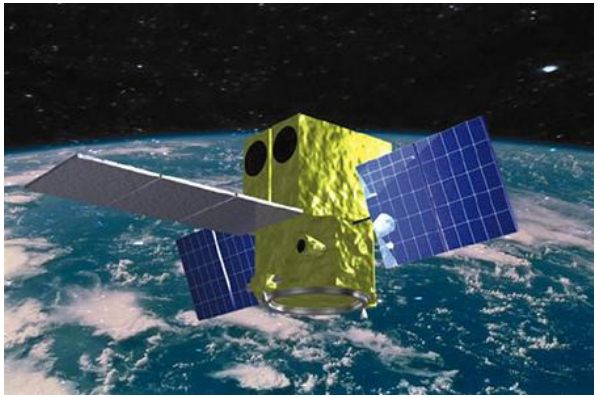


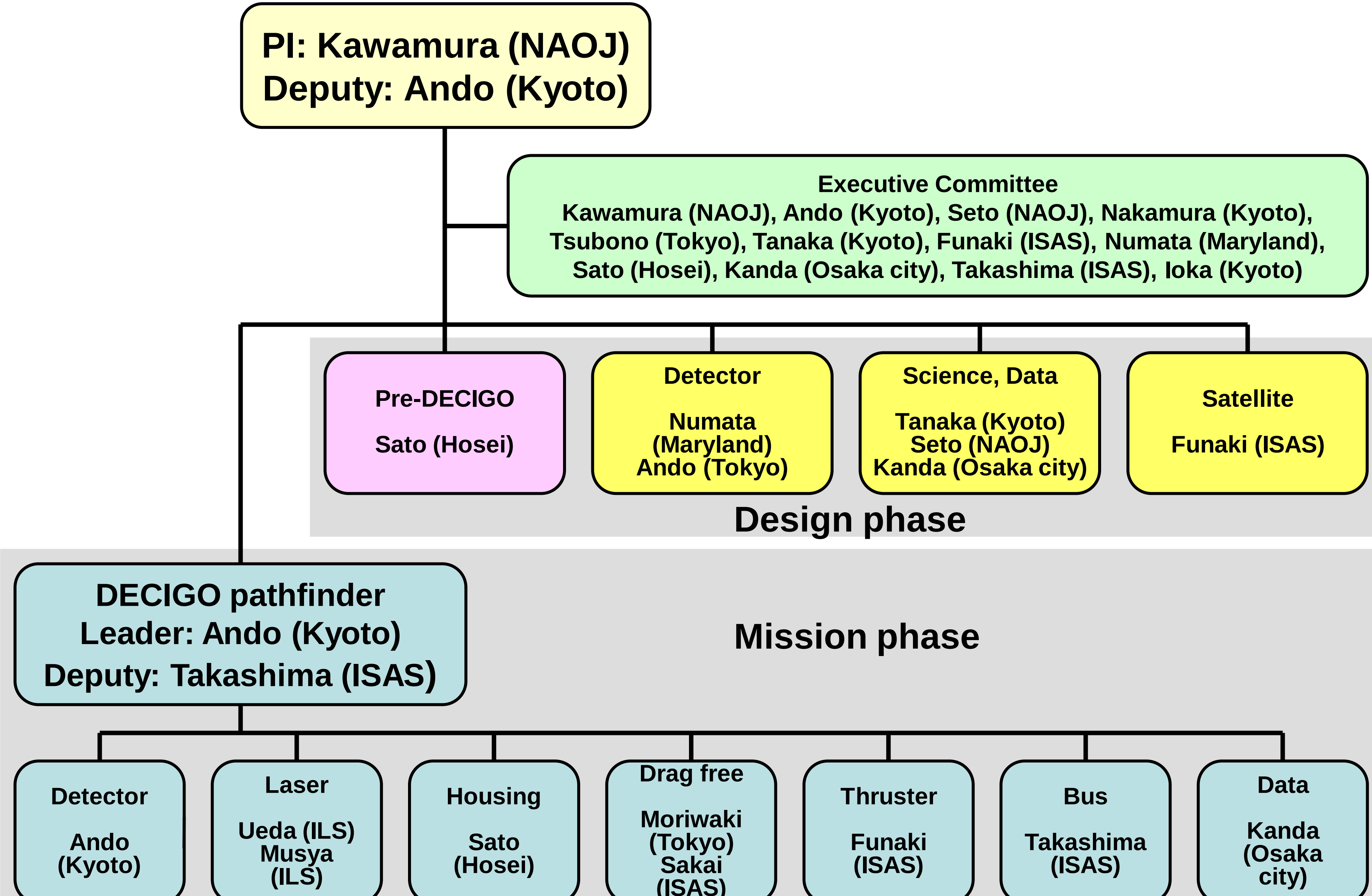
Image CG of TOPS
(design has been changed now)

Bus weight : ~ 200kg, Bus power : ~ 800W
Downlink ~ 2Mbps, Data storage ~ 1GByte
3-axes attitude control
SpaceWire-based data processing system

1st mission (2011) :
decided to be TOPS (Planetary science)
2nd and 3rd mission will be selected by 2009 March

15 Candidate missions (5 important candidates)
- DPF: GW observation
- DIOS: X-ray telescope for dark baryon investigation
- ERG: Plasma and particle detector for geo-space investigation
- Satellite for Magnet-plasma sail technology demonstration, ...

Interim organization



DECIGO-WG

Kazuhiro Agatsuma, Masaki Ando, Koh-suke Aoyanagi, Koji Arai, Akito Araya, Hideki Asada, Yoichi Aso, Takeshi Chiba, Toshikazu Ebisuzaki, Yumiko Ejiri, Motohiro Enoki, Yoshiharu Eriguchi, Masa-Katsu Fujimoto, Ryuichi Fujita, Mitsuhiro Fukushima, Ikkoh Funaki, Toshifumi Futamase, Katsuhiko Ganzu, Tomohiro Harada, Tatsuaki Hashimoto, Kazuhiro Hayama, Wataru Hikida, Yoshiaki Himemoto, Hisashi Hirabayashi, Takashi Hiramatsu, Feng-Lei Hong, Hideyuki Horisawa, Mizuhiko Hosokawa, Kiyotomo Ichiki, Takeshi Ikegami, Kaiki T. Inoue, Kunihito Ioka, Koji Ishidoshiro, Hideki Ishihara, Takehiko Ishikawa, Hideharu Ishizaki, Hiroyuki Ito, Yousuke Itoh, Nobuyuki Kanda, Seiji Kawamura, Nobuki Kawashima, Fumiko Kawazoe, Naoko Kishimoto, Kenta Kiuchi, Shiho Kobayashi, Kazunori Kohri, Hiroyuki Koizumi, Yasufumi Kojima, Keiko Kokeyama, Wataru Kokuyama, Kei Kotake, Yoshihide Kozai, Hideaki Kudoh, Hiroo Kunimori, Hitoshi Kuninaka, Kazuaki Kuroda, Kei-ichi Maeda, Hideo Matsuhara, Yasushi Mino, Osamu Miyakawa, Shinji Miyoki, Mutsuko Y. Morimoto, Tomoko Morioka , Toshiyuki Morisawa, Shigenori Moriwaki, Shinji Mukohyama, Mitsuru Musha, Shigeo Nagano, Isao Naito, Kouji Nakamura, Takashi Nakamura, Hiroyuki Nakano, Kenichi Nakao, Shinichi Nakasuka, Yoshinori Nakayama, Kazuhiro Nakazawa, Erina Nishida, Kazutaka Nishiyama, Atsushi Nishizawa, Yoshito Niwa, Kenji Numata, Masatake Ohashi, Naoko Ohishi, Masashi Ohkawa, Kouji Onozato, Kenichi Oohara, Norichika Sago, Motoyuki Saijo, Masaaki Sakagami, Shin-ichiro Sakai, Shihori Sakata, Misao Sasaki, Shuichi Sato, Takashi Sato, Naoki Seto, Masaru Shibata, Hisaaki Shinkai, Kentaro Somiya, Hajime Sotani, Naoshi Sugiyama, Yudai Suwa, Rieko Suzuki, Hideyuki Tagoshi, Fuminobu Takahashi, Kakeru Takahashi, Keitaro Takahashi, Ryutaro Takahashi, Ryuichi Takahashi, Tadayuki Takahashi, Hirotaka Takahashi, Takamori Akiteru, Tadashi Takano, Takeshi Takashima, Takahiro Tanaka, Keisuke Taniguchi, Atsushi Taruya, Hiroyuki Tashiro, Mitsuru Tokuda, Yasuo Torii, Morio Toyoshima, Kimio Tsubono, Shinji Tsujikawa, Yoshiki Tsunesada, Akitoshi Ueda, Ken-ichi Ueda, Masayoshi Utashima, Hiroshi Yamakawa, Kazuhiro Yamamoto, Toshitaka Yamazaki, Jun'ichi Yokoyama, Chul-Moon Yoo, Shijun Yoshida, Taizoh Yoshino

1st International LISA-DECIGO Workshop

- **Nov. 12-13, 2008 @ ISAS, Sagamihara, Japan**
- **Objectives:**
  - **Mutual understanding**
  - **Possible collaboration**
  - **Exposure of the missions to people in the neighboring fields**
- **Plenary talks:**
  - **Science of LISA & DECIGO, status of LPF & DPF**

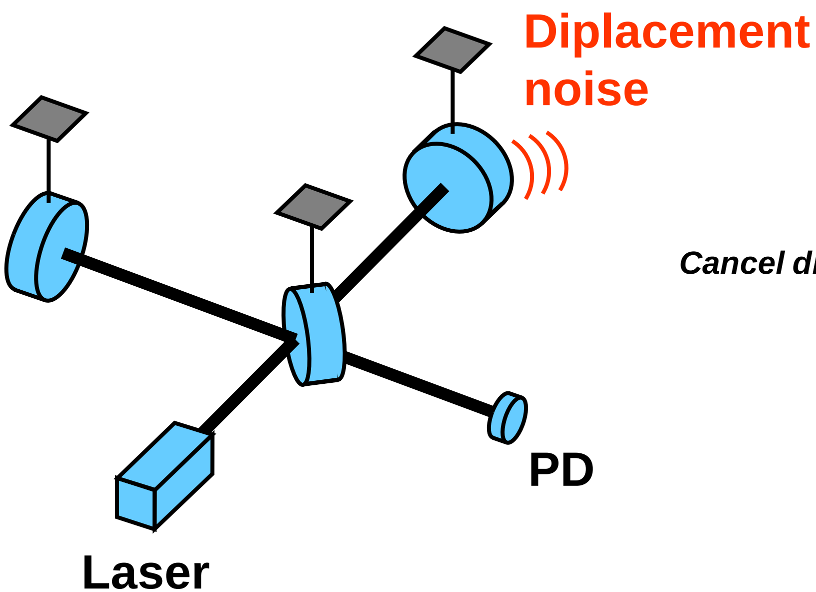
Possible breakthrough for 3rd-generation detectors:

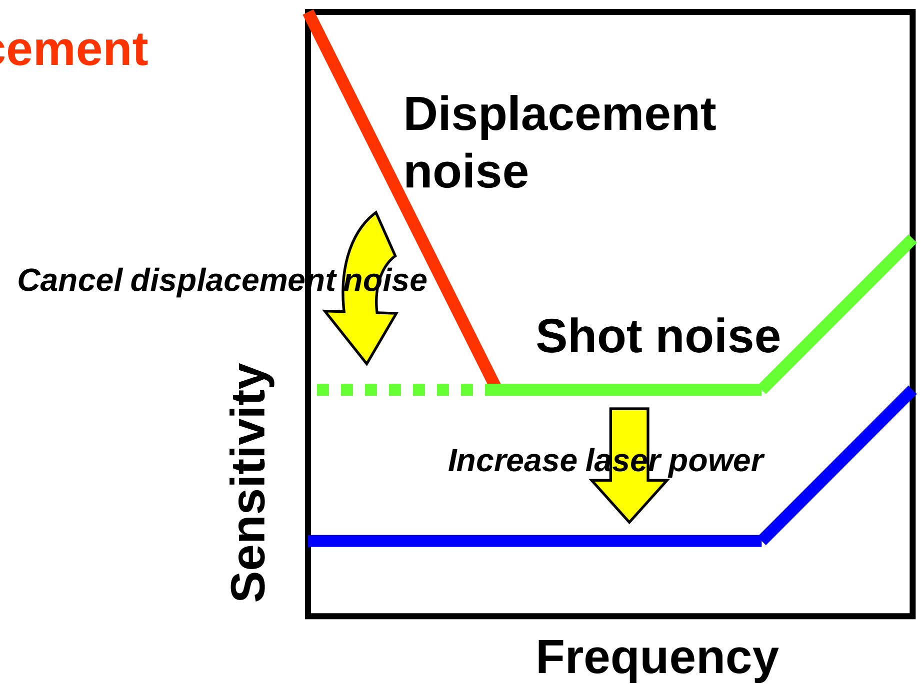
Displacement-noise free Interferometer

Kawamura and Chen, PRL, 93, (2004) 211103
Chen and Kawamura, PRL, 96 (2006) 231102

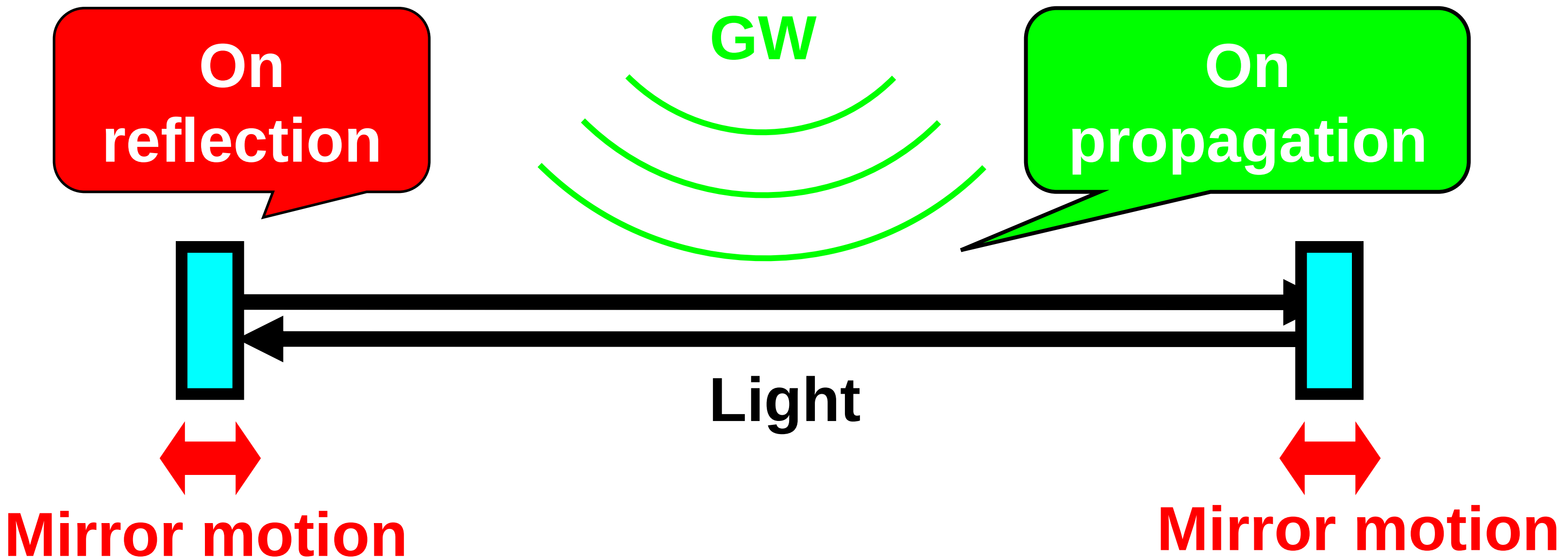
Motivation

- Displacement noise: seismic Noise, thermal noise, radiation pressure noise
- Cancel displacement noise ⇒ shot noise limited sensitivity
- Increase laser power ⇒ sensitivity improved indefinitely



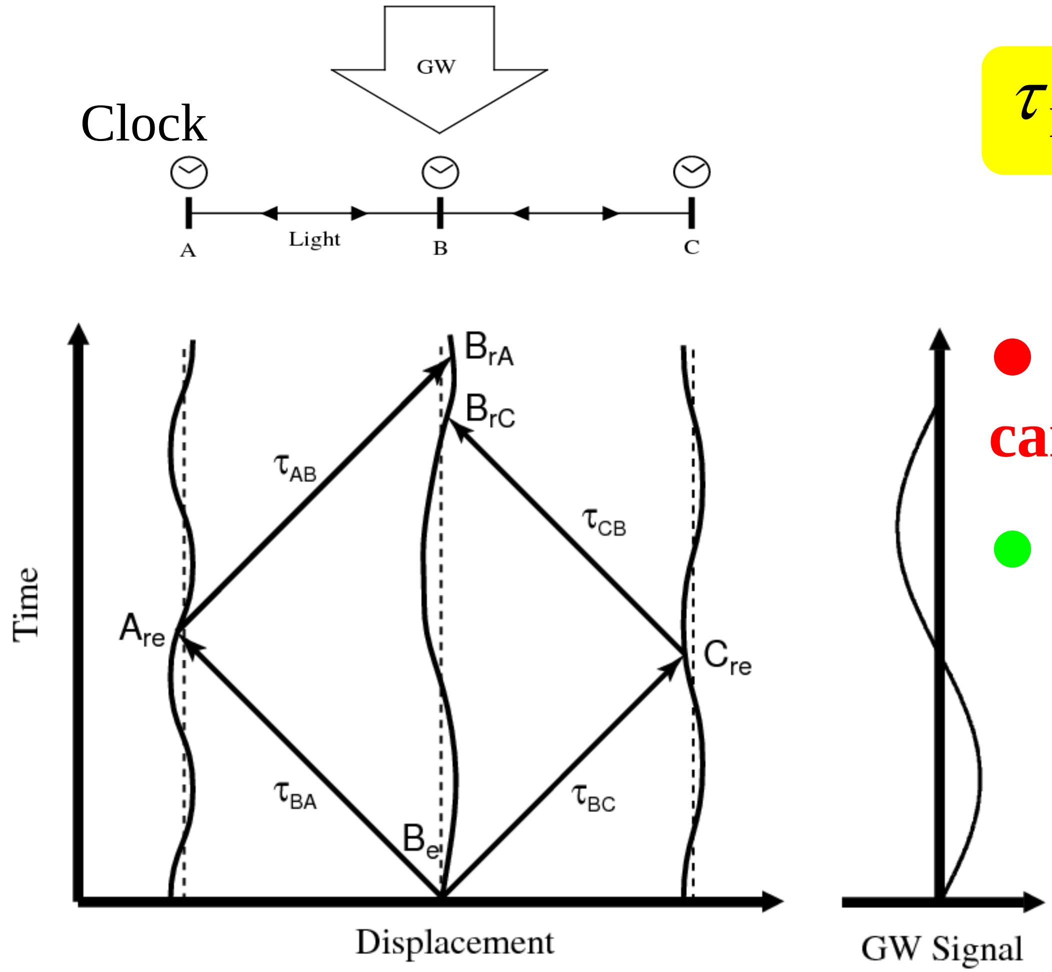


GW and mirror motion interact with light differently



Difference outstanding for
GW wavelength ~ distance between masses

Cancel motion of objects



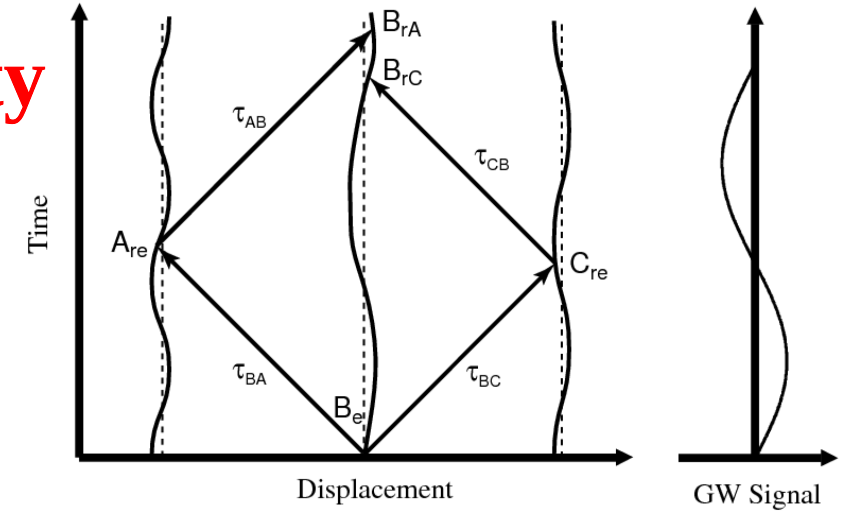
$$\tau_{BA} - \tau_{AB} + \tau_{BC} - \tau_{CB}$$

- **Motion of A, B, and C cancelled**
- **GW signal remains**

Why is it possible?

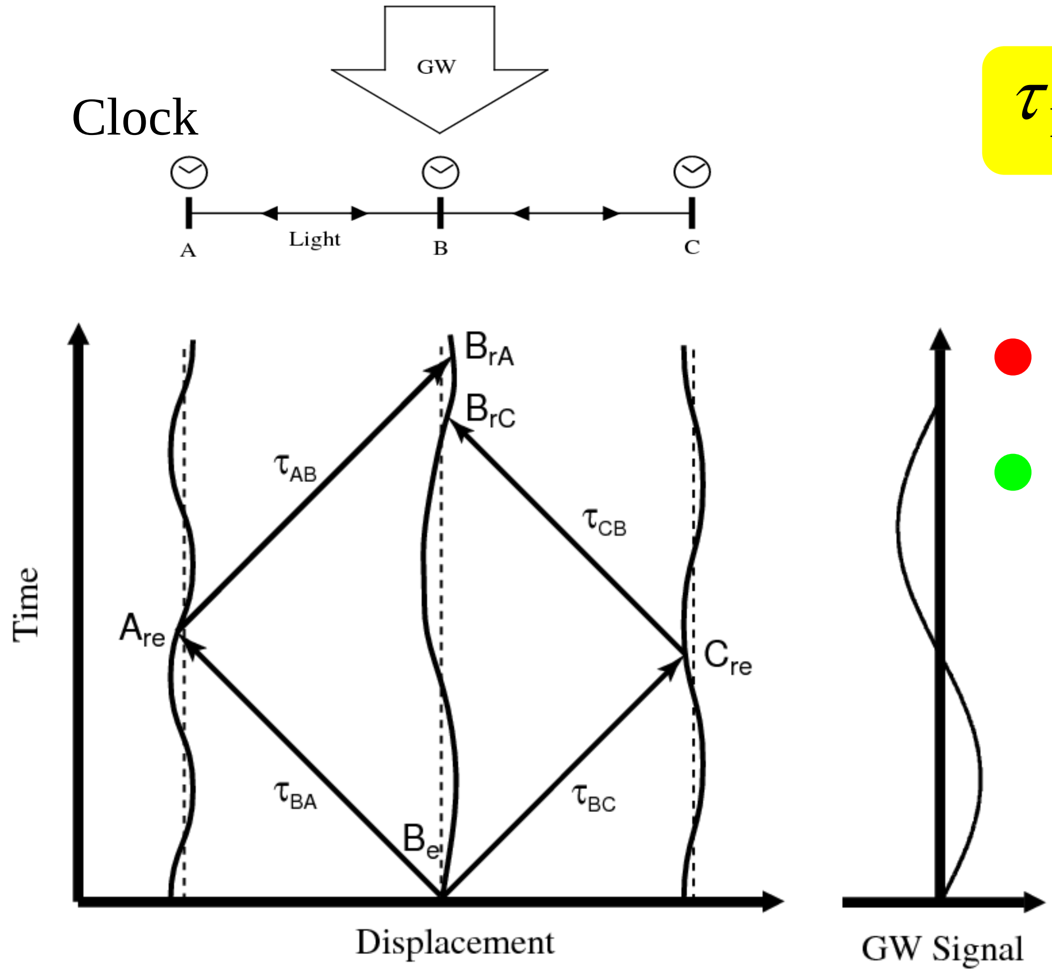
\# of MQ (4) > # of DOF (3)

MQ: Measurable quantity
DOF: Degree of freedom



Therefore a combination of MQs that is free from DOFs exists!

Clock noise?

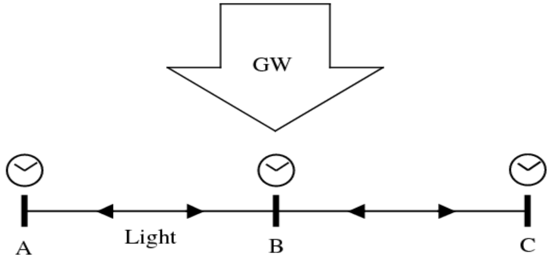


$$\tau_{BA} - \tau_{AB} + \tau_{BC} - \tau_{CB}$$

- **Motion: cancelled**
- **Clock noise: not cancelled**

Why?

# of DOF (Clock): 3
# of DOF (Displacement): 3
# of MQ: 4



Therefore it is not always possible to make a combination of MQs that is free from all the DOFs!

How can we cope with it?

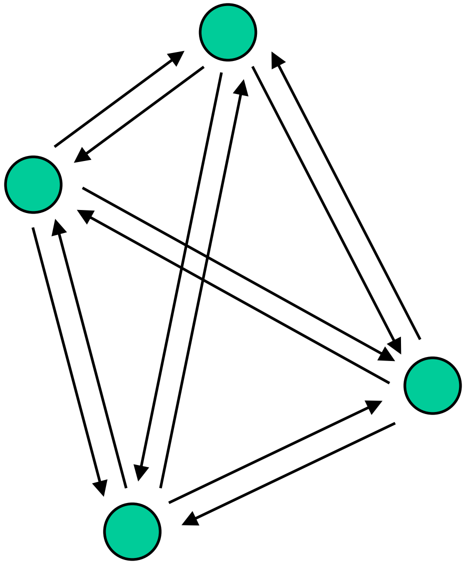
d: # of dimensions, N: # of Objects

# of DOF (Displacement) : Nd

# of DOF (Clock) : N

# of DOF (Total) : N(d+1)

# of MQ : N(N−1)



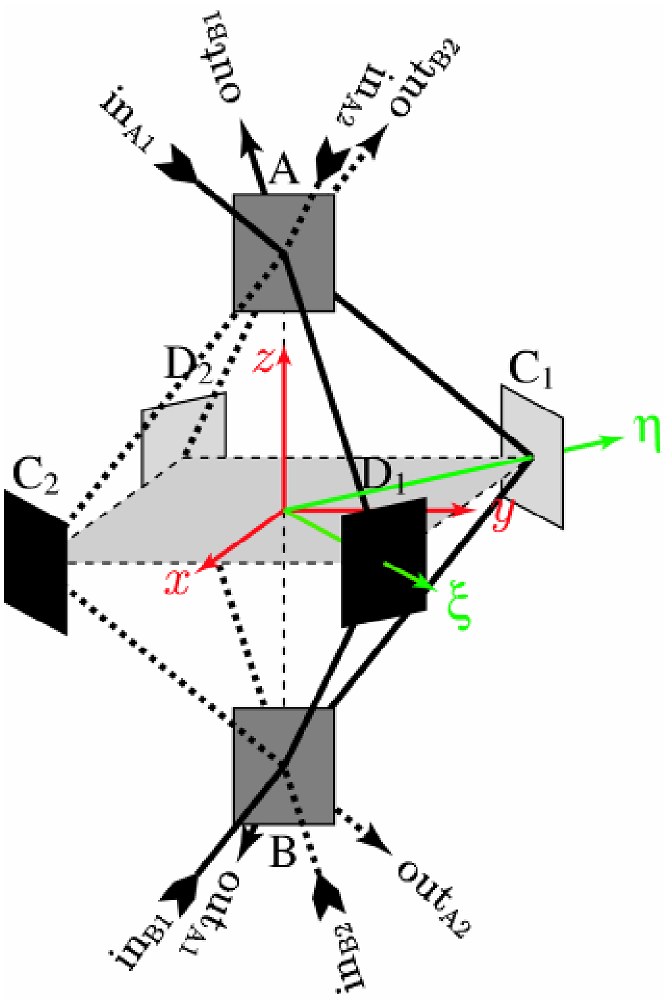
If N(N−1)>N(d+1) i.e. N>d+2

A combination of MQs that is free from DOFs exists!

Displacement-noise free interferometer

- **Propagation time measurement $\Rightarrow$ interferometer**
- **Motion of object $\Rightarrow$ displacement noise of mirrors**
- **Clock noise $\Rightarrow$ laser frequency noise**

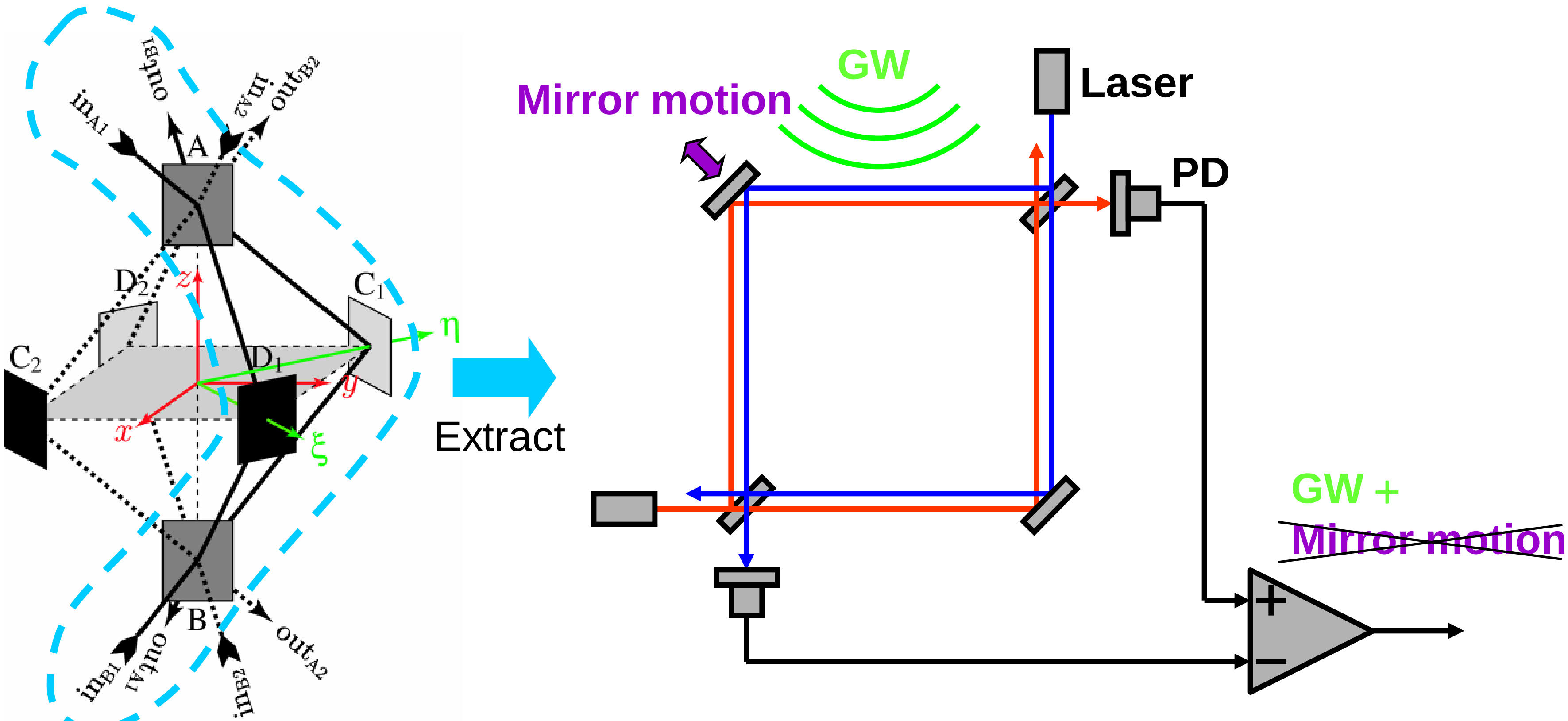
Example of DFI



- Two 3-d bi-directional MZ
- Take combination of 4 outputs
- Mirror motion completely cancelled
- GW signal remains (f^2)

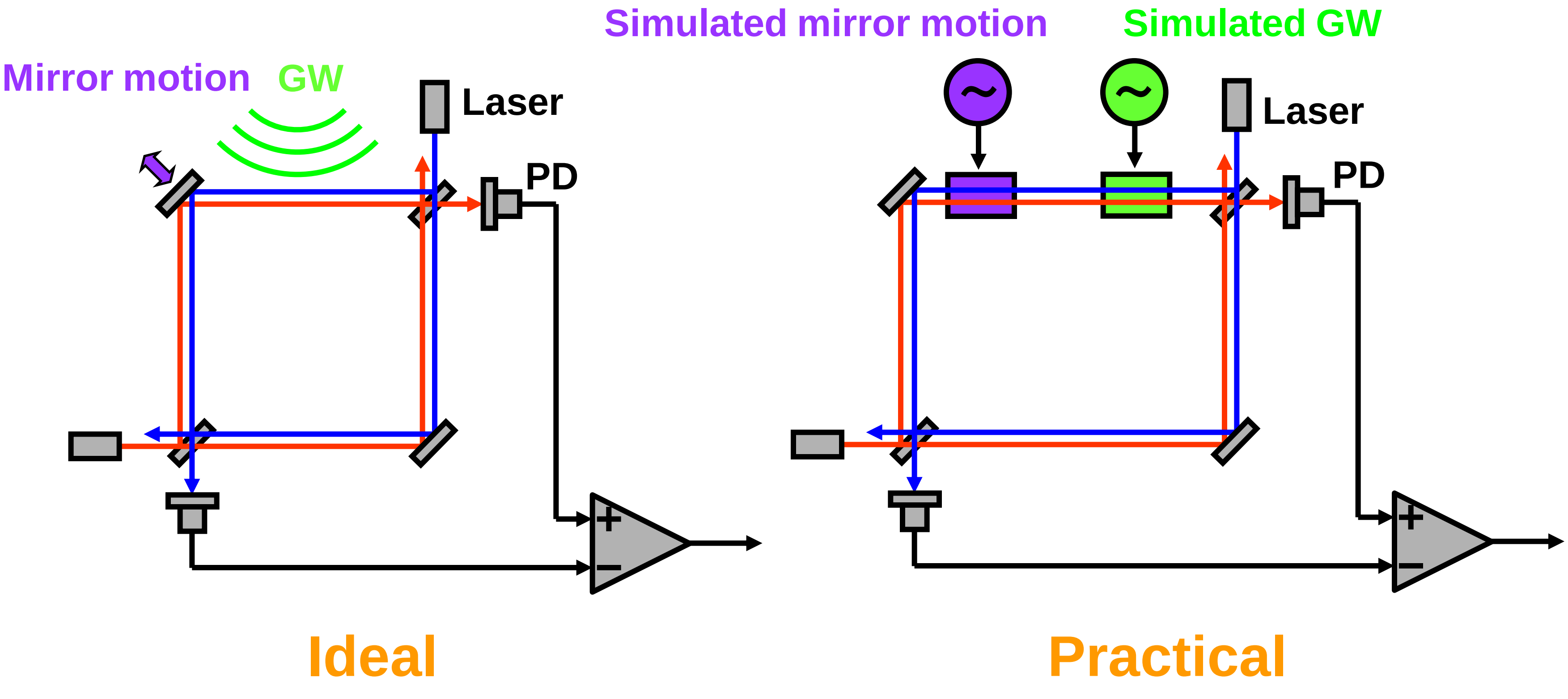
Experiment (Ideal)

- One bi-directional MZ



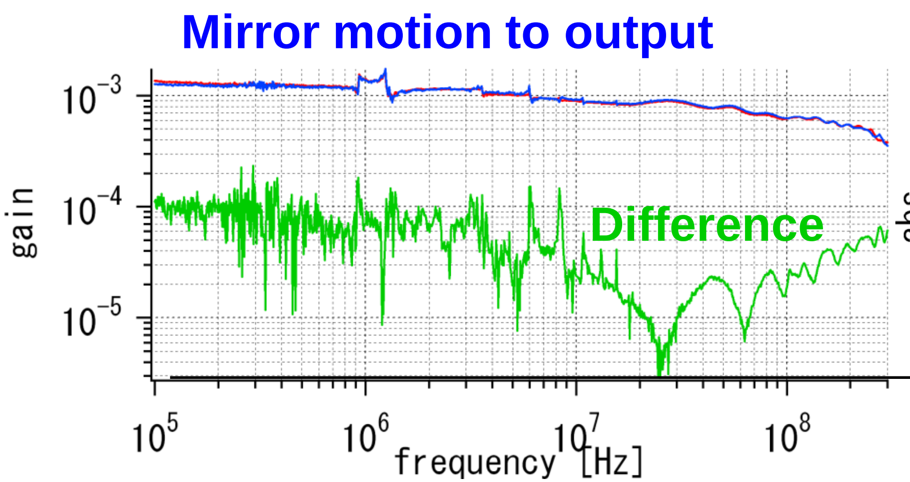
Experiment (Practical)

- EOM used for GW and mirror motion

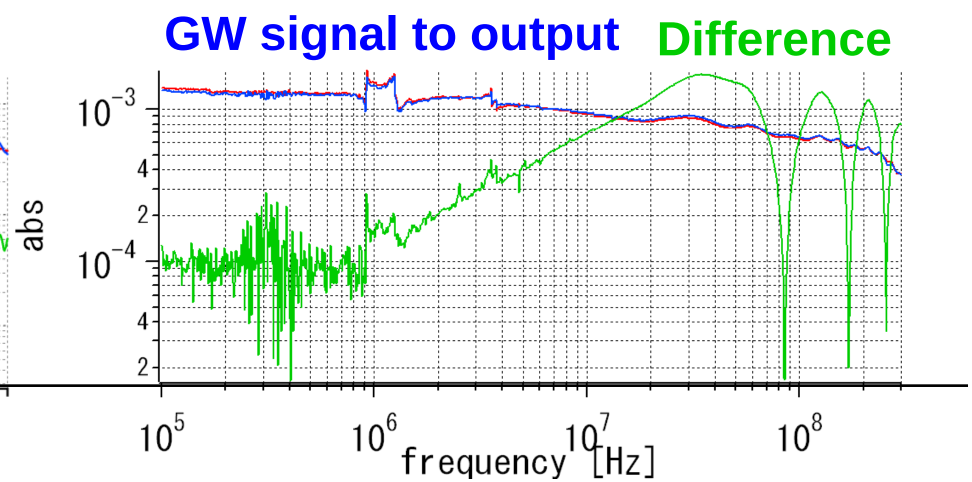


Results

- Mirror motion cancels out
- GW signal remains



Mirror motion



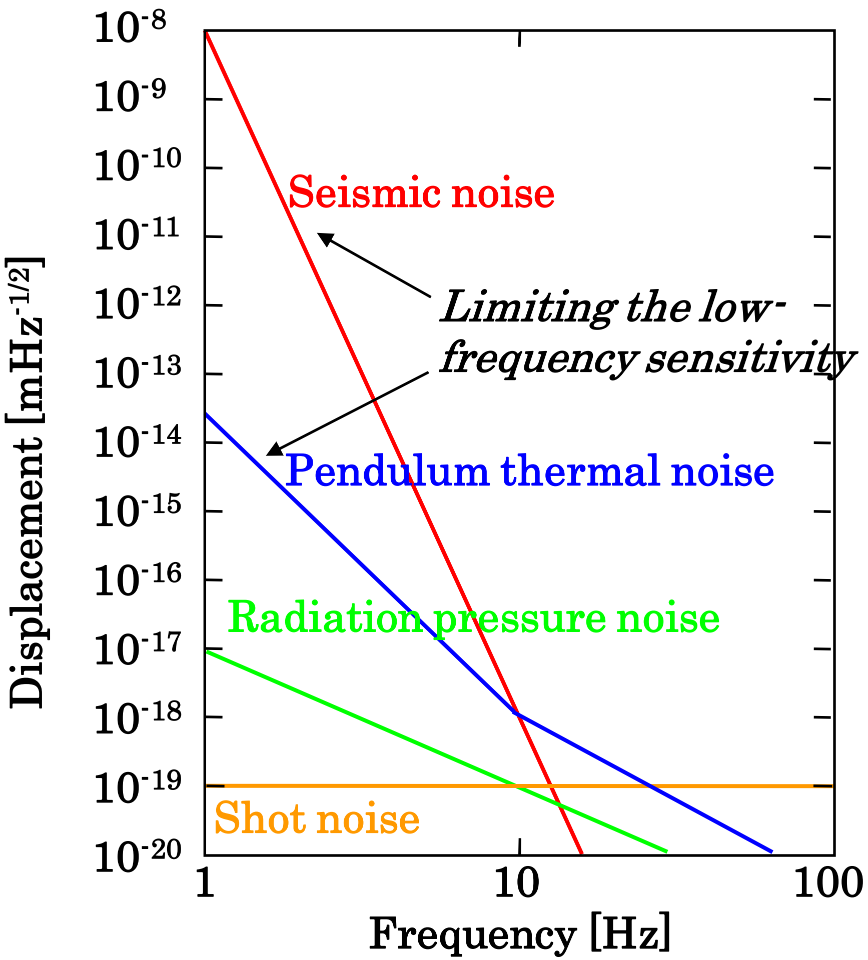
GW signal

Sato, Kokeyama, Ward, Kawamura, Chen, Pai, Somiya, PRL 98 (2007) 141101

Possible breakthrough for 3rd-generation detectors:

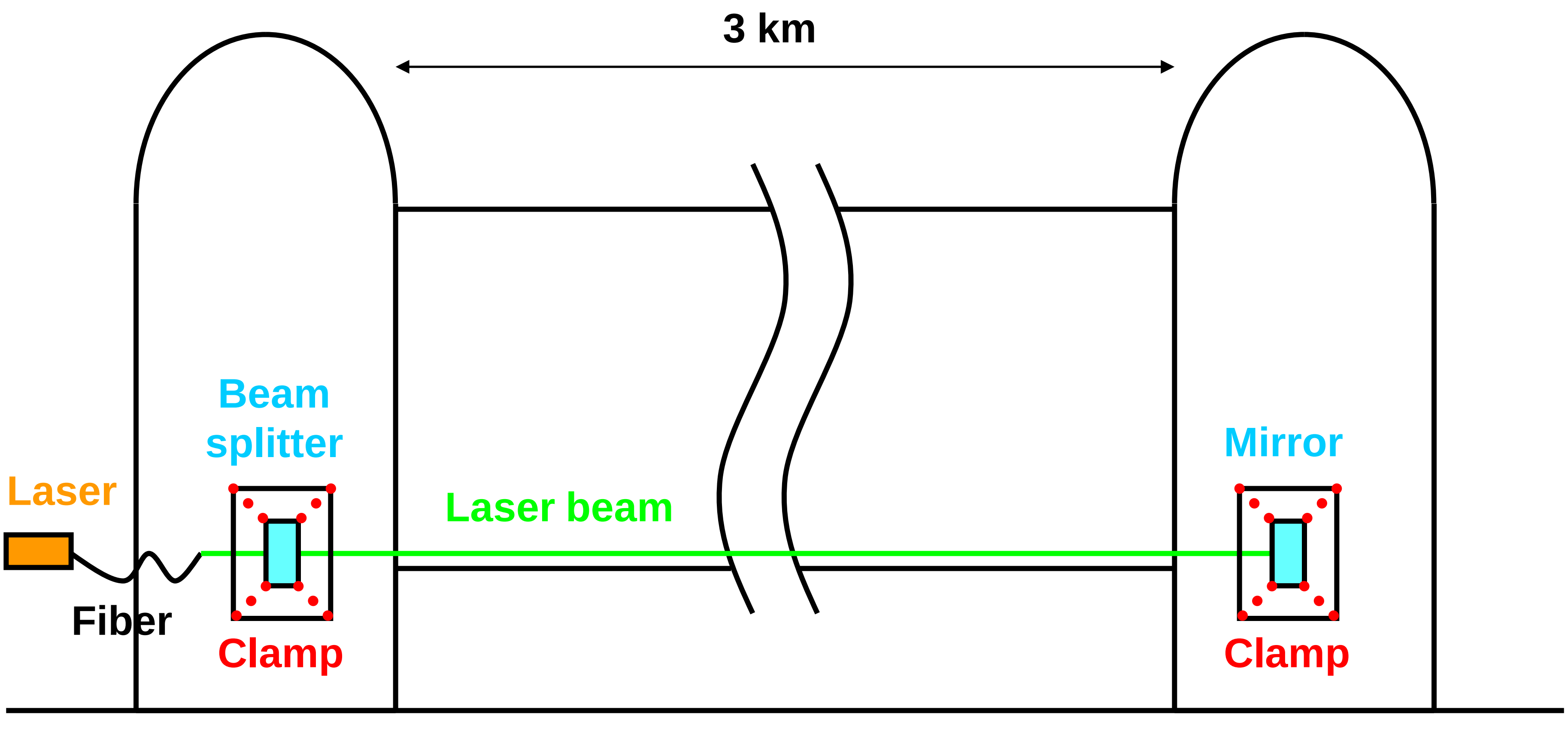
Juggling Interferometer

Motivation



- **Lower frequency gives higher GW signals.**
- **Suspension thermal noise and seismic noise are huge at low frequencies.**
- **What if we can remove suspension?**
- **Magnetic levitation is a kind of suspension.**
- **Free-fall experiment is just one shot.**

km-class juggling interferometer

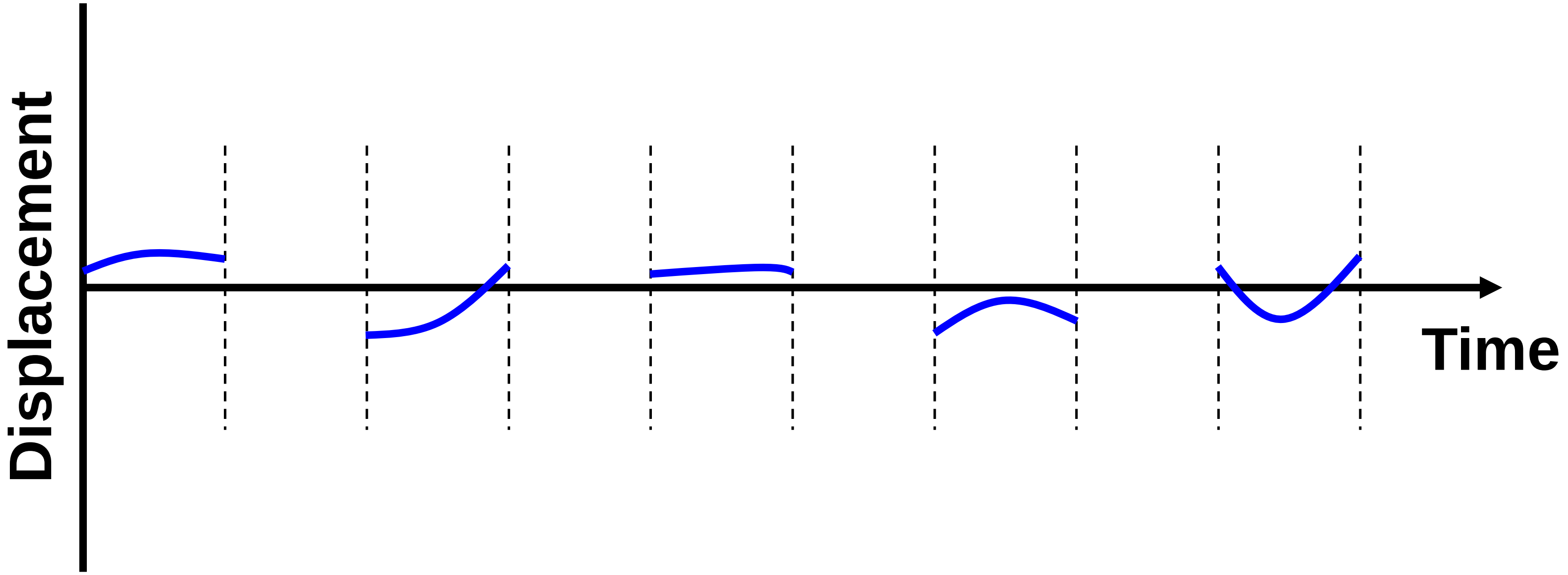


Simple Interferometer

- Simple Michelson interferometer
  - FP cavity is not necessary because the sensitivity is limited by displacement noise at low frequencies anyway
- No fringe lock
  - Fringe lock is not necessary because intensity noise can be suppressed and no power recycling is necessary

Data processing 1

- Produce displacement signal (x) from the two PD outputs



Noise caused by juggling

- x:
  - Longitudinal position on release fluctuates
- dx/dt:
  - Longitudinal velocity on release fluctuates
  - Angular velocity on release fluctuates, which couples with beam off-centering
- d^2x/dt^2:
  - Above two effects couple with each other
- x, dx/dt, d^2x/dt^2 are constant in each segment

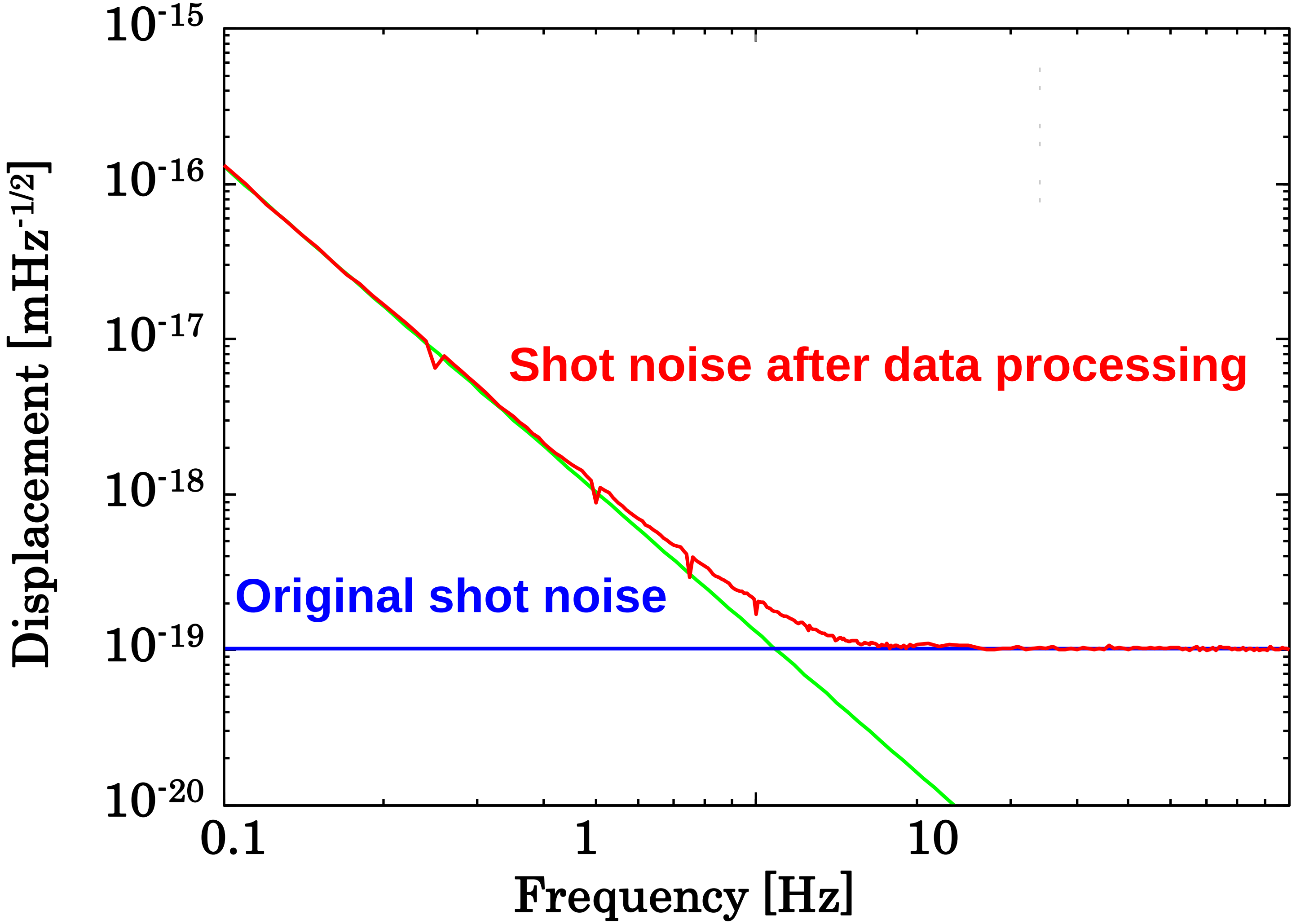
Data processing 2

- **In each segment, calculate $<x>$, $<dx/dt>$, $<d^2x/dt^2>$**
- **Remove them from the data**

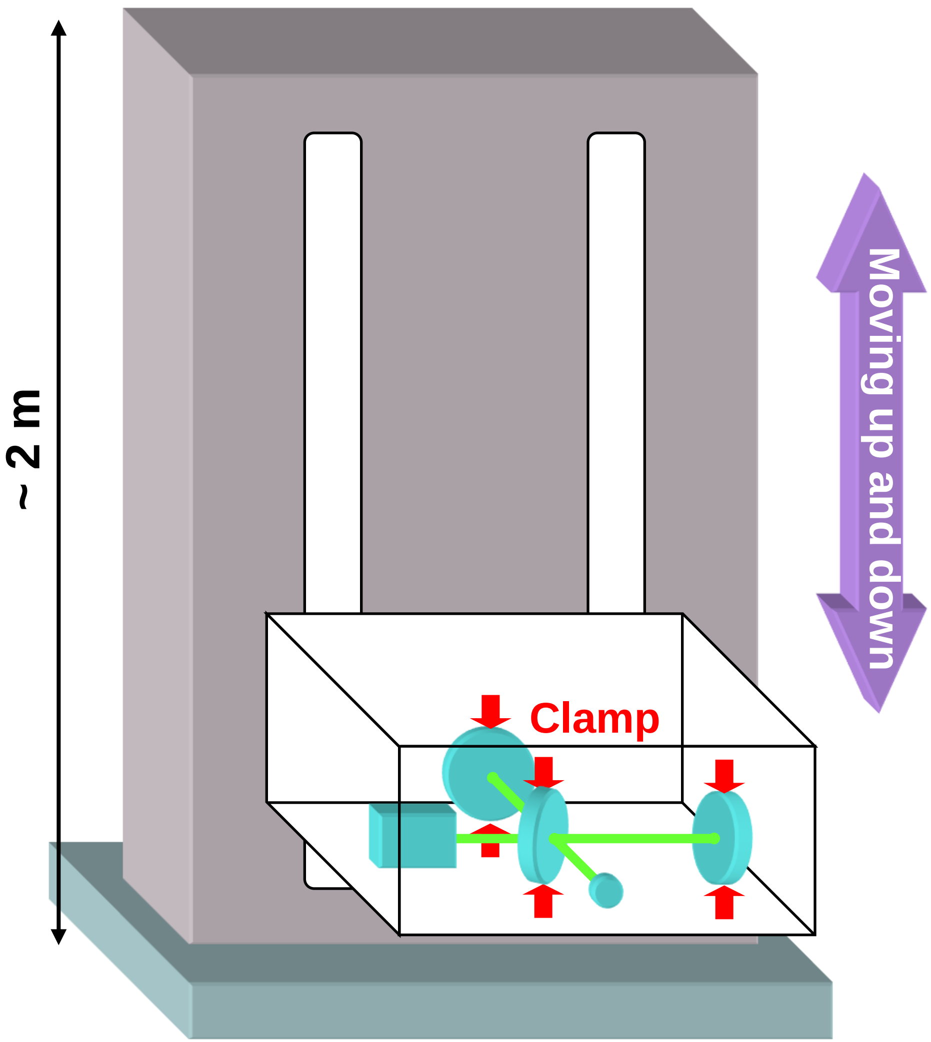
Loss of GW signal

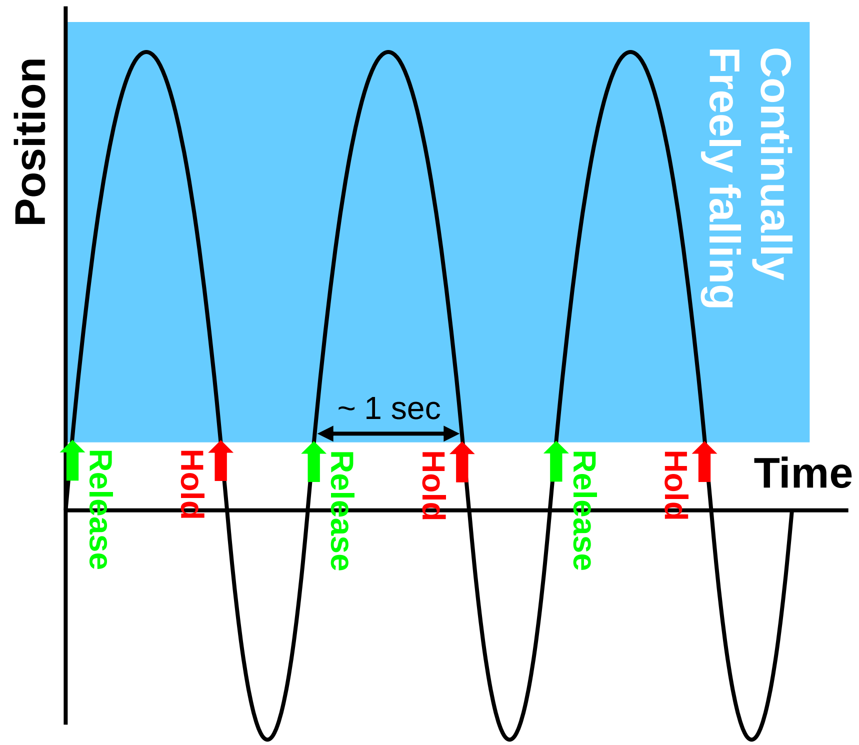
- A part of GW signal especially below 1 Hz is lost during the data processing 2.
- So is a part of any noise.
- S/N remains the same?

S/N degraded below 1 Hz



Juggling interferometer prototype





Application for budget

- This year I applied for basic-research budget with a juggling interferometer
- $500k for 4 years
- 20-30% adoption ratio

Summary

- GW will be detected within several years; GW astronomy will be established.
- DECIGO can detect GWs from the beginning of the universe.
- 3rd generation ground-based detectors need a breakthrough: DFI or Juggling interferometer could be it.